Chapter 5.

ANALYTICAL FRAMEWORK

In this chapter, the economic model used to determine efficient resource allocation for the case study, the Mooki basin, is presented. The optimisation process involves finding the resource distribution that maximises social economic welfare from a catchment manager's perspective, given resource constraints and environmental objectives. The solution provides profit maximising production mix for various water availabilities, in the incidence of government policy changes or increased competition for water.

5.1 SOCIAL OPTIMISATION v PRIVATE OPTIMISATION

There are two ways to model basin water allocation. One way is to determine optimal water allocation from a catchment manager's perspective, and the other is from an individual irrigator's perspective. The optimisation process from both viewpoints is similar, since each would have a common objective to maximise net benefit from production subject to resource constraints. The main difference is that a catchment planner would have the aim of maximise social wellbeing, an integral part of which involves maximising profit to farmers. This is done by distributing water according to its value at the margin across different users. From a private perspective, the opportunity cost of resource use is confined to the farm-level. The water scarcity rent and externalities which have not been priced, in the form of salinity and return flows, are not internalised in the private irrigator's water allocation decisions. As a result, a model simulating individual profit maximising objectives may generate results that deviate from what is socially desirable, due to the discrepancy in the opportunity costs included in the objective. There would be undeniable benefits from an approach that examines behaviour of individual producers, since results from such an analysis could be used to predict the effect of policy. However there remains the need for a policy direction towards socially optimal outcomes, which would not be the case when the problem is only examined from the perspective of individual producers. It is therefore useful to model from a social

perspective, in order to provide policy direction as to the least-cost means of achieving environmental targets and resource constraints at a basin-level. An optimisation model from a perspective of catchment manager is conceptualised below.

5.2 MODELLING COMPONENTS

The irrigation water management at the catchment level will be addressed through an integrated biophysical and economic modelling. The first component is the biophysical model, Soil and Water Assessment Tool (SWAT). This is a basin scale, physically-based hydrologic model that uses Geographic Information Systems (GIS) data to perform parameter estimation and geographical analysis. The agronomic and hydrological outputs form the input for an economic optimisation model, which maximises net catchment profit given resource constraints and environmental targets. This involves intra-seasonal static optimisation, through a linear programming (LP) model, and inter-seasonal dynamic optimisation of groundwater use. This two-stage decision making process ensures that net social benefit is maximised across the planning horizon, and enables the value of inter-temporal trade-offs of groundwater resources to be integrated into production decisions. Surface water allocations cannot be carried over and they have to be used within one season, due to the ephemeral nature of the Mooki. A planning horizon of ten years is considered. This is because the cut-back in future groundwater allocations, according to the groundwater Water Sharing Plan, is to be phased in over ten years. An additional reason is that amortization period of ten years was assumed for capital investments in alternative irrigation technology.

The economic impact of increased competition for water resources is also evaluated, by simulating the effect of an external water user in the regional water market. An empirically derived demand for water for a large coalmining company is used for this analysis.

5.3 MODEL SPECIFICATIONS

The driving force behind the economic modelling is profit maximisation by agents that use scarce resources. This is done from a catchment manager's perspective, for which profit maximising forms an important component in attaining maximum social welfare. The objective is to find the profit maximising distribution of water for the Mooki Basin subject to water availability and deep drainage (DD) constraints, given choices in crops grown, source of irrigation water, irrigation area, irrigation systems, and the opportunity to trade water. A benevolent catchment manager who could hypothetically exert control over these choices would therefore make optimal decisions with respect to these choice variables in such a way that maximises the net social benefits from agricultural activities, but at the same time takes into account resulting environmental impacts. The environmental impacts are predominantly caused by extractive water use and by DD, resulting in increased groundwater and soil salinity, and potential for water logging. Had the groundwater salt concentration of the Mooki been low, there would also be the externality of reduced return flows from improved irrigation efficiency. These effects enter into the catchment manager's decision problem, such that resources are distributed in a way that results with the greatest social benefit in the long-run. The following sections provide greater details of the modelling components.

5.3.1 The Optimisation Model

The optimisation process involves two-stages. One is a dynamic programming model to maximise expected net present value (NPV) across T periods in the light of the possibility for inter-temporal tradeoffs in groundwater allocations, currently in place in the case study catchment. The second stage is a linear programming (LP) model designed to optimise resource use across hydrological response units (HRUs) (N land parcels, denoted by subscript i) within a single period, t. These resource use decisions are based on the expected future surface water allocations. The objective function for the dynamic optimisation model is given by the recursive equation:

$$V_t\{G_{it}\} = \max_{G_{it}}\left[E\{\pi_t(G_{it})\} + \beta E\left\{V_{t+1}\left(\overline{Ga}_{it} - G_{it}\right)\right\}\right] \quad (i = T,\ldots,1) \qquad (1)$$

Where:

$V_t(.)$ is the optimal value function from period t to the end of the planning period, T;

β is the discount factor and equals $1/(1+r)$;

G_{it} is the volume of groundwater pumped by the i^{th} HRU in period t,

$\overline{Ga_{it}}$ is the groundwater allocation available for extraction by the i^{th} HRU in period t;

The term $\pi_t(G_{it})$ is the basin profit in period t, as a function of the control variable, G_{it} (groundwater use decisions of HRUs in period t). The value of $\pi_t(G_{it})$ is found through the LP model, which is used to perform static optimisation of resource use within one season. This is done via decision variables for individual HRUs: surface water use for crop j (S_{ijt}), groundwater use for crop j (G_{ijt}), crop choice (J_{it}), irrigation system choice (Z_{it}), and water allocations purchased (Wd_{it}) or sold (Ws_{it}).

This is represented by:

$$\Pi_t(G_{it}) = \sum_{n=1}^{N}\left(\sum_{j=1}^{J}\pi_{it}(S_{ijt}, G_{ijt}, Z_{it}, J_{it})\cdot AJ_{it} - P_w Wd_{it} + P_w Ws_{it}\right) \quad (2)$$

where $\pi_i(S_{ijt}, G_{ijt}, Z_{it}, J_{it}) = \left(P_j Y_{ijt} - C_{ijt}\right)\cdot J_{it} =$

$$= \left(P_j \cdot f_{ijt}\left(W_{ijt}\right) - \left(\sum_{z}^{Z} FCI_{iz} + WA_{ijt}(z)\cdot a_{ijz} + P_s S_{ijt} + P_p G_{ijt} + OtherCosts_j\right)\right)\cdot J_{it} \quad (3)$$

Refer to Inset 5.1 for a full description of the variables in Eqs. (2) and (3).

Irrigation water can either be diverted from surface water bodies or pumped from groundwater. Application costs are higher when using the groundwater source for each irrigation technology, because of pumping equipment and fuel (Smith and Richards 2003). However groundwater is a more reliable source than the surface water, and is therefore the marginal source used whenever there is shortage of surface water.

Inset 5.1

$\pi_{it}(.)$ is profit per hectare in the i^{th} HRU in period t, expressed as the sum of profit per hectare of J crops produced in the i^{th} HRU in period t;

AJ_{it} is the area planted under crop j in hectares of the i^{th} HRU in period t;

P_w is the market price of water;

Wd_{it} is the amount of water bought by the i^{th} HRU in period t through the water market;

Ws_{it} is the amount of water sold by the i^{th} HRU in period t through the water market;

S_{ijt} is the per hectare surface water applied to crop j in the i^{th} HRU in period t;

G_{ijt} is the per hectare ground water applied to crop j in the i^{th} HRU in period t;

J_{it} is the crop choice in the i^{th} HRU in period t, given by:

$$J_{it} = \begin{cases} 1 & if \ \ crop = j \\ 0 & otherwise \end{cases}$$

Z denotes to the irrigation system used for irrigation;

r is the discount rate;

P_j is the price received for crop j;

FCI_{iz} is the annualised fixed cost per hectare including initial investments and continued maintenance costs of using irrigation technology z in the i^{th} HRU;

W_{ijt} is the effective water consumption per hectare by crop j in i^{th} HRU in period t;

$WA_{ijt}(z)$ is the water applied per hectare to crop j in the i^{th} HRU in period t, and is a function of the irrigation system used;

a_{ijz} is the application cost of irrigation, depending on the choice of irrigation system z;

P_s is the per unit cost of using surface water, including the pumping cost from the river and usage charge;

P_p is the per unit cost of using groundwater, including the pumping costs from the aquifer and usage charge;

$OtherCosts_j$ is the fixed cost per hectare of producing crop j, excluding irrigation costs.

A distinction is made between effective water consumed by crop j (W_{ijt}) and applied water (WA_{ijt}) because the volume WA_{ijt} is likely to be greater due to losses in conveyance and application, depending on the irrigation system used (Foley and Raine 2001). The variable WA_{ijt} is contingent on the irrigation requirement per hectare for the crop in the i^{th} HRU, limited by the volume of surface and ground water available to it. This is augmented by water bought, Wd_{it}, and diminished by water sold, Ws_{it}. The total volume of water used for irrigating crops J in the i^{th} HRU in period t is subject to the following constraint:

$$0 \le \sum_{j=1}^{J} WA_{ijt}(z) \cdot AJ_{it} + Ws_{it} - Wd_{it} \le S_{it} + G_{it} \tag{4}$$

The volume of surface water allocation available for extraction, S_{it}, is a proportion of the total river flow at time t, $\delta \bar{S}max_t$. The volume of surface water that can be extracted is therefore subject to the following constraint:

$$S_{it} = \delta \bar{S}max_{it} \tag{5}$$

The term $\bar{S}max_t$ refers to the maximum total extraction limit, which is in turn determined by the total available river flow in period t. This is discussed in section 5.3.2. The conditions on G_{it} will be discussed further with reference to the dynamic programming.

5.3.2 Environmental Constraints

The environmental constraints are imposed on an annual basis, in the form of DD (which has implications for the occurrence of salinity) and environmental flow targets. These are defined in the LP model as:

$$\sum_{n=1}^{N} \sum_{j=1}^{J} (WA_{ijt} - W_{ijt}) \le DD_t \tag{6}$$

$$\bar{S}max_t \le \overline{FL}_t - CTP_t \tag{7}$$

Where $\sum_{j=1}^{J}(WA_{ijt} - W_{ijt})$ is the water lost to DD in application, given by the difference between applied and effectively consumed water for all crops in the N HRUs. The total DD in water application must be less than or equal to a set target for the basin in period t, DD_{it}. This constraint is to analyse the effect of meeting end-of-valley targets, aimed at reducing salinity contribution from the basin to the Murray-Darling River system.

Constraint (7) specifies that $\overline{Smax}_t$ must not exceed the basin river flow in period t, $\overline{FL}_{it}$, less the Commence-To-Pump limit, CTP_t (the level that in-river flow must reach before extractions can begin). This constraint on surface water use simulates the surface Water Sharing Plan for the case study, which limits the extractive water taken from the river and ensures that environmental flows are provided. The term CTP_t is synonymous to environmental flow rules, and these rules were implemented in SWAT. The effect of further environmental flow rules is exemplified through the constraint on water extractions in Eq. (7), which is parameterised to evaluate the effect of different environmental flow levels on basin profit. This essentially represents a reallocation of extractive water use towards environmental purposes. Annual surface water allocations are therefore successively reduced from the full allocation to simulate the economic impact of increased environmental flow requirements. Similarly, the economic impacts of DD targets are parameterised by varying the value of DD_t in constraint (6). The value of DD is also reduced successively from the unconstrained occurrence associated with full water allocations. The relationship between these environmental constraints and its associated economic impact can thus be derived, and used to form cost functions for achieving environmental targets. The following sections present the optimality conditions given these environmental, and resource constraints.

5.3.3 Static Optimisation Framework

The static optimisation problem, for efficient resource use in the i^{th} HRU, can be represented by the following Lagrangian adapted from the model presented in profit Eq. (3), and constraint Eqs. (4) and (6):

$$\begin{aligned} L\left(S_{ijt}, G_{ijt}, DD_{ijt}\right) = & \left(P_j \cdot f_{ijt}\left(W_{ijt}\right) - \left(\sum_z^Z FCI_{iz} + WA_{ijt} \cdot a_{ijz} + P_s S_{ijt} + P_p G_{ijt} + OtherCosts_j\right)\right) \cdot J_{it} - P_w Wd_{it} + P_w Ws_{it} \\ & - \lambda_{DD}\left(\sum_{i=1}^{N}\sum_{j=1}^{J}\left(WA_{ijt} - W_{ijt}\right) - DD_t\right) \\ & - \lambda_w\left(\sum_{j=1}^{J} WA_{ijt} \cdot AJ_{it} + Ws_{it} - Wd_{it} - S_{it} - G_{it}\right) \end{aligned} \tag{8}$$

where λ_{DD} is the Lagrangian multiplier on deep drainage constraint, which can be interpreted as a shadow value of deep drainage (DD), and λ_{iw} is the Lagrangian multiplier on the water availability constraint, which can be interpreted as the shadow value of water for the i^{th} HRU. Drainage is regarded as 'pollution' that is conjoint with the use of water to produce irrigated crops. To simplify the discussion of theoretical solutions to the LP problem, some notational substitutions are made. The term $\sum_{i=1}^{N}\sum_{j=1}^{J}\left(WA_{ijt}-W_{ijt}\right)$ is substituted by $g\left(DD_{ijt}\right)$, to denote the total drainage in the basin as a function of the drainage in each HRU. Similarly, the term $\sum_{j=1}^{J}WA_{ijt}\cdot AJ_{it}+Ws_{it}-Wd_{it}$ is substituted by $h\left(S_{ijt},G_{ijt}\right)$, to denote basin water use as a function of surface and groundwater use in each HRU. Assuming an internal solution exists, the first-order condition (FOC) for optimality with respect to surface and groundwater used by the i^{th} HRU, and the associated 'optimal' pollution in the form of drainage, DD_{ijt}, are represented by:

$$\frac{\partial L}{\partial DD_{ijt}}=\left(P_j\cdot\frac{\partial f_{ijt}\left(W_{ijt}\right)}{\partial DD_{ijt}}-\frac{\partial WA_{ijt}}{\partial DD_{ijt}}\cdot a_{ijz}\right)\cdot J_{it}-\lambda_{DD}\frac{\partial g\left(DD_{ijt}\right)}{\partial DD_{ijt}}=0 \tag{9}$$

$$\frac{\partial L}{\partial S_{ijt}}=\left(P_j\cdot\frac{\partial f_{ijt}\left(W_{ijt}\right)}{\partial S_{ijt}}-\frac{\partial WA_{ijt}}{\partial S_{ijt}}\cdot a_{ijz}-P_s\right)\cdot J_{it}-\lambda_{iw}\left(\frac{\partial h\left(S_{ijt},G_{ijt}\right)}{\partial S_{ijt}}\right)=0 \tag{10}$$

$$\frac{\partial L}{\partial G_{ijt}}=\left(P_j\cdot\frac{\partial f_{ijt}\left(W_{ijt}\right)}{\partial G_{ijt}}-\frac{\partial WA_{ijt}}{\partial G_{ijt}}\cdot a_{ijz}-P_p\right)\cdot J_{it}-\lambda_{iw}\left(\frac{\partial h\left(S_{ijt},G_{ijt}\right)}{\partial G_{ijt}}\right)=0 \tag{11}$$

$$\frac{\partial L}{\partial \lambda_{dd}}=g\left(DD_{ijt}\right)-DD_t=0 \tag{12}$$

$$\frac{\partial L}{\partial \lambda_{iw}}=h\left(S_{ijt},G_{ijt}\right)-S_{it}-G_{it}=0 \tag{13}$$

Eq. (9) suggests that the optimal level of DD_{ijt} should be such that its marginal value in production (alternatively the marginal benefit of pollution as defined in Hartwick and Olewiler, 1986), $P_j\cdot\frac{\partial f_{ijt}\left(W_{ijt}\right)}{\partial DD_{ijt}}$, equates with the application cost associated with reducing

deep drainage (marginal cost of abatement), $\frac{\partial WA_{ijt}}{\partial DD_{ijt}} \cdot a_{ijz}$, plus the marginal value of emitting DD elsewhere in the catchment, $\lambda_{DD} \frac{\partial g\left(DD_{ijt}\right)}{\partial DD_{ijt}}$. The occurrence of DD is associated with the water use in the basin such that, without water trade, reductions in DD are confined to reductions in associated water use within the HRU. In the presence of water trade, DD becomes mobile and can be transferred to various parts of the basin. This then resembles a DD market, where DD is transferred through water trade, and the 'efficient' DD_{ijt} occurrence on a basin scale is then achieved as drainage is shifted to its highest value use.

Eq. (10) suggests the optimal level of surface water use S_{ijt} should occur at a point where its marginal value in production, $P_j \cdot \frac{\partial f_{ijt}\left(W_{ijt}\right)}{\partial S_{ijt}}$, equates with the application cost (marginal factor cost) of S_{ijt}, $\frac{\partial WA_{ijt}}{\partial S_{ijt}} \cdot a_{ijz}$, plus the opportunity cost of S_{ijt} in the water market, and the opportunity cost of S_{ijt} in production elsewhere in the catchment, $\lambda_{tw}\left(\frac{\partial h\left(S_{ijt}, G_{ijt}\right)}{\partial S_{ijt}}\right)$. In the absence of water trade, the opportunity cost of S_{ijt} is zero and the opportunity cost of water use is confined to the marginal value product (MVP) of irrigated production within the HRU. Where a water market exists, water is traded to its highest value use within the catchment such that the MVP of S_{ijt} is equated across the HRUs. This leads to an efficient outcome that maximises basin profit from surface water use.

Eq. (11) suggests the optimal level of G_{ijt} is where its marginal value in production, $P_j \cdot \frac{\partial f_{ijt}\left(W_{ijt}\right)}{\partial G_{ijt}}$, equates to the application cost of groundwater (marginal factor cost) G_{ijt}, $\frac{\partial WA_{ijt}}{\partial G_{ijt}} \cdot a_{ijz}$, and the opportunity cost of G_{ijt} in production elsewhere in the HRU,

$\lambda_{tw}\left(\frac{\partial h(S_{ijt}, G_{ijt})}{\partial G_{ijt}}\right)$. Since groundwater is not traded in the water market, its opportunity cost is limited to the *MVP* of irrigated crops within the HRU. Equations (12) and (13) denote the requirement that resource constraints are exactly met.

5.3.4 Dynamic Programming Framework

The dynamic constraint on using groundwater can be represented as follows. The volume of groundwater pumped by HRU i in period t, G_{it}, must be less than its groundwater allocations available in that period, $\overline{Ga}_{it}$. Excess allocations that are unused can be rolled over to the next season, to a maximum of three consecutive years. In addition, in any one season a maximum amount of two-season's worth of allocations can be extracted (DLWC 2003). This only applies for groundwater resources, because surface water can not be banked in an unregulated system.

Given the inter-temporal nature of groundwater extraction, the optimisation of groundwater use across ten years through the control variable, G_{it} (HRU groundwater use in period t), is represented by the recursive Eq. (1) which is reproduced here for the convenience of the reader:

$$V_t\{G_{it}\} = \max_{G_{it}}\left[E\{\pi_t(G_{it})\} + \beta E\left\{V_{t+1}\left(\overline{Ga}_{it} - G_{it}\right)\right\}\right] \quad (i = 9,\ldots,1) \tag{1}$$

Assuming a planning period of 10 years, the final value of stock remaining at the 10th (final) period:

$$V_{10}\{G_{i,10}\} = F\{G_{i,10}\} \tag{14}$$

And boundary conditions:

$$G_{i1} = \overline{Ga}_{i1} \tag{15}$$

$$\lambda_{10} = dF / d\overline{Ga}_{i,10} \tag{16}$$

Where the first boundary condition, Eq. (15), is the initial stock level which equals the available groundwater allocation in period one ($\overline{Ga}_{it}$). The second condition, Eq. (16), is the inter-temporal value of the stock at the final period.

The available water allocation in each period t ($\overline{Ga}_{it}$) is the sum of seasonal allocations ($\overline{G}_{it}$) over three-consecutive periods:

$$\overline{Ga}_{it} = \sum_{t}^{t+2} \overline{G}_{it} \tag{17}$$

With a condition on the control variable, G_{it}, that the maximum volume used in one period is confined by two-consecutive period's water allocation:

$$G_{it} \leq \sum_{t}^{t+1} \overline{G}_{it} \tag{18}$$

And the necessary conditions for inter-temporal optimality:

$$\frac{\partial \pi_t(.)}{\partial G_{it}} = -\beta \lambda_{t+1} \left(\frac{\partial \overline{Ga}_{i+1}}{\partial G_i} \right) \text{ and } \lambda_t = \frac{\partial \pi_t(.)}{\partial \overline{Ga}_t} + \beta \lambda_{t+1} \left(\frac{\partial \overline{Ga}_{i,t+1}}{\partial G_{i,t}} \right) \tag{19}$$

This first term suggests that the immediate gains (losses) must equal to the present value (PV) of future losses (gains) in determining G_{it}^*. That is, the optimal choice of G_{it} should take into account the user cost: groundwater extractions should be increased until the marginal gains offset the PV of future losses, and vice versa, until the inter-temporal optimality condition holds. The second condition suggests that the optimal increase in the value of groundwater stock in period t, equals the additional period gain plus the discounted value of groundwater stock at period $t+1$.

5.3.5 Conceptualising Water Trade

In any given period, an irrigator can choose to buy or sell surface water through the water market. This decision can be conceptualised in the following way. An irrigator offers to sell some water on the market if the market price of water is greater than its MVP in irrigated agricultural production, and conversely the irrigator becomes a water demander at the margin if the market value of water is lower than the MVP in production (Figure 5.1). This buying and selling behaviour depends on each irrigators' derived demand for

water, Q_d, at an exogenous price, P_w, and surface water allocation, Q_1, *ceteris paribus*. The mechanism for water trade for an individual irrigator is illustrated in Figure 5.1, with the gains from trade for the buyer denoted by area *ADE*, and for the seller the gains from trade are shown by area *ABC*.

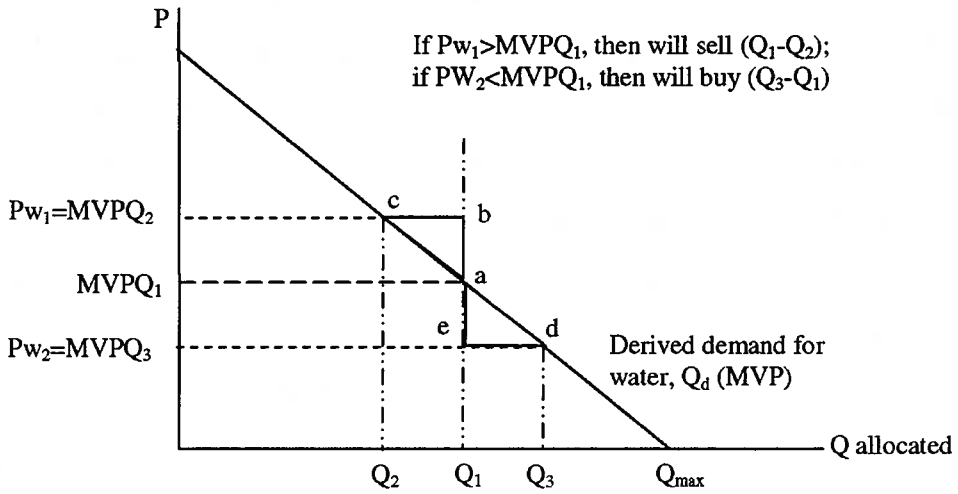

Figure 5.1: Irrigator's water demand and supply behaviour.

Despite the perceived benefits of water trade, many producers in the Mooki do not participate in the recently established water market because the purchase of water allocations is considered too expensive. Instead, some irrigators have commented that it is more cost-effective to invest in water saving technologies (Morgan 2005, pers. comm.). There are also perceived risks associated with offloading entitlements now and buying them back at higher prices in future. For the buyer, the entitlement only ensures a share of available flows of varying reliability, which reduces the expected value of the investment. For these reasons, water trading is regarded as unfavourable by many irrigators. However, if the benefits of temporarily trading water as a commodity could be credibly demonstrated, it may encourage trade, especially if it can be shown to augment the returns from investments in water efficient technology.

In this thesis, water prices are parameterised exogenously, such that market prices are unaffected by the purchasing and selling activity of irrigators in the catchment. The model takes the form of an interregional competition model as per Heady et al. (1973),

whereby each irrigator has its own resources but can also compete for a shared resource, subject to transportation costs. In terms of water, the transportation cost could be represented as the water loss associated with 'transporting' water upstream or downstream. However, it is assumed that intra-regional water trade in a small catchment would be relatively efficient and the transport coefficient would be close to 100%. This interregional competition model is similar to spatial equilibrium models (Takayama and Judge 1971), except that the price here is exogenously set, rather than endogenously determined in the model. While an interregional trade model does not result in an equilibrium (endogenous) price of water in trade, the equilibrium water price can be represented by the shadow value of water when the price of water is set to zero, $P_w = 0$, since, at zero cost, the irrigator will continue to demand water until its value of the marginal product falls to zero. Where water supply is binding, its shadow value for the considered HRUs would represent the market-clearing price.

5.3.6 Internal and External Water Trading

An external trader is introduced to the model by including an additional term in the objective function, Eq. (2), to represent the value of water to an external agent:

$$\Pi_t(G_{it}) = \sum_{n=1}^{N}\left(\sum_{j=1}^{J}\pi_i(t)\cdot AJ_{it} - P_w Wd_{it} + P_w Ws_{it}\right) + \int f(P_w)\,dP_w \tag{20}$$

A linear factor demand for water is assumed for the external buyer, in the form of $f(P_w) = a - bP_w$, and the objective is to maximise the gain from water trade (internally) to other irrigators, or trade to the external agent. In the presence of an external buyer, equilibrium trade occurs where marginal value product (MVP) is equated across the irrigators and the external buyer of water:

$$MVP_i(W_{ijt}) = MVP_k(W_{kjt}) = \ldots = MVP_E(W_E) \tag{21}$$

Where W_E is the water demanded by the external agent.

5.3.7 Water Allocation and Crop Choice

The optimal allocation of water from a social perspective is such that the *MVP* of the last unit of water used for each crop is equated with all private and social costs associated with the crop produced. It is assumed that the primary irrigation water demand would be sourced from the river until the cost of using surface water, P_s, outweighs the cost of groundwater, P_p, or if surface water is limiting (Zilberman and Lipper 2002). The producer has the option of growing dryland crops in response to water shortages if it becomes the most profitable option. When the farmer decides to switch to dryland production, the operating cost associated with irrigation is eliminated from the objective function for that period. The fixed costs of the irrigation technology, however, would be sustained regardless of whether dryland or irrigated crop is produced because the investment has already been made. An additional condition has been defined to represent the dryland production option, whereby if $j=m$ and m is a dryland crop, production costs become the fixed costs of the irrigation system plus other dryland production costs, i.e. the cost function in Eq. (3) becomes $C_{ijt} = \sum_{z}^{Z} FCI_{tz} + \{\text{dryland costs}\}$.

5.4 SUMMARY OF CHAPTER 5

The combined linear programming and dynamic programming economic model used in this thesis builds on theories of optimality, and is applied to the case study Mooki catchment in the Namoi Valley. The underlying assumptions of the model are justified based on the characteristics specific to the Mooki. The next chapter will provide a description of specific features of the Mooki basin that form considerations for the modelling framework.

Chapter 6.

CASE STUDY – THE MOOKI BASIN

A description of the case study considered in this thesis, the Mooki basin in the Namoi Valley, is presented in this chapter. Firstly, a geographical description of the Mooki basin is provided. This is followed by the various characteristics that are specific to this catchment and are addressed in this thesis.

6.1 GEOGRAPHY OF THE CASE STUDY AREA – THE MOOKI BASIN

The Mooki River basin is a tributary of the Namoi River Valley located in northern NSW, and forms part of the Murray-Darling Basin. The Mooki basin lies between the townships of Gunnedah and Quirindi, and includes the upstream reaches of Phillips, Warrah and Quirindi Creek water sources (Figure 6.1). These irrigation areas form part of the Upper Namoi and produce 21% of the irrigated production in Namoi, valued at AUD$526 million (11% of the value of NSW irrigated industry). This is despite total irrigated agriculture covering just 1.5% of the catchment (NSW Irrigators' Council 2001; Aluwihare et al. 2001; Trewin 2006).

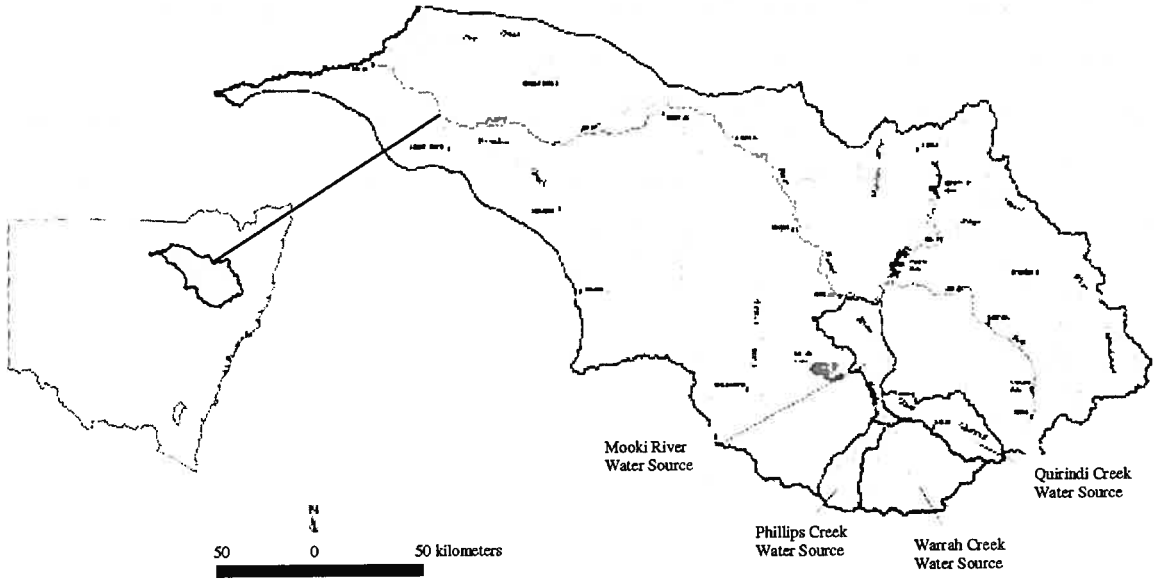

Figure 6.1: Location of the Mooki basin (shaded) in the Namoi catchment (Source: DIPNR 2004b).

Irrigators in the Mooki Basin hold unregulated licences, meaning there is no upstream head dam to 'regulate' flows downstream. As a result, producers in unregulated systems held area-based licences, and were confined by the area they can irrigate rather than the volume extracted. Due to the extreme variability of flows in the Mooki, irrigators make the most of passing flows by pumping as much water as possible whenever the opportunity arises. The median flow is 10ML/day, but for 25% of the year no flows occur in the Mooki, and for almost 20% of the year flows are above 100ML/day (Figure 6.2). Flows above 1,000ML/day are rare, occurring just 4% of the time although this is highly variable from year to year. Flows above 3,000ML/day occur less than 2% of the time (DIPNR 2004b). Given this distribution of flow, large on-farm storages are therefore common in the Mooki River basin and extraction occurs wherever there is enough water in the river. Without strict rules constraining individual irrigators' extraction level, there is a tendency for inefficient (too high) levels of water being extracted.

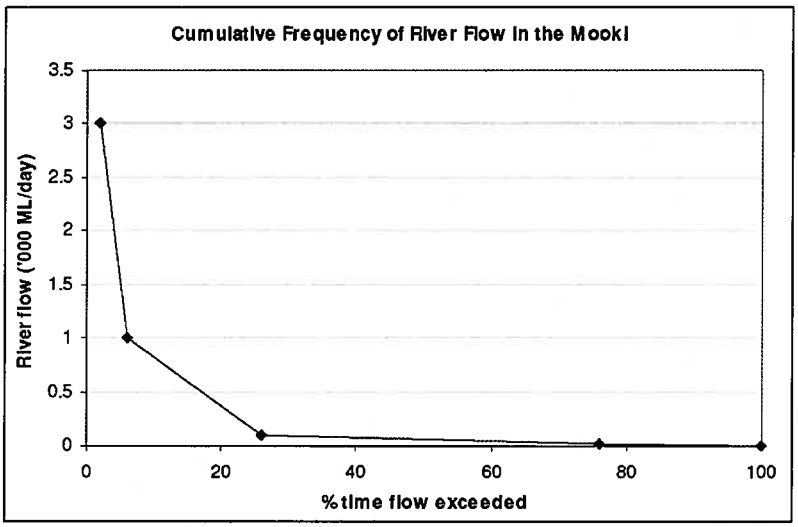

Figure 6.2: River flow in the Mooki (source: adapted from DIPNR 2004b).

As with many other catchments in the MDB, Namoi has recently had a number of environmental policies put in place. All catchments in NSW are now required to have Water Sharing Plans (WSP) for both surface water and groundwater, to limit extractions and to ensure fair distribution. With the introduction of the WSP, these area-based licences are converted into volume-based licences, essentially based on an estimate of irrigation requirements from its history of use. Surface WSP stipulates a minimum environmental flow requirement as well as a set of extraction rules for irrigators sharing

the same hydrological system. Groundwater has been a significant water source for the region since the 1980s, during which groundwater entitlements have been offered as supplementary water to river extractions. However, due to the over-allocation, there are now plans to severely cut back the number of groundwater entitlements, up to 90% in certain zones. The groundwater WSP is to be phased in over the next ten years (CARE 2003).

The set of WSP rules governing the pumping of river flow varies depending on the irrigation area and on the level of flow. Essentially, pumping cannot commence until flows exceed a Commence-To-Pump (CTP) level, which amounts to imposition of an environmental flow rule. For the Mooki Water Source, the CTP is 100ML/day before extractions may begin; for Phillips Creek Water Source and Quirindi Creek Water Source, the CTP is 2ML/day; for the Warrah Creek Water Source the CTP is 4ML/day (DIPNR 2004b). However, flows above this level could be fully extracted. While the limits on individual extractions should mean equal share of flows, the uppermost irrigator inevitably has priority to available flow (up to his/her daily extraction limit) and less becomes available to downstream irrigators (Powell 2006, pers. comm.). These are considerations that enter into biophysical simulations of surface water access by different areas within the Mooki.

The total area of the Mooki Basin as reported in DIPNR (2004b) is 3,741km^2 (374,100ha), which is somewhat smaller than the GIS referenced area in the biophysical model of 4,525km^2. This discrepancy is due to the uncertainty with regards to the actual size of the catchment, since in flood years surround water course flow into the Mooki and affect the delineation of the catchment boundary (Vervoort 2006, pers. comm.). However, the difference in catchment boundary does not affect the landuse distribution, which was based on 2002 data from DIPNR as shown in Table 6-1. It was assumed that all irrigated areas are producing cotton, which makes up 397 km^2.

Table 6-1: Landuses in Mooki Basin (source: Vervoort 2006, pers. comm.).

Landuse	Area of Basin (ha)
Pasture	273,939
Row-crops	105,759
Irrigated crops	39,700
Forest-mixed	22,631
Urban	6,690
Water	3,426

6.2 COTTON PRODUCTION IN THE NAMOI VALLEY

The first irrigated cotton operation in Australia began in the Namoi Valley during the 1960s (Thomson 1979), which has become the second largest cotton growing region in Australia (CCCCRC 2007). Along with the production of cottonseed oil, a significant oil seed crop in Australia, the cotton industry is regarded as the highest value crop in NSW (Anthony 1998). However, it is also one of the highest water consuming agricultural industries. More than 84%of Australian cotton is grown under irrigation, which accounts for about 1,819GL of agricultural water use in 2004-05 (Cotton Australia 2007; Trewin 2006). This represents 18% of irrigation water use in Australia, making it the second largest consumer of water following pasture for grazing (28.7%). On a per hectare basis, cotton also rates as the second highest consumer of water (Trewin 2006). The average gross value of cotton per megalitre is lower than sugar but higher than rice, which are also water intensive industries (Table 6-2). While the cotton industry in Australia has a good reputation for being the highest yielding and most water efficient in the world (Tennakoon and Milroy 2003), there remains the case for improving the industry's water use efficiency.

Table 6-2: Water use and value of irrigation industries in Australia (source: Trewin 2006).

Crop	Average volume applied ('000ML)	Average application rate (ML/ha)	Average gross value ($/ML)
Rice	618.9	12.1	163
Cotton	1,819.3	6.7	519
Sugar cane	1,171.9	5.5	836
Fruit trees	177.3	5	-
Pasture for grazing	2,896.5	3.4	-

Of the six largest cotton producing regions in Australia, the highest crop water use efficiency was found to be 3.2kg/ha/mm in the Darling Downs, and the lowest was 2.0kg/ha/mm in the Namoi (Tennakoon and Milroy 2003). This translates to 9.8 bales/ha for Darling Downs and 6.2 bales/ha for Namoi, assuming crop water requirements of 7ML/ha. This derived yield for Namoi is very low compared to figures reported in Boyce (2005), which reported yields of 9.1-10.3 bales/ha for upper and lower Namoi. Anecdotal evidence also suggests that irrigators in Namoi get around 8-10 bales/ha, applying 7-8ML/ha of irrigation water (Norrie 2006, pers. comm.). Based on these figures, it appears that cotton yield in the Namoi can range between 6-10bales/ha, with a water consumption of around 7ML/ha (Tennakoon and Milroy 2003).

6.3 DEEP DRAINAGE IN THE NAMOI VALLEY

As discussed in the earlier chapters, salinity is closely linked to groundwater hydrology. The cultivation of shallow-rooted crops and clearance of native vegetation has increased the level of deep drainage, leading to saline shallow watertables. Rising watertable levels can contribute to soil salinisation and saline deep aquifers (Mawhinney 2005). Deep drainage refers to water that moves below the maximum effective plant zone, having not been absorbed by vegetation, gradually filling (recharging) shallow aquifers and bringing salts to the surface. Saline water can also seep from the ground and permanently intersect with the base of the river as return flow (UNL 2007; DEWR 2007).

Some drainage is required to carry salts out of the soil, and the rate of deep drainage should be kept to the natural contribution from rainfall. However, where this natural rate

is exceeded, excessive levels of drainage occur and contribute to rising watertable and increased salinity levels. The dynamics of salinity, however, makes it difficult to establish exactly how deep drainage contributes to salinity, and how long it takes to reach a new equilibrium; soils with high drainage rates can take as short as one year to achieve equilibrium, but low draining soils can take many decades (Jolly et al. 2001). This time lag creates difficulties in establishing the damage drainage causes, given that by the time an increase in salinity is detected the system has already shifted to a new equilibrium, and the benefits of reducing drainage now will not be realised for several decades after (Silburn and Montgomery 2005).

The amount of deep drainage which occurs in the Namoi, and other catchments, is uncertain. It is generally assumed that deep drainage can be close to zero for heavy clay soils in the northern inland areas. Namoi soils (sodic grey vertisols) have low, but not insignificant, drainage due to lower permeability (Silburn and Montgomery 2005). The average drainage per irrigation is 0.015ML/ha (1.7%) for Namoi, which is very low relative to the adjacent Gwydir valley (14%). The review in Silburn and Montgomery (2005) shows annual deep drainage for the Namoi ranging from 0.03-9 ML/ha per year, although averaging around 1-2ML/ha per year.

The interception of groundwater aquifers with the river is not thought to occur in the Mooki, since the shallow and deep aquifers sit far below the stream bank and rarely rise enough to 'return flow' to the river (Lavitt 1999; Vervoort 2007, pers. comm.). Deep drainage does not become groundwater supply in the Mooki, due to the segregated shallow and deep groundwater layers. The shallow aquifer sits on an unconfined layer above the deep aquifer which is where groundwater pumping occurs (Table 6-3). Deep drainage, however, recharges the shallow aquifer which has a very high salinity and is unsuitable for irrigation. Where there is significant drawdown on the deep aquifer due to pumping, some shallow aquifer water could leak into the deep aquifer, potentially increasing the salinity level (Vervoort 2007, pers. comm.). For the Namoi region, the time lag between deep drainage and recharge to the shallow aquifer was found to be relatively short (Karen Ivkovic 2005, pers. comm.). This suggests that any changes in

deep drainage will be realised quickly. While the exact nature of the interaction between deep drainage and the groundwater aquifers are up to conjecture, the focus should be to reduce deep drainage thereby salinity risk. For greater detail on groundwater hydraulics, see Appendix A.

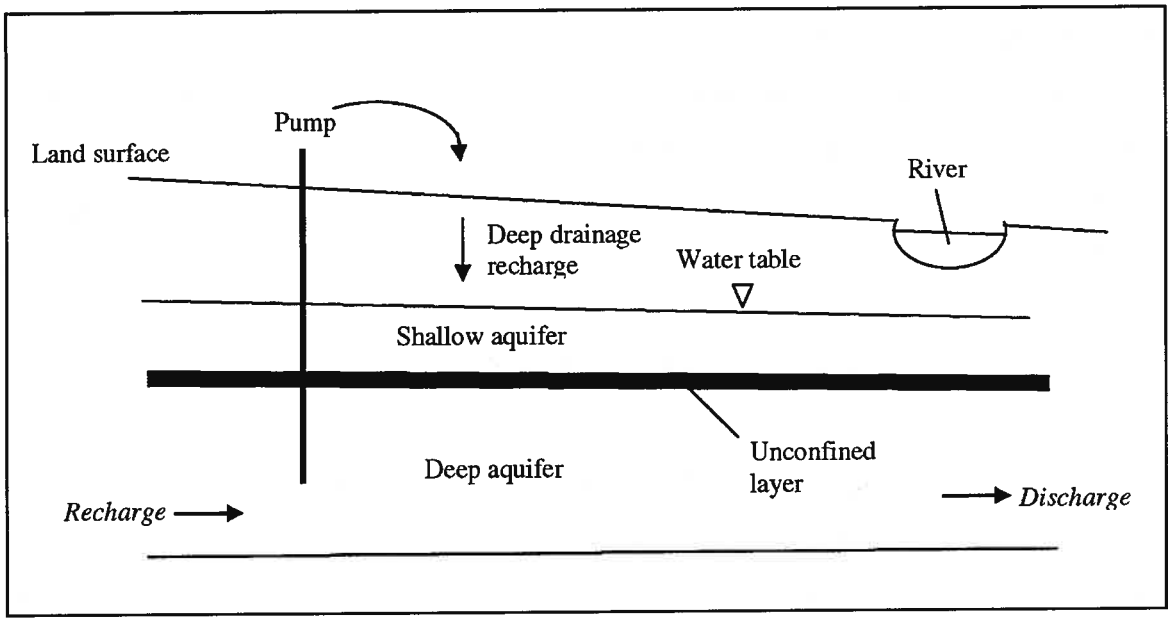

Figure 6.3: Shallow and deep aquifer interaction in the Mooki (source: Vervoort 2007, pers. comm.)

6.4 SALINITY IN THE NAMOI VALLEY

Depending on the standard that is considered, salinity in Namoi can either be below target or significantly over. According to the Australian and New Zealand Environment and Conservation Council (ANZECC) recommendations, 330µS/cm is the limit for healthy ecosystem protection[2]. However, the Namoi Catchment Blueprint allows a higher target of 550µS/cm as a more realistic target due to the history of human activity in the catchment (DLWC 2002), which is in line with keeping the end-of-valley salinity target at Morgan[3] (in South Australia) below 800µS/cm. Salinity readings can also be expressed as decisiemens per metre (dS/m) or as a salt load according to the following equation:

$$1\ dS/m = 1{,}000\ EC\ (or\ \mu S/cm) = approx.\ 640\ mg/kg$$

[2] µS/cm is the electrical conductivity (EC) reading for salinity concentration in water.
[3] Morgan is where the salinity measurement is taken, upstream of the mouth of the river Murray in South Australia.

That is, one megalitre with an electrical conductivity (EC) of 1,000µS/cm contains about 640kg of salts[4]. The soil salinity that results depend on the class of soil; the slower draining, the higher soil salinity is because the salt content of water seems to be retained in the soil. Poorly drained clay soil can become three times as saline as the water applied, so the water salinity limit (the maximum EC of irrigation water to avoid losses in crop yield) should be about one-third of the soil salinity. For example, for very slow draining soils, the water salinity limit is 330µS/cm given a crop EC tolerance of 1,000µS/cm. (NSW DPI 2006b).

A comparison of median EC at three locations downstream of major cotton-growing areas, at Namoi River (Bugilbone), Mehi River (at Bronte), and Barwon River (Mungindi) is presented in Figure 6.4. This figure shows highest median EC readings at Namoi Valley in most years (Mawhinney 2005).

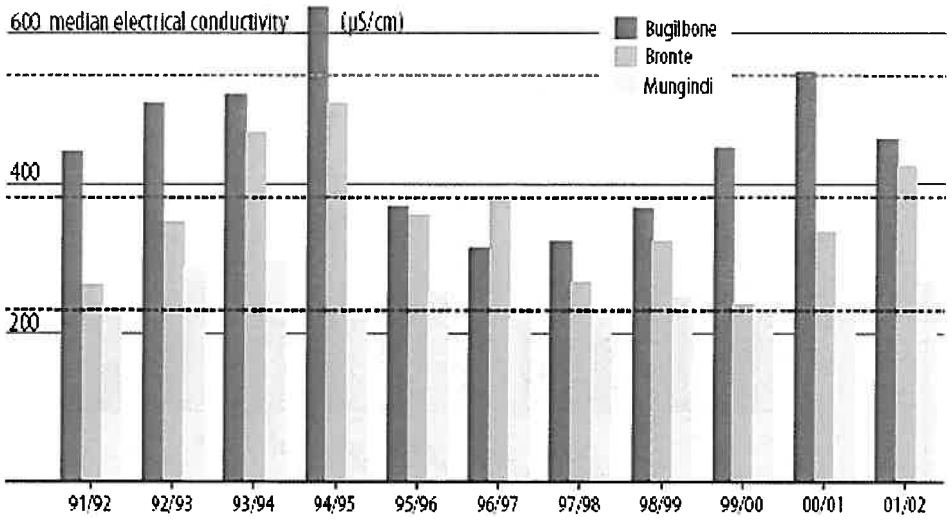

Figure 6.4: Mean EC for major cotton growing valleys (Source: Mawhinney 2005 p.269).

While Namoi is relatively saline, currently there is little impact on agriculture within the catchment. The cost of salinity to agricultural producers in the Namoi, Gwydir and Border Rivers region totals $6Mill per year, majority of which is associated with

[4] The salt load can vary between 600-800 mg/kg depending on the chemical composition of water.

infrastructure and maintenance costs. Less than $2Mill of this is attributed to losses in agricultural income (Wilson and Ivey 2001). One reason for a salinity target in the Namoi is to ameliorate the downstream impact of salinity discharged from Namoi on the Barwon-Darling system, which flows into the Murray-Darling. However, given the relatively high salt tolerance of cotton, which has a salt tolerance level of 1,700µS/cm, there is little incentive for cotton irrigators in Namoi to internalise their salinity contributions into their production decisions. However, river salinity as high as 1,000µS/cm has been recorded in Gunnedah on occasion, which could cause crop losses of up to 10% if irrigation is conducted during the seeding stages (NSW DPI 2006b).

The median reading for the Mooki over 2003-06 was 534µS/cm, which suggests that for every megalitre (ML) of deep drainage, 342kg of salt is carried into the river (assuming a one-to-one ration between drainage and salt load). This reading places Mooki within the target salinity level specified in the Namoi Catchment Blueprint of 550µS/cm, with the highest median EC reading recorded in Mooki River (Breeza) and Coxs Creek (Boggabri) over 2000-2001.

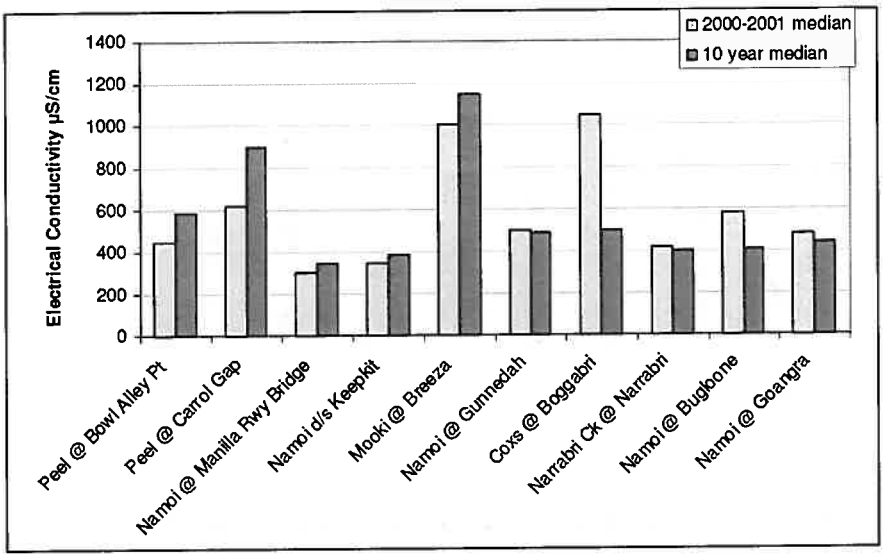

Figure 6.5: Median electrical conductivity in the Namoi Catchment (source: DLWC 2002)

In terms of salt load, the end-of-valley target for the whole of Namoi at Goangra is 127,600t/yr. This Blueprint salt load target suggests that the maximum level of deep drainage for the whole of Namoi should be:

$$\frac{127,600,000kg}{534\mu S/cm} = 238,951ML/yr$$

For the Mooki itself, the salt load measurement is 3,000t/yr which translates to 5,618ML of deep drainage assuming an EC of 534µS/cm. This was an exceptionally low reading, attributed to the low flows experienced during the 2003/04 season (DLWC 2002). During normal flow years, the salt load contribution from the Mooki is expected to be higher.

6.5 GROUNDWATER ENTITLEMENT REDUCTION

Irrigators in the Namoi have developed a reliance on groundwater as a result of early water policies. Conjunctive licences to withdraw groundwater were initially handed out to irrigators to alleviate water shortages from severe drought in 1983-84, which subsequently remained as a staple water source (Haisman 2005). Due to policies set at the time, which effectively implied 'mining' of the groundwater resources, the number of extractive groundwater licences became over-allocated. This led to severe declines in groundwater levels that were noticeable within three years of distribution (Hamparsum 2004). Irrigators had become aware of the depletion and agreed to voluntary cuts to entitlements of up to 35% in 1995. It was not until the end of the 1990s that the NSW government had moved towards sustainable management of groundwater resources, eventually resulting in the groundwater Water Sharing Plan (WSP) in 2002 following from the writing of the Water Management Act 2000 (CARE 2003). The groundwater WSP was gazetted in December 2002, although it did not commence until the 2004-05 irrigation season (CARE 2003). The intention of the groundwater WSP was to limit the aquifer access licences (AAL) to its 'sustainable' recharge level determined for each Zone, such that its use can be maintained indefinitely without depleting the resource. The estimated sustainable extraction rate will be reviewed and adjusted if necessary.

However, it stands to reason that all recharge estimates are subject to significant uncertainty. It has also been suggested that there is no such thing as a 'sustainable' yield that can be indefinitely maintained. This is due to long-term effects on deep aquifer discharge and recharges (see Figure 6.3), which changes from its equilibrium state when

groundwater is pumped (Alley and Leake 2004). Groundwater pumping may increase the upstream recharge rate while reducing the downstream discharge rate, which affects the groundwater supply to irrigators at both ends of the aquifer system. A more appropriate term would be groundwater 'capture', which implies there are third-party impacts upstream or downstream of the pumping site (Bredehoeft 2006). In this sense, there is a trade-off between upstream and downstream use of groundwater that should be factored into economic decisions. Nevertheless, the concept of sustainable recharge has been used by the Department of Natural Resources for its WSP determinations based on simulations of rainwater infiltration, without consideration for changes in groundwater equilibrium from pumping the 'sustainable' recharge (Vervoort 2007, pers. comm.).

Each groundwater source area is divided into zones; the Upper Namoi (UN) covers 3,800km^2 upstream of Narrabri, containing 12 zones. The Lower Namoi (LN) is managed as one zone, covering 7,630km^2 downstream of Narrabri to Walgett (Figure 6.6). Groundwater serves as the main source of irrigation water in UN although surface water is preferred due to lower pumping costs (CARE 2003; Morgan 2005, pers. comm.).

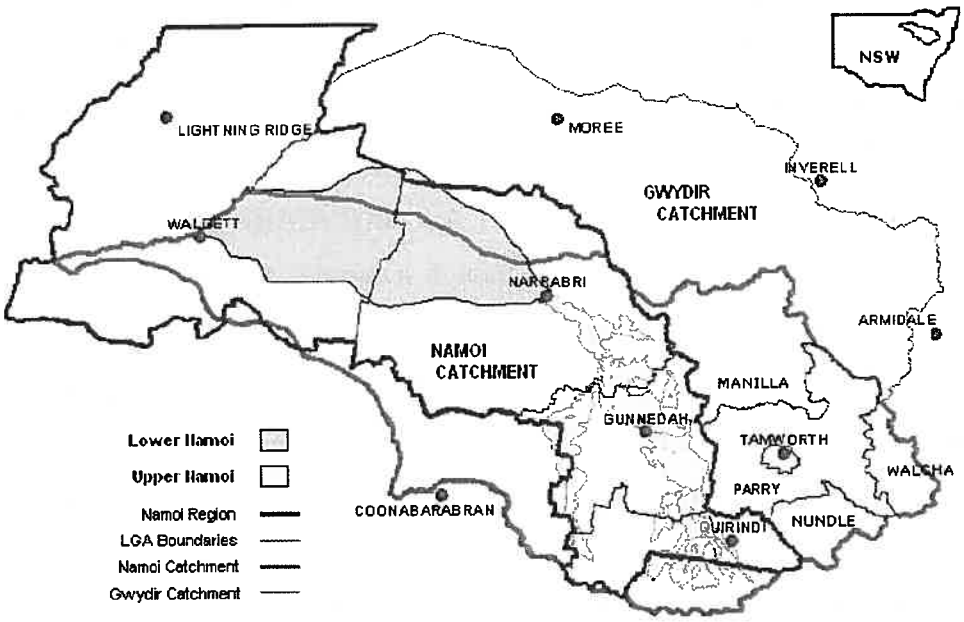

Figure 6.6: Upper and lower Namoi (Source: CARE 2003).

A majority of irrigators in the Namoi are expected to have their groundwater entitlements (AAL) cut by between 41-87% in the UN, including Mooki and its upstream reaches, and 51% in the LN region. While these cuts are significant, the intention of the groundwater WSP was to limit the aquifer access licences (AAL) to its sustainable groundwater recharge level determined for each Zone. The reduction to entitlements is zone-specific, with greater reductions in some zones than others (Figure 6.7 and Table 6-3). The entitlement reductions to be made are inclusive of the voluntary cuts of 10-35% in the mid 1990s (CARE 2003).

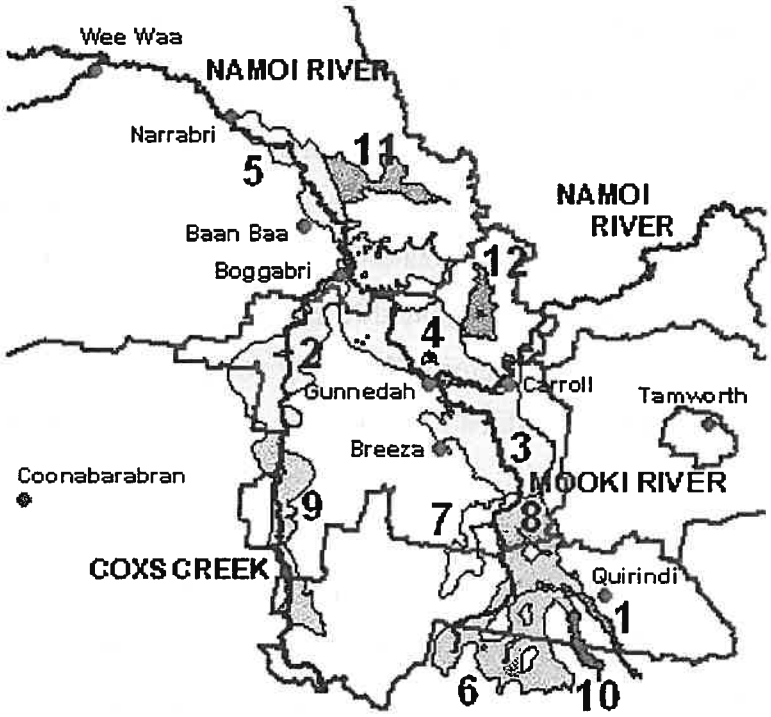

Figure 6.7: The Upper Namoi zones (source: CARE 2003).

The amended access licences under the groundwater WSP are based on a reduction of the yearly entitlements on existing licences. Essentially, the amended AAL is a portion of the total available recharge after high priority allocations (TWS) have first been met. At the start of each water year (in July), available water determinations are announced for each water source for AAL and supplementary licences and accredited to the licence holder's water account.

Table 6-3: Reduction in entitlements in the Mooki Basin (source: Aquillina 2003 p.13).

Zone	Reduction (%)
1	87
3	69
6	-
7	41
8	67
10	-

However, there remains no record of groundwater allocations on the public register of water licences (DNR 2007), even though the groundwater WSP has been gazetted since 2002. In this thesis, it is assumed that the available sustainable recharge remains unchanged and is fully allocated during the planning period. Therefore, while the term 'AAL' refers to groundwater entitlements, in this thesis its meaning is synonymous with the share of groundwater recharge or groundwater allocations. These terms will be used interchangeably when referring to groundwater allocations. The estimated annual recharge determined in the groundwater WSP for all zones is shown in Appendix B. For the relevant zones in this thesis, which lie within the Mooki Basin, the share of recharge (net of TWS) is shown in Table 6-4.

Given the significant reduction in entitlements, there are obvious implications for irrigators in the Mooki. Supplementary water allocations (SPW) were issued to irrigators with a history of use greater than their new share component to reduce the economic impact, given by history of use minus the amended access licence share component. These supplementary licences will be reduced after year 5 and phased out completely after year 10 of the WSP. During this time, financial assistance such as incentives for on-farm water use efficiency investments, business diversification, farm investment plans or purchasing additional licences will be available.

Table 6-4: Groundwater allocations (AAL), supplementary water (SPW) and extraction limits.

Zones	Gw AAL	Gw SPW		Gw Total		% Share Total Allocation
		Yr 1-5	Yr 6-10	Yr 1-5	Yr 6-10	
1	992	1,071	669	2,063	1,661	4
3	16,338	7,645	4,247	23,983	20,585	43
6	6,915	-	-	6,915	6,915	12
7	2,810	205	205	3,015	3,015	5
8	13,794	5,693	3,163	19,487	16,957	35
10	949	-	-	949	949	2
			Total	56,412	50,082	100

While these policies have the objective of assisting irrigators to adjust to the recent changes, and to reduce the social impact of reductions in groundwater entitlements, it appears to contradict the objective of achieving greater allocative efficiency in the water economy. Reducing groundwater entitlement according to history of use is uneconomic and unfair because it rewards those who were inefficient. Furthermore, financial assistance for investments in water efficiency (such as irrigation systems) or purchases of water licences provide distortionary signals and allow for inefficient irrigators to remain in operation. This precludes the reallocation of water to its highest value use.

Banking allocations, which was previously not permitted, has also been allowed in part to compensate for the cut-back in groundwater entitlements. Unused volumes can be carried over to the following year to a maximum of 300% of the share component, and for one water year a 200% extraction of the share component is permitted. Basically, in any year the maximum groundwater use is the two-season allocation, and in any three-rolling years total extractions must not exceed the three-year allocation. This banking rule also applies to surface water allocations; however due to the uncertainty in river flow irrigators in the Mooki Basin generally use the entire allocation within one water year (Hamparsum 2006, pers. comm.).

6.6 WATER CHARGES

A surface Water Sharing Plan (WSP) has been gazetted for the Mooki Basin in 2004 and there are now 26 Water Access Licences (WAL) under the current Water Management Act. The first Available Water Determination (AWD) was made on 1st July 2004 (Powell et al. 2003). AWD is the volume of water available for extraction at the start of a water year. This is expressed as either a percentage or volume per unit of share component. For example, the AWD for the 2004 water year for 'Unregulated River' licences was 2 megalitres (ML) per unit share held by the irrigator (Table 6-5).

Although no gauges are in place between Breeza and the downstream gauge at Ruvigne, the extraction rules are enforced through a penalty system. If the downstream gauge records flow levels below the stipulated CTP, it indicates that irrigators in the basin are 'cheating' and over-extracting above their licensed volume. As a penalty, if the averaged extraction across three years exceeds the stipulated long-term extraction limit by 5% or more, the extraction rules will be revised downwards. Irrigators therefore have incentive to comply, because otherwise the river access licences will be reduced by an amount that brings total water extraction back in line with the long-term extraction limit (Powell 2005, pers. comm.; DIPNR 2004b).

Table 6-5: Water Access Licences in Mooki water source under Water Management Act 2000 (DIPNR website 2005b)

Access Licence Category	No. of WAL	Total Share Component	Share Component Unit	Cumulative AWD	Cumulative AWD Unit	Water made Available (ML)
Domestic and Stock	3	23.5	ML	200	% of Share Component	47.0
Local Water Utility	0	0	ML	0	% of Share Component	0.0
Domestic and Stock	9	82.0	ML	200	% of Share Component	164.0
Unregulated River	26	29,526.5	unit shares	2	ML per share	59,053.0

WAL holders are charged the greater of a base charge of $54.31/yr, a two-part tariff consisting of an entitlement charge and usage charge per ML actually extracted, or a volume of entitlement charge (dollars per unit share or ML). The maximum two-part tariffs which applied for 2005 onwards are shown in Table 6-6, indexed to the CPI (IPART 2005; IPART 2006). For the Namoi, a two-part tariff applies to all irrigators.

Table 6-6: Water charge for 2005-06 onwards (source: IPART 2005 p.9).

	Maximum annual charges				
	Area based charge ($/ha)	Volume of entitlement charge ($/ML)	Two-part tariff		Usage charge only (local water utilities and major utilities ($/ML)
			entitlement ($/ML of entitlement or $/unit share)	Usage ($/ML)	
Border	12.26	3.82	2.3	1.53	1.72
Gwydir	12.26	3.82	2.3	1.53	1.72
Namoi	12.26	3.82	2.3	1.53	1.72
Peel	12.26	3.82	2.3	1.53	1.72
Lachlan	13.57	3.07	1.85	1.24	1.88
Macquarie	13.57	4.52	2.71	1.8	1.88
Far West	13.57	2.07	1.26	0.84	1.88
Murray	7.72	3.09	1.85	1.24	0.97
Murrumbidgee	13.57	5.43	3.26	2.16	1.88
North Coast	13.57	4.1	2.47	1.65	1.88
Hunter	11.75	2.65	1.6	1.07	1.63
South Coast	13.57	3	1.8	1.2	1.88

Groundwater licences are also subject to entitlement and usage charge indexed to the CPI. The applicable charge for the extractor depends on whether they are located in Groundwater Management Areas (GMA) that are metered, or in non-managed areas that are not metered. Irrigators within a GMA are subject to a base charge per property plus entitlement and usage charges, while non-GMA extractors are subject to a base charge per property plus an entitlement fee (IPART 2005). The groundwater management plan for the Mooki has not been finalised (NWC 2005), which suggests that the groundwater source is non-GMA and irrigators only pay a fixed cost for water (Table 6-7). This is discussed further in the following chapter.

Table 6-7: Charges for ground water access licence holders in the Namoi (source: IPART 2005 p. 21).

	Base charge ($/ property)	Entitlement charge ($/ML)	Usage Charge ($/ML)
GMA	187.72	0.85	0.43
Non-GMA	81.48	0.85	-

6.7 IRRIGATION SYSTEMS: PIVOT v DRIP

The main irrigation systems used in the cotton industry is furrow, pivot and drip irrigation. In NSW, the total area under drip systems is 54,000ha and for pivot irrigation systems is 63,000ha, while furrow irrigation occupies 678,000ha (Trewin 2006). Relative to 910,000ha of irrigated area, drip and pivot represent 5.9% and 6.9% of irrigation systems used. In Australia, the proportion of cotton irrigators that have adopted water efficient irrigation technologies is even smaller. Less than 4% of Australian cotton crop is grown under large irrigation machines, while less than 2% are grown under drip systems (Raine et al. 2000; Foley and Raine 2001). There are different reasons for the low adoption rate of water efficient technologies.

One of the reasons why pivots are not more commonly used is due of land constraints, which restrict irrigation system choices to furrow or require expensive earth works to prepare the land for pivot systems. There are also maintenance problems with pivot systems; in particular there is a steep learning curve to operate the machine (Figure 6.8a and b). The water savings, however, makes investing in pivot a more cost-efficient alternative to purchasing water entitlements. Field experiments have shown yield improvements while using 35-37% less water compared to furrow systems, due to greater control over water application (Foley and Raine 2001).

Due to the high costs of installation and maintenance, drip irrigation systems have generally not been favoured. The system itself costs around double that of pivot systems, but with a relatively short lifespan. It also needs to be removed every year when the cropping area is being prepared or cultivated. While anecdotal evidence suggests that drip irrigation allows for significant water savings, there is only a small yield increase to

offset the capital investment. The capital is thought to be better spent on purchasing water entitlements (Morgan 2005, pers. comm.; O'Halloran 2005). Therefore, while the level of water savings is beneficial, unless there is chronic water shortage it does not appear to be cost-effective.

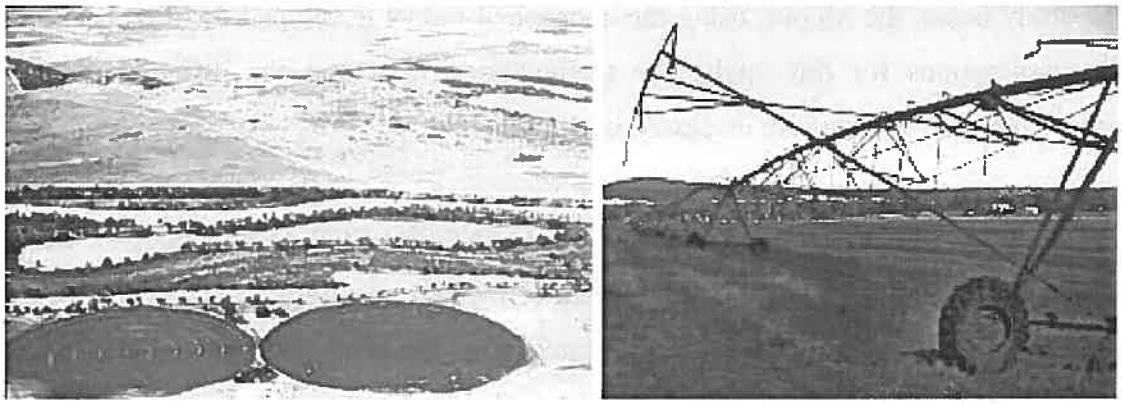

Figure 6.8: (a) Land prepared for centre pivot irrigation systems (source: MDBC 2006c); (b) centre pivot or lateral move machine (source: Foley and Raine 2001)

6.8 SUMMARY

The characteristics inherent to the case study, the Mooki basin, have been presented in this chapter. This was to clarify the assumptions that have been made in the modelling approach, and to highlight the environmental and resource concerns relating to this particular catchment. In the following chapter, the data and methodology used to carry out the analysis in this thesis is presented.

Chapter 7.

DATA AND METHODOLOGY

In this chapter, the aim is to describe the steps taken to carry out the analysis based on the case study basin, the Mooki, using the conceptual model developed for this thesis. The data assumptions for this study, the methodology used and the different scenarios simulated for the analysis are discussed in detail.

7.1 THE BIOPHYSICAL MODEL: SOIL AND WATER ASSESSMENT TOOL

Available Geographical Information System (GIS) and geophysical data specific to the case study Mooki were used for this research. The GIS used include Digital Elevation Model (DEM) data (Geosciences Australia) and soil data layer (University of Sydney Database and Department of Natural Resources – DNR), agricultural management data (NSW DPI), precipitation data and other climatic data (Commonwealth Bureau of Meteorology – BOM), and stream flow data (DNR). Land use data were also derived from a land use survey by DNR. In SWAT, the catchment was partitioned into 32 sub-basins, defined as a unique collection of streams that drain to a single outlet. Together, the 32 sub-basins contain 608 hydrologic response units (HRUs). An HRU is defined as a homogeneous land unit with a specific soil type and land use. A GIS image of the modelled catchment is given in Figure 7.1.

The total number of irrigated cotton HRUs referenced is 53, making up total area of 397km^2. These HRUs are scattered across three irrigation areas referenced as Ruvigne, Caroona, and Breeza. Each of these irrigation areas roughly corresponds with the Mooki River Water Source, Phillips and Warrah Water Source, and Quirindi Water Source in the surface Water Sharing Plan, respectively.

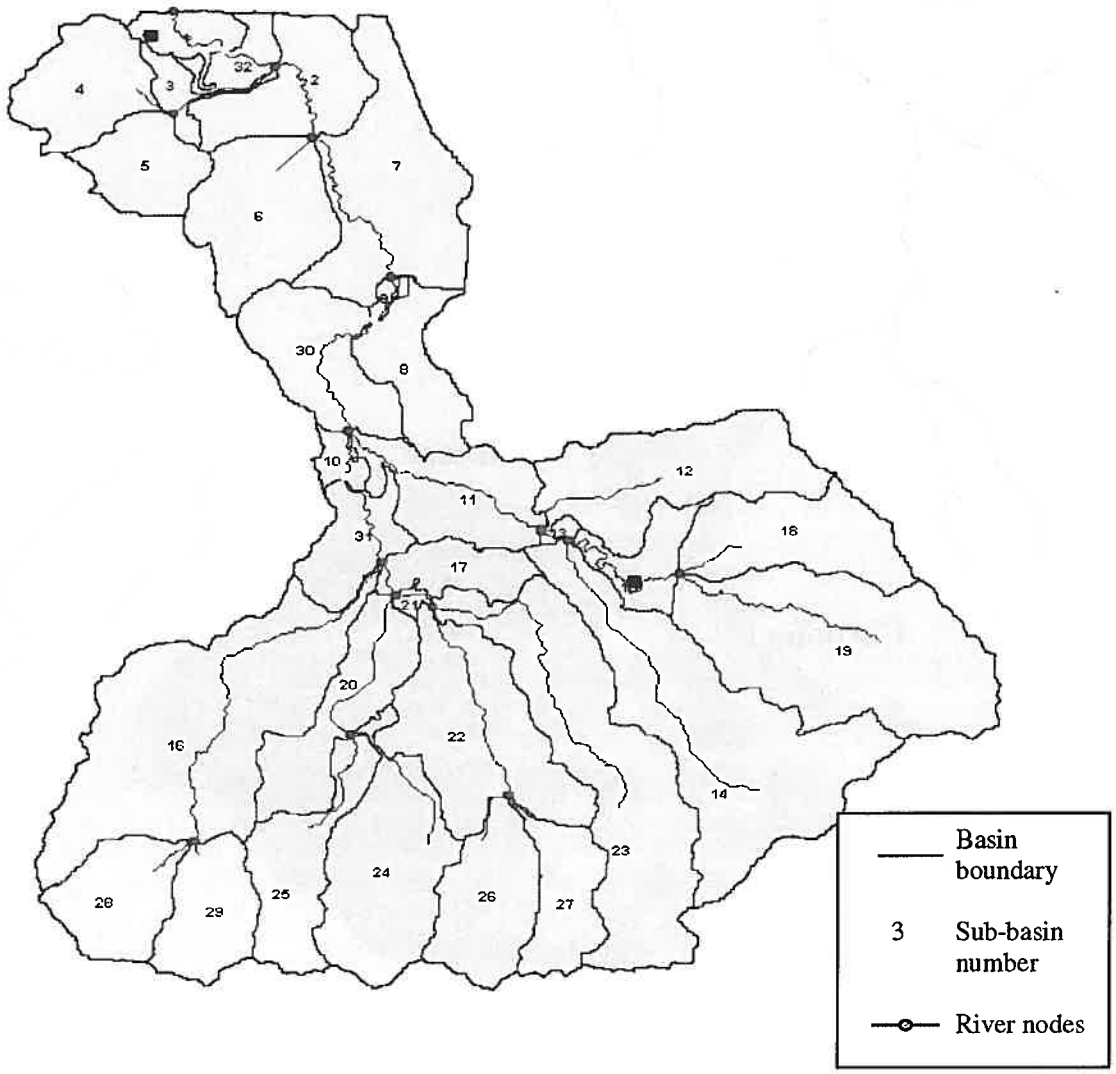

Figure 7.1: GIS delineation of the Mooki.

Within Ruvigne, irrigated cotton HRUs are situated in the downstream sub-basins 2-5, 7, 11, 31, 32; in Caroona, these HRUs are situated in the upstream sub-basins 16, 22-27; and in Breeza the HRUs are located in upstream sub-basins 15, 18, 19. Each of the three irrigation areas has a 'node' in SWAT that measures how much water is available for HRUs within the irrigation area (Figure 7.2). The scope of the analysis is narrowed to these 53 irrigated cotton HRUs, each of which is regarded as an individual farm. This assumption was made in line with the conjecture that soil types dictate the crops that are grown, so it is reasonable to assume that these land parcels could be modelled and are indeed as individual farms, even though they may be a part of a larger farm in a cadastral sense, or more farms might be situated in an HRU.

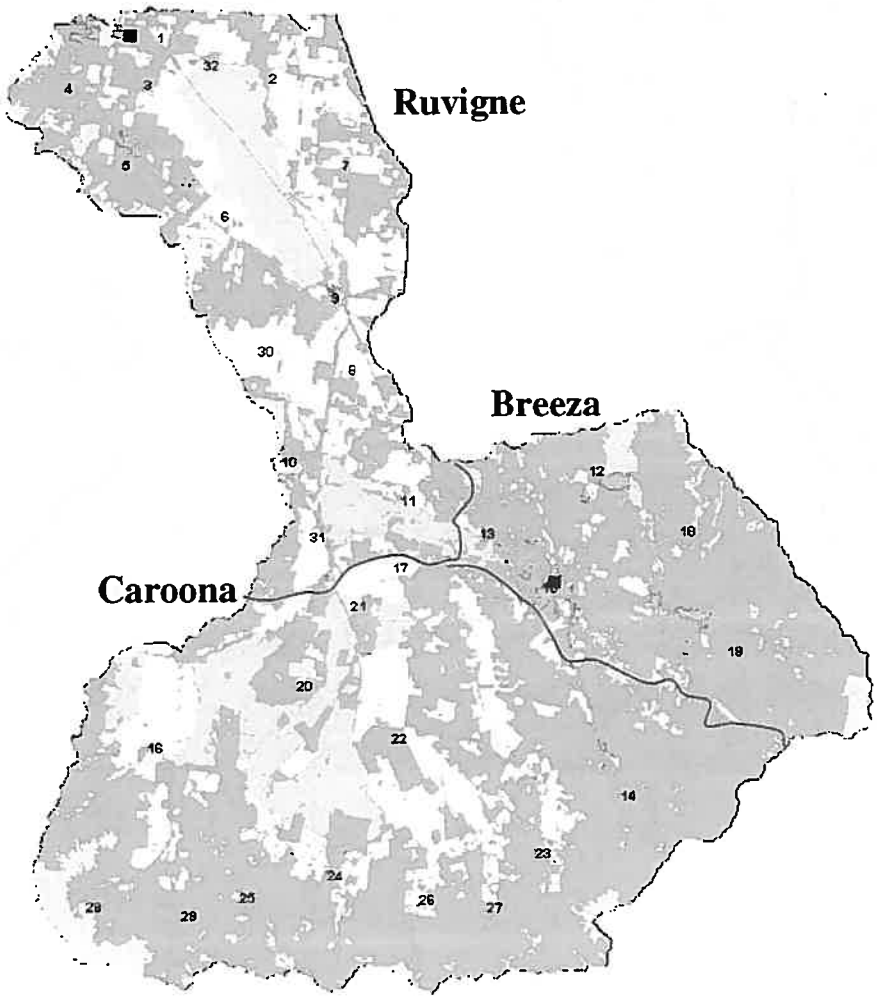

Figure 7.2: SWAT delineation of irrigated areas in the Mooki Basin (in orange).

Simulations were run in SWAT over ten years to obtain production outcomes for each HRU under the simulated activities outlined in Table 7-1. For each production activity, the SWAT model generated biophysical information, significantly relating to water use, associated deep drainage, and yield. The yield obtained for the HRUs generated in SWAT was weighed against the average yield over the HRUs, to reflect its relative productivity. This relative yield was then fitted to a discrete probability distribution of yields for corresponding northern NSW crops, based on the period 1965-2005 (ABARE 2005). The distributions for the crops under consideration – irrigated cotton, dryland cotton, dryland wheat, and grain sorghum – were used.

Table 7-1: Set of possible production activities for each HRU.

Activity number	Crop production	Source of water	Irrigation[5]
1	Cotton	Surface	Furrow (120mm/10,000m^2)
2	Cotton	Ground	Furrow (120mm/10,000m^2)
3	Cotton	Surface	Pivot (50mm/10,000m^2)
4	Cotton	Ground	Pivot (50mm/10,000m^2)
5	Cotton	Surface	Drip (according to soil deficit)
6	Cotton	Ground	Drip (according to soil deficit)
7	Grain/Sorghum	None (Dryland)	None
8	Wheat	None (Dryland)	None
9	Dryland Cotton	None (Dryland)	None

The biophysical information generated from SWAT were used as an input into a catchment level mathematical programming model with an objective to maximise net social benefit from the HRUs, subject to environmental constraints and constraints on water availability. The revenue, variable and fixed costs, and profit were calculated for these outcomes using price data obtained from NSW Department of Primary Industry Budget Sheets (NSW DPI 2006a). The revenue for cotton was given by income obtained from sale of cotton lint and cotton seed, and the cost was given by a per hectare cost of production ($OtherCosts_j$ in Eq. (1)) plus variable costs associated with irrigation. These variable costs include usage charge per megalitre (ML), taken from the 2005-2006 IPART water price determination[6], and pumping costs under furrow irrigation per ML according to figures from NSW Department of Primary Industries. The pumping cost varies depending on the source of water used, with groundwater being more expensive due to higher pumping costs.

The water availability constraint was set according to Eq. (4), and the deep drainage (DD) constraint was set according to Eq. (10). The environmental flow constraint, *CTP*, was imposed by setting a command in SWAT which requires that a specified minimum river flow level is present before water extraction for irrigation can begin. This was set

[5] 100mm per 10,000m^2 = 1ML over 1 hectare

[6] The current pricing arrangements do not factor in the water scarcity rent in pricing water, and is priced only for cost-recovery of water services.

according to the surface Water Sharing Plan (WSP), depending on the water source in which the HRU is located. The value of these constraints was then varied (parameterised) to determine the impact of various environmental policies on the basin economy.

7.2 SIMULATION SCENARIOS

Simulations of the economic model were run using the optimisation program, 'What's Best!' (Lindo Systems 2007), with the objective to determine the profit-maximising combination of choices for the whole basin (including crop choice, source and quantity of water in irrigation, irrigation systems used, and amounts of water traded), given resource and environmental constraints. Each scenario was designed to address the research questions framed in Chapter 1. There were four separate treatments under which every simulation scenario was run. The first treatment is the Status Quo (Treatment One), which was simulated to establish a baseline to be used for comparison. Under this treatment irrigators only undertake furrow irrigation, and use only the water allocated initially without the opportunity to trade water. The second treatment (Treatment Two) simulates a different technological setting. Irrigators are able to use alternative irrigation technologies (furrow, pivot irrigation, or drip). However in this treatment, there are no opportunities to trade water. In the third treatment (Treatment Three), alternative irrigation systems (AIS) can also be used, and in addition there is the opportunity to buy and sell water in a water market. In the fourth treatment, an external agent is introduced to the water market and competes for water with internal irrigators.

Under all four treatments, the common choice variables were crop choice, water source, and cropping area. Irrigation water per hectare was assumed to be fixed. The reason for this was that crop water demand is fairly inelastic, and anecdotal evidence suggests that irrigators generally reduce irrigation area rather than irrigation rate to maximise yield per hectare. Therefore, factor input per hectare and yield is assumed to be in fixed proportions, as are economic revenue and costs, in line with proportionality assumptions underlying linear programming (LP) models (Paris 1991). As a result, the shadow value to water use is reflected through the additional area that can be irrigated. Profit is therefore linearly increasing with water applied, and imposing a constraint on water use

reduces the number of hectares under irrigated cotton. So the *pattern* of optimal location of irrigated industries across the basin landscape would be established, rather than an optimal *irrigation rate* for an irrigation enterprise.

Surface water allocation for each HRU is proportional to its size, so larger HRUs have a greater share of allocations available to its irrigation area, and smaller HRUs have a smaller share. Meanwhile, the deep drainage (DD) constraint is set on a basin-scale, such that the total drainage occurring is constrained at the basin level, and its spatial distribution is dependent on its associated water use across the basin. Under each setting, the impacts of DD and water caps are examined by parameterising the water and DD constraints. Water caps are successively reduced from the 2004 season's surface water allocation of 59,000ML, while drainage caps are reduced from the DD occurrence given the season's water allocations. The change in profit with gradual falls in these constraints is then used to form cost curves for reducing drainage or increasing environmental flows. The difference in the costs of meeting the environmental targets *between* each setting is a proxy for the benefit of adopting water efficient technologies (AIS) and water trading, while the difference in the costs under scenarios *within* each treatment represents the benefit of each policy instrument. A comparison is also made of the DD (which contributes to salt load), water use and profit obtained under each scenario. This is done in part to determine the efficacy of water and DD instruments to achieve environmental targets, pertaining to environmental flows and salinity reduction, at the least cost.

The results from these simulated scenarios shed some light on the value of markets in ameliorating the economic impact of environmental targets on the catchment. Where the water market is present in the third treatment, the cap on DD essentially resembles a (indirect) drainage cap-and-trade scheme. This is under the assumption of perfect information regarding the relationship between water applied and DD. The introduction of a separate DD instrument to contend with salinity is an attempt to remedy the market failure arising from the conjoined nature of water use and salinity. However, the usefulness of dual-instruments to manage these conjunctive resources is debatable since

the administrative costs of dual-instruments will be quite high, meanwhile there is much uncertainty regarding its effectiveness in reducing environmental damage.

The presence of an external water buyer (a coal mine in this instance) is also simulated, and the effects on water use patterns in the catchment is analysed. For a given water market price, P_w, irrigators could choose to trade internally to other irrigators for crop production, or externally to the coal mine. It is assumed that only surface water could be traded. For simplicity, the gain from external water trade is calculated in terms of net benefit to the external agent from being able to use water, based on its derived demand for water estimated from industry data. The (exogenous) water price is parameterised in the interval from zero to $160/ML. Water sellers can make a profit from the volume which meets market demand at the given price, both internally and externally. As P_w increases or decreases, an irrigator would become a water supplier or demander depending on its derived demand for water, implicit in the LP. This allows for an analysis of the effect of water price changes on water demand and supply in the water market. Inset 7.1.presents a summary of the four treatments and the three policy scenarios:

Inset 7.1

Treatment One – Status Quo, no alternative irrigation systems (AIS) or water trade

Scenario 1.1 Base Case: no constraints except current environmental flow stipulations set out in the WSP.

Scenario 1.2 Water Cap (successively reducing water supply)

Scenario 1.3 Drainage Cap (successively reducing allowable drainage)

Treatment Two – Simulate use of alternative irrigation technologies (AIS), no water trade

Scenario 2.1 Base Case: no constraints except current environmental flow stipulations set out in the WSP, introduce AIS

Scenario 2.2 Water Cap

Scenario 2.3 Drainage Cap

Treatment Three – Simulate the introduction of water trading and AIS

Scenario 3.1 Base Case: no constraints except current environmental flow stipulations set out in the WSP, introduce water trade

Scenario 3.2 Water Cap

Scenario 3.3 Drainage Cap

Treatment Four – Simulate water trading, AIS and an External Water User

Scenario 4.1 Base Case: no constraints except current environmental flow stipulations set out in the WSP (identical to Scenario 3.1)

Scenario 4.2 Increase water prices successively, with trade among agricultural users only

Scenario 3.3 Increase water prices successively, with trade among agricultural and non-agricultural users.

7.3 DATA AND ASSUMPTIONS

7.3.1 Surface Water allocations

It is difficult to determine the actual history of use with respect to surface water for unregulated river systems. There is no legislated metering required for unregulated systems, and any private meters are regarded as confidential information that is not publicly disclosed. As a result, there is insufficient information to accurately determine river flow and implement extraction rules according to the flow class, or check on compliance. Withdrawal volumes could therefore only be estimated according to best guess (Hudson 2005, pers. comm..).

Therefore, although the number of licences issued and consequently the entitlements are observable for each Zone, it was not possible to identify the exact location of irrigators who hold water licences. Based on limited information, only an estimate of extractions could be made. The HRUs were divided according to the Zone in which they are located, and the Total Share Component (TSC), which refers to the surface water rights held, were summed together. This was used to estimate the proportion share of the basin water supply received in each Zone (Table 7-2).

The water availability for the zones was then compared to the estimates of river supply from SWAT. At each 'node' for Breeza, Ruvigne and Caroona there would be 'storage' for all HRUs to extract from, with the 'storage volume' determined through SWAT estimates of river flow at each node. On average, the estimated storage volume in one year was 34,518ML, with 2,762ML extracted at Caroona (8%), 10,679ML extracted at Breeza (31%), and 21,077ML extracted at Ruvigne (61%). The total storage water supply was rounded to 35,000ML for ease of calculation. While the total surface water available is quite similar between the SWAT estimates and the TSC recorded, the distribution between zones is somewhat different. According to CARE (2003), zones 1, 7 and 10 have no surface water entitlements, which suggest that irrigators in these zones are solely reliant on groundwater. However, SWAT simulations show that some surface water is actually available to these zones. It can be assumed that these irrigators will make use of the passing in-river flows to supplement their groundwater supplies.

Table 7-2: Surface water access in each SWAT node compared to SWAT estimates (adapted from Care 2003, p. 35),

SWAT Node	Zones	Sub-basins	TSC (ML)	SWAT estimate Area (ha)	SWAT estimate Surface Water (ML)
Ruvigne	3	2-5, 7, 32	25,158	12,113	21,000
	8	31, 11	4,989	5,502	
Caroona	6	22, 24-27	332	13,064	3,000
	10	23	-	200	
Breeza	1	15, 18, 19	-	8,217	11,000
	7	16	-	601	
		Total	33,241	39,699	35,000

Redistribution was therefore made to account for the access to surface water, such that access to river water is possible in all zones. This was done according to the irrigation water requirement for individual zones. The total surface water requirement for each HRU was estimated assuming that all HRUs produce irrigated cotton using surface water. The proportion share of Water Made Available is given by the ratio of surface water requirement in a particular Zone to the sum of water required by all zones. Each HRU has a share of the water available to its Zone, proportional to its size. This leads to a distribution which corresponds to the size of the irrigation area: Ruvigne receives 51% of the total Water Made Available; Caroona receives 35%; and Breeza receives 14% (Table 7-3). The methodology of distributing water based on land size and history of use is akin to the way government initially issued area-based water licences in unregulated systems. It was assumed that the proportional share of total availability in each Zone is unchanged, such that the water available in each Zone is in fixed proportions of the Water Made Available to each irrigation area.

Table 7-3: Surface water requirements in each Zone and share of water available, based on outcomes of SWAT simulations.

SWAT Node	Zone	Surface Water Required	% share of total availability
Ruvigne	3	41,643	20.67
	8	61,857	30.71
Caroona	6	65,556	32.55
	10	3,128	1.55
Breeza	1	28,190	14.00
	7	1,044	0.52
	TOT	201,416	100

7.3.2 Groundwater allocations

The purpose of the groundwater Water Sharing Plan (WSP) was to reduce water extractions to sustainable levels, equal to the recharge rate determined for each groundwater Zone in the Upper Namoi. This is envisaged to allow groundwater use to be maintained indefinitely into the future, at a consistent rate of use that has been stipulated for the next ten years. As mentioned earlier, the zones examined in this thesis are 1, 3, 6, 7, 8, and 10, which fall within the Mooki Basin. While it was not possible to verify the exact overlap of these zones and the sub-basins in SWAT, the GIS delineation of sub-basins in Figure 7.1 and the Zone referenced in Figure 6.7 were overlain to estimate the boundaries of each Zone. The groundwater entitlements and the supplementary water (SPW) for each of the relevant zones, as well as the irrigation areas in which the zones are located, are presented in Table 7-4. It is uncertain which of these HRUs belong to Groundwater Management Areas (GMA), for which the usage charge associated with groundwater use is different to non-GMA zones (see Section 6.6). To keep factor costs constant, it was assumed that the water usage charge (price per ML of water used) is the same as for the surface water. This then confines the cost differential between water sources to pumping costs, which form a more significant portion of costs associated with water use. It was also assumed that the proportion of groundwater allocation in each Zone is unchanged, such that the groundwater available to a Zone is in constant proportion of the total availability ("% Share Total Allocation").

In this study groundwater allocations were not reduced beyond the specified reductions in the groundwater WSP, so that total extraction remained at its estimated sustainable groundwater use across the planning period. Based on the groundwater entitlements, Ruvigne has the greatest share of groundwater resources, followed by Caroona then Breeza.

Table 7-4: Groundwater (Gw) allocations according to irrigation areas within Mooki.

	Zone	Gw Entitlements	Gw SPW		Gw Total		% Share Total Allocation
			Yr 1-5	Yr 6-10	Yr 1-5	Yr 6-10	
Ruvigne	3	16,338	7,645	4,247	23,983	20,585	43
	8	13,794	5,693	3,163	19,487	16,957	35
Caroona	6	6,915	-	-	6,915	6,915	12
	10	949	-	-	949	949	2
Breeza	1	992	1,071	669	2,063	1,661	4
	7	2,810	205	205	3,015	3,015	5
				Total	56,412	50,082	100

There are also carry-over rules that apply to groundwater allocations. In any year, a maximum of two-season's allocations can be used, while total extractions across three-rolling years must not exceed allocations received during this time. The limits on groundwater extraction over the planning period are shown in Table 7-5. The drop in allocations after year 5 is due to the phasing out of supplementary groundwater extraction licences.

Table 7-5: Annual groundwater (Gw) allocations and extraction limits.

Yr	Gw Total Annual Allocation (ML)	Two-year Gw Total Extraction Limit (ML)	Three-year Total Gw Extraction Limit (ML)
1-4	56,412	112,824	162,906
5	56,412	106,494	156,576
6-10	50,082	100,164	150,246

With reference to the dynamic programming model, the groundwater available for extraction each period, $\overline{Ga_{it}}$, is subject to the two-year extraction and three-year extraction limits shown above.

7.3.3 Parameter Assumptions

7.3.3.1 Crop yields

Assumptions for irrigated cotton yields were based on the 10-year trend reported by ABARE (2005), NSW DPI (2006a), Boyce (2005) and Tennakoon and Milroy (2003). The average irrigated cotton yield (bales[7]/ha) has increased from 5bales/ha in the 1960s, when irrigated cotton first began in Australia, to 8bales/ha in 2001 (ABARE 2006). From NSW DPI (2006a) and Boyce (2005), it has become common to achieve yields of 8-10bales/ha. Anecdotal evidence also suggests that yields between 8-10bales/ha is fairly common. However, Tennakoon and Milroy (2003) have reported yields of 6 bales/ha in the Namoi Valley. The yield estimate from SWAT was therefore standardised to a yield range of [6, 10], assuming a normal distribution with mean of 7.4 bales/ha and standard deviation (S.D.) of 1.3. Dryland cotton yield assumptions were based on NSW DPI (2006a) and Marshall et al. (2002). The yield range for dryland cotton was assumed to be [0.9, 4], with a mean of 2.6 bales/ha and S.D. of 0.9. Cotton seed was also sold as a by-product to cotton lint production. Based on NSW DPI (2006a), the ratio of seed to lint was assumed to be 1.59; i.e. for every kilogram (kg) of cotton lint, 1.59kg of seed is produced.

Other dryland crops grown in the Namoi region include wheat and sorghum. These dryland crop yields were similarly based on NSW DPI (2006a) and ABARE (2005). A distribution with mean 3.6 t/ha and S.D. of 1.4 was assumed for wheat, with yield range of [1.5, 6]. A mean yield of 4 t/ha was assumed for dryland sorghum, with a yield range of [3, 5] and S.D. of 0.6.

[7] One bale is 227kg

7.3.3.2 *Crop Prices and Input Costs*

Price and cost data were based on ABS (2005) and NSW DPI (2006a) for the Northern Zone. The 10 year-average price received for cotton was $2/kg, with production costs, excluding water, of around $2,333/ha. The price of cotton seed was assumed to be $175/t. For dryland cotton, prices received for lint and seed were the same, except that the production costs were much lower at $965/ha. Of course, the yield of dryland cotton was also much lower compared to irrigated cotton. The price of dryland wheat was around $150/t while the cost of production was around $309/ha. The average price for grain sorghum was $140/t while production costs were $375/ha (NSW DPI 2006a; ABS 2005). For the purposes of this study, all prices were assumed in real terms to exclude the effect of inflation. The crop yield, price and cost assumed in this thesis are shown in Table 7-6.

Table 7-6: Crop yield, price and cost assumptions.

Crop	Mean yield	S.D.	Crop Price ($)	Cost per hectare ($)
Irrigated Cotton	7.4 bales/ha	1.49	2/kg	2,333
Dryland Cotton	2.6 bales/ha	0.9	(454/bale)	965
Dryland Wheat	3.6 t/ha	1.4	150/t	309
Dryland Sorghum	4 t/ha	0.6	140/t	375

7.3.3.3 *Water Charge*

The water prices assumed were according to the Independent Pricing and Regulatory Tribunal determinations. Only the usage charge of $1.53/ML has been included in variable costs, since the entitlement charge is regarded as a sunk cost for holding the water right. Nevertheless, the charge for water itself makes up only a fraction of the costs associated with using water. Most of the costs of using surface or groundwater were due to expenditure on fuel used for water pumping (see Table 7-9), which forms the most significant factor in water use decisions. Again, all prices were assumed to be in real terms.

7.3.4 *Irrigation Scheduling*

In SWAT, there are a set of 'management files' through which HRUs are given commands, such as crop planting, harvest, irrigation, fertilisation etc. In this study, the

only irrigation crop considered is cotton, for which irrigation scheduling is regarded as an important determinant of yield. Too much or too little water at crucial times in a season could cause significant yield losses (Milroy et al. 2002). The sensitivity of cotton crops to irrigation is in-built into SWAT, and much attention was given to the formulation of a set of appropriate irrigation scheduling. The decision criterion in SWAT of whether to irrigate or not was to satisfy crop water demand, given the in-stream flow at the scheduled irrigation time and the irrigation rate specified by the user.

There were two ways users can define irrigation events: by heat-unit irrigation and date-irrigation. Irrigation according to heat-units is more realistic, since irrigation can be timed according to the stages in crop growth. However, this method has high computational requirements and through trial simulations did not produce good yield response. Date-irrigation sets specific dates for irrigation to occur, although scheduled irrigation events are not necessarily in sync with crop requirements. Both heat-unit and date-irrigation scheduling have disadvantages in which irrigation timing was not perfectly aligned with water requirements; but in this instance date scheduling was more accurate than heat-unit irrigation and was chosen for this study. Full details regarding the setup of irrigation scheduling is given in Appendix C.

7.3.5 External Buyer – Derived Demand for Water

Production data taken from a large Australian-based mining firm production and sustainability report was used to determine the water demand function in coal mining Due to the relatively more constrained access to water resources for the mine, coal production was taken as a function of water available. A quadratic relationship was assumed, and a regression was run using the available data set, consisting of six years of observations.

Table 7-7: Coal production and water use (source: BHP 2006; BHP 2007).

Yr	Tot production ('000 t)	Fresh Water Intensity (litres/t)	Inferred Water demand (ML)
2001	4,877	290	1,414
2002	4,997	290	1,449
2003	7,783	240	1,868
2004	9,692	290	2,811
2005	9,695	220	2,133
2006	10,089	230	2,320

Assuming no coal can be produced without water, such that the intercept is zero, the estimated production function was $Coal = -0.1721W^2 + 4318.2W$, with R^2=0.81 and s.e. of 1,169,471. The factor demand function was then obtained by invoking Hotelling's Lemma:

$$\pi = P_y\left(-0.172W^2 + 4318.2W\right) - P_w W$$

$$\frac{\partial \pi}{\partial W} = P_y\left(-0.344W + 4318.2\right) - P_w = 0$$

$$W = \left(\frac{P_w}{P_y} - 4318.2\right) \Big/ (-0.344)$$

$$= \frac{4318.2}{0.344} - \frac{1}{0.344} \cdot \frac{P_{wy}}{P}$$

Where P_y is the output price for coal, P_w is the market price of water, and W is the quantity of water used in coal production. Assuming $P_y = \$45$ per ton (ABARE 2006), the coal mine's derived demand for water is $W^* = 12{,}522 - P_w/15.48$.

7.3.6 Water Efficient Irrigation Systems

Once an investment is made in an alternative system, the irrigator is locked into the system due to the need to recoup initial investment. The repayment period is assumed to be ten years, with annualised fixed costs incurred by the irrigator for the remainder of that period once the investment is made. The average capital cost and annualised repayments (at 5% interest over ten years) are shown in Table 7-8.

Table 7-8: Capital investment and annualised fixed costs (adapted from Foley and Raine 2001).

Annualised Fixed Costs	Capital Cost/Ha $ (ave)	Annualised Fixed Cost/Ha ($)
Pivot or Linear Move low pressure (river)	2,000	$246.68
Pivot or Linear Move low pressure (bore)	2,400	$296.01
Drip/Jet spray	4,500	$555.02

The operational cost of water efficient irrigation systems is shown in Table 7-9. The cost of operation is based on the fuel consumption required to deliver water to the field, which .increase with pressure requirements ("pumping head") for the system. It is assumed that all irrigators use diesel-fuelled systems at a cost of 75c/litre, which is considered to be the higher end of fuel costs (Smith 2005, pers. comm.).

Table 7-9: Operational costs of different irrigation systems (source: Smith and Richards 2003)

Irrigation System	Labour requirement	Assumed Pumping Head (metres)						Pumping Costs $ per Megalitre			
		Static Lift	Pipe Friction	Hose Loss	Operating Pressure		Total Head	Diesel Cost per litre @ cents = $			
								40	45	55	**75**
Surface Furrow (River)	high	10					10	5.06	5.69	6.95	9.48
Surface Furrow (Bore)	high	30	5				35	17.70	19.91	24.33	33.18
Pivot or Linear Move low pressure (river)	low	10	10		10		30	15.17	17.06	20.86	28.44
Pivot or Linear Move low pressure (bore)	low	30	10		10		50	25.28	28.44	34.76	47.40
Drip/Jet spray	low	25	15		10		50	25.28	28.44	34.76	47.40

7.4 OTHER CONSIDERATIONS

7.4.1 Deep Drainage and Return Flows in the Mooki

As mentioned in earlier chapters, increasing water use efficiency would have two opposing effects; the reduction in deep drainage (to the natural level of recharge) would lead to reduced salinity risk, but on the other hand it would also have an adverse effect in reducing return flows (Heaney and Beare 2001). If water quality has negligible effects on crop growth then the upstream user would only reduce deep drainage to the extent which does not impede with downstream supply.

The contribution return flows make to in-stream or groundwater supply can be estimated through SWAT, which simulates groundwater recharge and return flows through water balance equations. However, the 'optimal' level of return flows for maximising basin profits would require that the deep drainage and return flow relationship for every HRU, under every production activity is considered in the optimisation problem. This would command enormous computational expense, because each time one upstream HRU varies its landuse activity, there are downstream repercussions in terms of water supply changes. The number of possible outcomes is therefore a permutation of the number of choice variables and HRUs (see Appendix D). Moreover, a new simulation needs to be conducted each time a constraint changes. From a programming perspective, one optimisation would require an amount of time and technical resources beyond the scope of this thesis. It is therefore not feasible to include the entire range of possible outcomes in the presence of return flows. An alternative would be to aggregate the HRUs to reduce the number of possible outcomes, which at best could be lumped according to the irrigation areas (Ruvigne, Caroona, and Breeza). However, this takes away the advantage of using spatially explicit information.

The effect return flows have on river salinity depends, amongst other factors, on the salinity of groundwater where return flows originate (Heaney and Beare 2001). If the recharge is high and ground water salinity is high, the salt concentration may decrease if the amount of saline recharge transported to the river system is reduced. Reducing deep drainage therefore lowers the negative externalities imposed on downstream users. In

contrast, if return flows originate from irrigation areas with relatively low underlying groundwater salt concentration, it can provide dilution flows downstream. Return flows would then provide positive contributions to downstream water supply and diluting effects, so trade or improved irrigation efficiency reduces these beneficial return flows. For the Mooki, there are no significant salinity problems within the catchment, but the salt load and EC reading for the Mooki and Namoi Rivers are relatively high compared to other cotton producing catchments (see Section 6.4). The main concern is the salt load contribution to the downstream Barwon-Darling River, which carries the salt into the Murray-Darling system. Given the relatively high salt concentration in the Namoi and Mooki Rivers, and its high river-aquifer connectivity, it is considered optimal to minimise the level of saline return flows since it generate greater negative than positive externalities.

7.5 SUMMARY OF CHAPTER 7

In this chapter, the data and the methodology used in the modelling process were presented. The interdisciplinary approach, involving the use of the biophysical model, SWAT, was first described. Attention was given to the way SWAT delineates the basin, which allows for a spatially explicit examination of the water resource use. This was followed by a detailed discussion of the data and assumptions made in the model, which were according to the characteristics of the case study basin, the Mooki, as introduced in Chapter 6. In this next chapter, the results of the empirical study are analysed, to shed light on the effectiveness of various catchment policies aimed at correcting these distributional problems.

Chapter 8.

RESULTS OF THE EMPIRICAL STUDY

In this chapter, the results of the empirical research based on the case study of the Mooki catchment are presented. The results are discussed in the following way. In Section 8.1, a summary statistics of the different simulation treatments is provided. This enables a general overview of the outcomes under the assumptions made for each treatment. This is followed by a review of the inter-temporal resource use, focusing on the role of the carry-over rules for groundwater allocations, in Section 8.2. An analysis of the change in production activities, with respect to changes in water allocation and deep drainage, is then presented in Section 8.3. Changes in basin profit and water use for various environmental flow policies are then examined in Section 8.4. In Section 8.5, the effect of a dual-instrument on basin profit is assessed, through simultaneously imposing deep drainage caps and surface water caps. This is followed by a comparison of the effectiveness of using each instrument separately in achieving environmental objectives and minimising the impact on basin profit, in Section 8.6. For each of the above sections, the focus in on the three treatments: Treatment One (Status Quo: furrow irrigation only); Treatment Two (with alternative irrigation systems – AIS – pivot and drip irrigation); and Treatment Three (with water trading and AIS). In Section 8.7, the results under Treatment Four (external water trade) are presented. This is to examine the economic implications of increased competition for water from an agent outside of the region. A comparison is then made to the outcome where only internal water trading is allowed. Where water trading is considered, under Treatment Three, the market price for water is assumed to be zero, such that water trading is costless. Any 'trade' of water is simply a reallocation to its highest value use, and represents the maximum value of establishing a water market in the case study basin. The impact of water market price changes is only considered in Treatment Four.

8.1 SUMMARY STATISTICS

8.1.1 Summary of Activities

As mentioned in Chapter 7, there are nine production activities that are considered. These are reproduced here for ease of reference (Table 8-1).

Table 8-1: Description of activities.

Activity number	Source of water	Crop production	Irrigation
1	Surface	Cotton	Furrow
2	Ground	Cotton	Furrow
3	Surface	Cotton	Pivot
4	Ground	Cotton	Pivot
5	Surface	Cotton	Drip
6	Ground	Cotton	Drip
7	Dryland	Grain/Sorghum	-
8	Dryland	Wheat	-
9	Dryland	Cotton	-

The average SWAT output parameters and profitability of each activity is shown in Table 8-2. Between the nine possible activities, pivot irrigation using groundwater (activity 4) is the most profitable activity. However, this is very similar to the profit under activity 2, which also source groundwater but using the less water efficient furrow systems. Likewise, pivot irrigation using surface water (activity 3) is also comparable to furrow irrigation using surface water (activity 1). This suggests that, the yield increase under pivot systems just offset the increased capital outlay, making it marginally more profitable than traditional furrow systems. However, pivot systems have additional benefits in terms of reduced water use and deep drainage (DD), allowing for greater water use efficiency. Drip irrigation (activities 5 and 6) has the lowest average profit/ha of the irrigation systems, although it has the greatest water savings and DD reduction compared to other irrigation systems. This is because of the significantly greater capital investment required, which is more than double the cost of pivot systems. Furthermore, crop yield does not increase appreciably. Drip irrigation is therefore not very profitable because the yield improvement is inadequate to cover the significant capital outlay. These outcomes are in line with anecdotal evidence; many irrigators report water savings and

yield increase under pivot systems, but not significant yield increase under drip irrigation. This makes drip an unfavourable option because there is no yield increase to recoup the capital investment, despite significant water savings. In this regard, pivot systems have the advantage of allowing irrigators to maintain profitability in situations where water supply is scarce.

Table 8-2: Summary of activities.

Activities	Ave. Profit ($/ha)	Ave. Irrigation (ML/ha)	Ave. DD (ML)/ha	Ave. Yield[8] /ha
1	1,074.18	6.30	1.25	6.89
2	1,199.80	8.44	2.03	7.41
3	1,097.29	5.63	1.18	7.47
4	1,209.03	7.65	1.52	7.95
5	585.59	5.37	1.14	6.99
6	648.90	6.09	1.33	7.26
7	308.61	-	-	3.93
8	136.40	-	-	3.77
9	475.02	-	-	2.49

A general trend that is observed from the above table is that, for any irrigation system, the profit where groundwater is used (activities 2,4 and 6) is greater than where surface water is used (activities 1,3 and 5). This is despite the cost of groundwater being higher than surface water. The difference in profit between ground and surface water is on account of the reliability of the water source, which affects crop yields. In the SWAT model, on-farm storages cannot be modelled for each HRU so surface water cannot be pumped and stored on-farm. Therefore water sourced from the river is applied directly to the crops when it is available. The irregularity of river flow in an unregulated system means that irrigation occurs less frequently, and can be insufficient to meet crop water requirement, leading to lower yields. On the other hand, the relative reliability of groundwater means it is more readily available and full irrigation occurs at regular intervals. As a result, irrigation water, yield and DD are lower when sourcing surface water and higher when groundwater is used. Therefore, even though groundwater is more costly to use, the

[8] Cotton in bales per ha (activities 1-6, and 9), wheat and sorghum in tons per hectare (activities 7 and 8).

security of supply allows greater crop yields which offsets the pumping cost. In a sense, the extra cost of pumping groundwater can be regarded as a 'premium' paid for increased security of supply, which is compensated by increased yields. It is therefore the water source that is relied upon by irrigators in the Mooki basin, which is in line with reality. This result also reflects the significance of secure water supplies, which enables the capital cost of water efficient technologies to be recouped and provides an incentive for irrigators to make the investment.

Considering dryland crop choices, dryland cotton (activity 9) is the most profitable dryland production. While this is less than half the profitability of irrigated cotton, compared to wheat and sorghum, it is the preferred dryland crop as water becomes scarce. This will be observed in the following sections.

8.1.2 Comparison of Base Case Scenarios

In this section, a comparison is made between the Base Case scenarios under each treatment. The following table shows the resource use and annual profit given the 2005 surface water allocation of 59,000ML, and 56,412ML groundwater allocation (Table 8-3). Seasonal water allocations are assumed to be fixed throughout the planning period of 10 years.

Table 8-3: Base Case scenarios water use and annual profit

Treatment	Base Case Scenarios				
	Surface Water Use (ML)	Groundwater Use (ML)	Total Water Use (ML)	DD (ML)	Profit/yr ($Mill)
One	53,628	56,059	109,687	25,419	35.32
Two	58,698	56,200	114,898	24,200	36.85
Three	59,000	56,241	115,241	24,710	40.15

The increase in annual profit moving from Treatment One (status quo) to Treatment Two (no water trade, with alternative irrigation systems – AIS) is $1.5 Mill, which the increase in surface water use is 5,070ML. Total water use increases by 5,211ML. That is, when AIS are available profit increases by 4% while surface water use increases by 9%, or

4.7% in total water use. This is while DD falls by 1,219ML, or 5%. This result suggests that, water use efficiency increases where AIS are used, although irrigators take advantage of the increased water efficiency to expand production, leading to an increase in water use and profit.

A comparison between Treatment Two and Treatment Three (with trade and AIS) shows that profit increases by $3.3Mill, and surface water use by 302ML. Relative to Treatment Two, this equates to a 9% increase in profit for a 1% increase in surface water use. In terms of total water use, an increase of 0.3% is observed. This result suggests that a relatively large increase in profit is achieved for a small increase in water use where there is water trade, although DD increases by 2% relative to Treatment Two. However, DD is still lower relative to Treatment One; drainage falls by 3% despite an increase in total water use of 5%, while profit increase by 10% compared to the status quo.

Considering the relative change in profit to water use under each treatment, it appears that AIS and water trading can improve catchment profit and water use efficiency. This is despite an increase in total water used. Some producers that initially could not grow irrigated cotton profitably under furrow systems (Treatment One) find it possible to profitably produce irrigated cotton where water efficient technologies are available (Treatment Two), which leads to an increase in water use and fewer losses to drainage. Furthermore, where water trading is possible, water demand in the catchment is further increased as previously inactive allocations are mobilised (Treatment Three). While water trading leads to greater water use, it also allows for the highest profit due to greater allocative efficiency, and reduced unproductive water lost to DD. There is a natural incentive for water to be used efficiently by creating a market value for water, since there is an opportunity cost associated with water lost to drainage. The objective of reducing DD can therefore be achieved through the creation of a water market or promoting the use of AIS, without the need for additional administrative control over water use.

8.2 INTER-TEMPORAL RESOURCE USE – STOCHASTIC SURFACE WATER

Due to the carry-over rules for groundwater allocations, dynamic resource use decisions need to be made with respect to groundwater use. Each year, extractions must not exceed the two-year water allocation, while total extractions within three-rolling years must not exceed the three-year allocation. While the same rules apply for surface water, the ephemeral nature of the river flow in the Mooki (an unregulated system) means that it is optimal to extract river water whenever the opportunity arises, such that surface allocations are exhausted within the season (Hamparsum 2006, pers. comm.). Due to the phasing-out of supplementary groundwater entitlements scheduled after year 5 of the groundwater Water Sharing Plan, there are two sets of extraction constraints over the 10-year planning period. The extraction limits were shown in Chapter 7 but are replicated here for ease of reference (Table 8-4).

Table 8-4: Groundwater (Gw) allocations and extraction limits.

Yr	Gw Annual Allocation (ML)	Two-year Gw Extraction Limit (ML)	Three-year Gw Extraction Limit (ML)
1-4	56,412	112,824	162,906
5	56,412	106,494	156,576
6-10	50,082	100,164	150,246

Under the Base Case scenario of each of the treatments, the rate of groundwater extractions is much lower than the two-year and three-year extraction limits, as shown in the previous section (see Table 8-3). Rather than exhausting the entire two-year groundwater allocation within one season, optimal extraction appears to be at a point close to its annual allocations. The reason for this is because the temporal value of groundwater resources is integrated into the resource use decisions, such that the rate of extraction is reduced to where the discounted value of the groundwater resource is equated between periods. Where there is no stochasticity in surface water supply or other parameters, surface and groundwater use (and hence deep drainage occurrence) is fairly consistent because optimal production in one season is not different from year to year. This is a consistent trend throughout all three treatments, and after year 5 resource use

drops slightly due to cuts in entitlements, but also maintains a regular production pattern. Under conditions of stochastic surface water supply, *ceteris paribus*, the optimal groundwater extraction rate is expected to differ from year to year depending on the river flow available.

Stochastic surface water scenarios were analysed for all treatments, to examine how irrigators may choose to 'bank' or 'borrow' groundwater allocations. The surface water supply was set annually according to each of the 8 years simulated in SWAT, from 1996 (year 1) to 2003 (year 8). Water allocation for 2004 (year 9) was assumed to be the same as allocations for 2005 (year 10) of 59,000ML (Table 8-5).

Table 8-5: Stochastic and deterministic water supply.

Year	Surface Water Allocation (ML/yr)		Groundwater Allocation (ML/yr)
	Stochastic	Deterministic	Deterministic
1	27,579		
2	31,265		
3	97,346		56,412
4	33,727		
5	64,840	59,000	
6	64,623		
7	14,931		
8	26,394		50,082
9	59,000		
10			

8.2.1 Treatment One – Status Quo

Under Treatment One, where surface water is stochastic, the rate of groundwater extraction moves in the opposite direction of surface water supply (Figure 8.1). This is expected because, where surface water is erratic, some banking or borrowing of groundwater allocations is needed to compensate for the irregularity of the alternate water source. Where surface water is deterministic, however, it is not necessary to hedge groundwater allocation so the rate of groundwater extractions is constant and close to the annual allocation. It can be inferred that, where surface water is stochastic, some banking and borrowing of groundwater allocations occur, but where surface water is deterministic

and constant, annual groundwater allocations are used up every year. That is, there is no banking or borrowing. This suggests that the carry-over rule for groundwater is especially important for irrigators in an unregulated system, to reduce the economic impact of the scarcity and irregularity of surface water.

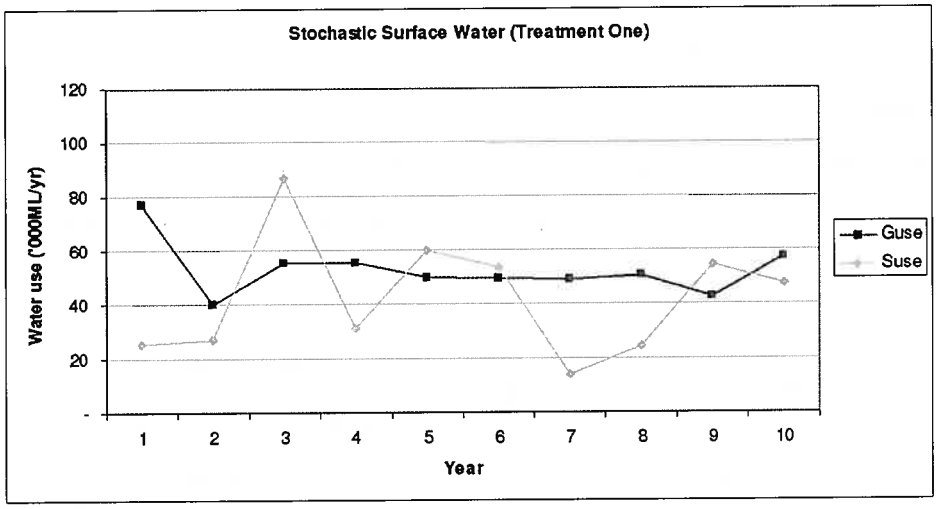

Figure 8.1: Groundwater use (Guse) with stochastic surface water (Suse), Treatment One.

8.2.2 Treatment Two – No Trade, with Alternative Irrigation Systems (AIS)

Under Treatment Two, the observed trend in groundwater use is similar to Treatment One, although there is less carry-over of groundwater allocations. Groundwater extraction generally moves in opposing direction to surface water supply, at a rate that compensates for the lack of (or surplus in) surface water (Figure 8.2). Where surface water allocations are constant from year to year, groundwater use is constant and no borrowing or banking occurs. On the other hand, where surface water is stochastic, some groundwater banking or borrowing would occur although under Treatment Two only a small amount is carried over.

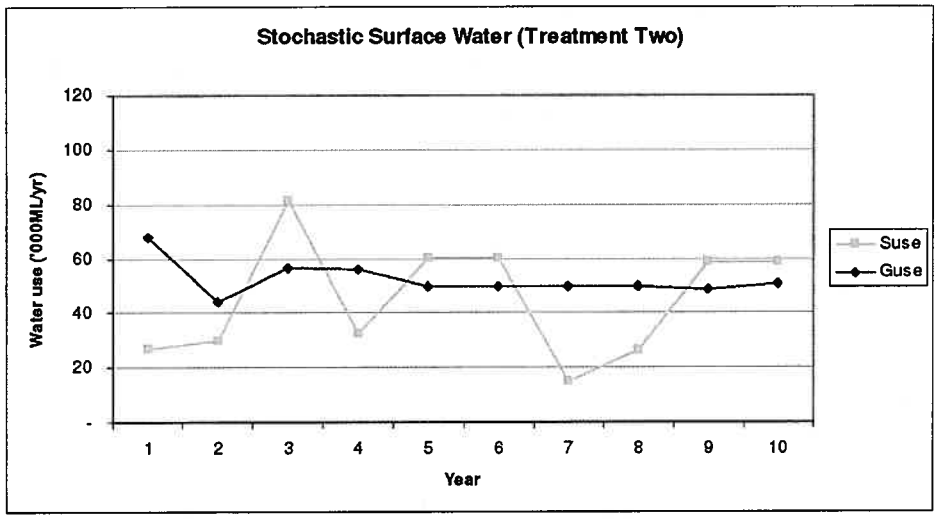

Figure 8.2: Groundwater use (Guse) with stochastic surface water (Suse), Treatment Two.

8.2.3 Treatment Three – With Trade and Alternative Irrigation Systems (AIS)

Under Treatment Three, the water use pattern is also similar to Treatments One and Two. There is a negative correlation between the rates of groundwater extraction and surface water supply, where surface water is stochastic (Figure 8.3). Where surface water supply is certain and constant, groundwater use is likewise constant and the full annual allocation is used without any banking. This again highlights the importance of the carry-over rule for the Mooki, since, under all three treatments, the banking and borrowing of groundwater appears to be a significant adjustment mechanism to the erratic nature of surface water supply.

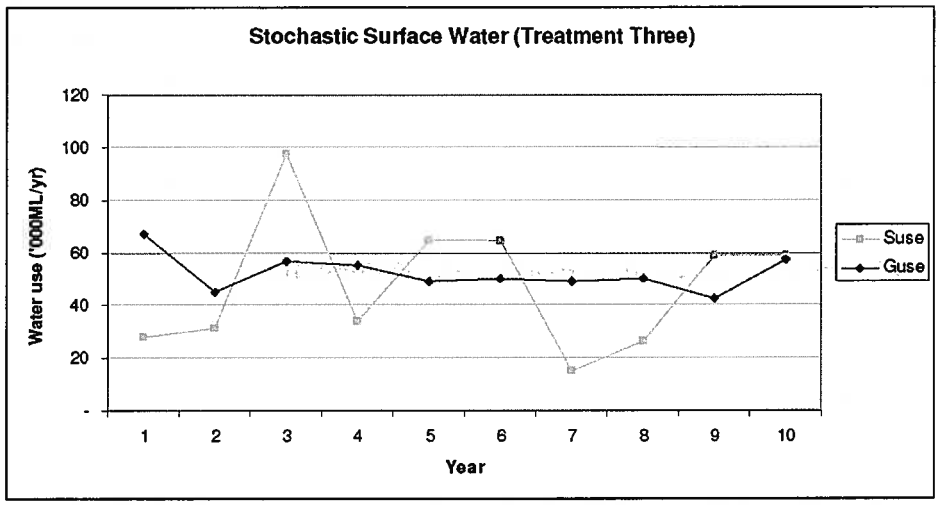

Figure 8.3: Groundwater use (Guse) with stochastic surface water (Suse), Treatment Three.

8.2.4 Summary of Inter-temporal Resource Use

Where surface water is certain and unchanged from year to year, the groundwater carry-over rule does not appear to have much currency since the optimal extraction rate is essentially the annual allocation. This is because the profit-maximising production pattern is unchanged from year to year. However, where surface water is stochastic, the carry-over rule is essential to ameliorate the economic impact of the erratic nature of river supplies. However, the rate of banking or borrowing does not appear to vary significantly between treatments. As can be seen in Figure 8.4, groundwater borrowing occurs when surface water (Sw) is low, and banking occurs when surface water supply is high. The groundwater-borrowing behaviour corresponding to Treatment One (T.One), Treatment Two (T.Two) and Treatment Three (T.Three) are positive when borrowing (above the x-axis), and negative when banking (below the x-axis). Where there is no carry-over or borrowing of groundwater allocations, the lines sit on the x-axis, which occur for much of the planning period. This is because the rate of extraction is subject to the two-year and three-year extraction limits, such that groundwater use remains relatively close to its annual allocations each year. Given that there is effectively an 'expiry date' for groundwater allocations, it is optimal to extract groundwater at a rate corresponding to the increase in groundwater stock. It seems that the carry-over rules are the dominating factor in banking decisions.

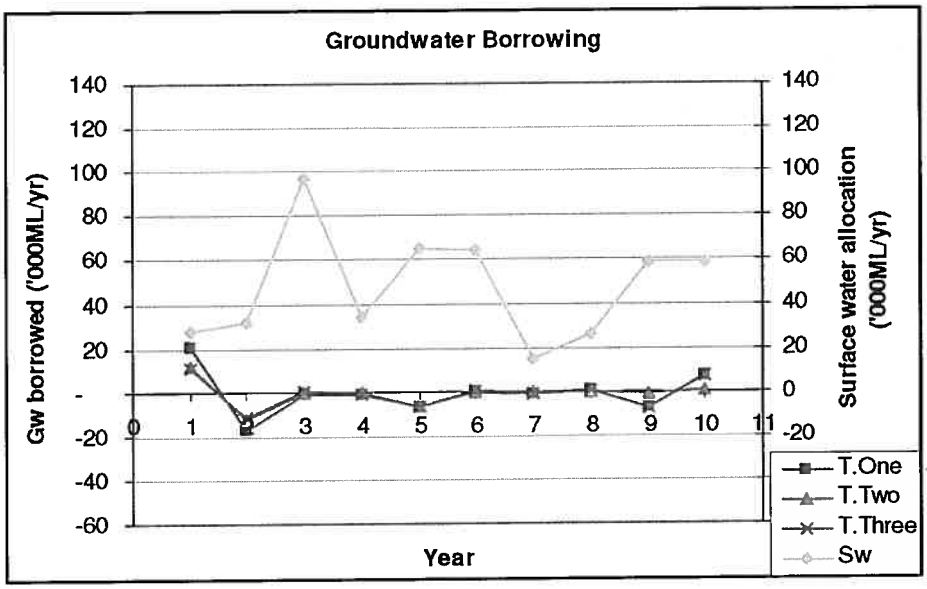

Figure 8.4: Comparing groundwater borrowing under the three treatments.

For the sections to follow, the analyses are based on the expected value of annual water supply, such that surface water is deterministic and constant over the planning period. This is to separate the impact of uncertain water supply from the impact of environmental policy on irrigators in the Mooki, such that the focus remains on the expected outcome of policy changes and how irrigators can adjust at least cost. It is assumed that for each season, the expected volume of surface water available is as estimated by the Department of Natural Resources (2007) of 59,000ML for the Mooki. Annual groundwater allocations are also assumed to remain at the expected volume of recharge according to the groundwater Water Sharing Plan (CARE 2003).

8.3 PRODUCTION ACTIVITY CHANGES

In this section, production activity changes under water and deep drainage (DD) constraints are discussed. Results are presented in three sub-sections, according to the treatment being considered. Each sub-section begins with a discussion of production activities under the Base Case scenario of the treatment (with full season's water allocations and no constraints on DD). This is followed by a discussion on the changes in production activity when water caps are imposed, and when DD caps are imposed. With surface water caps, the outcome under water caps of 55,000ML, 40,000ML and 20,000ML are compared. This is to simulate the impact of future reductions in surface water supply, potentially from the government buy-back of entitlements for environmental flows. With DD caps, the outcome under DD caps of 20,000ML, 14,000ML and 10,000ML are also compared. The purpose is to simulate the impact of basin-wide DD caps that may be required to meet end-of-valley salinity targets. Under each scenario, the results are further disaggregated into irrigation areas (Ruvigne, Breeza and Caroona), which allows for a clearer understanding of the trends observed. Production activity changes are examined based on one season, which is representative of all other seasons due to the relatively consistent production across the planning period.

8.3.1 Treatment One – Status Quo

8.3.1.1 Scenario 1.1 – Base Case

For now, only activities 1 and 2 (furrow irrigation sourcing surface and groundwater, respectively) are considered, since the assumption under Treatment One (Status Quo) is that only traditional furrow irrigation systems are used. Water trading is also not considered in this treatment. Dryland crops that can alternatively be produced include wheat (activity 7), sorghum (activity 8) and dryland cotton (activity 9). These dryland cropping options are constant for all treatments.

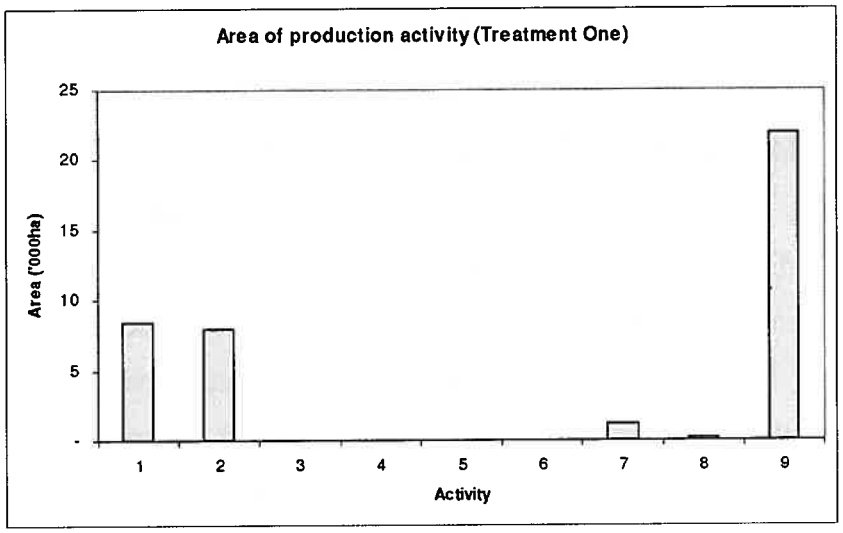

Figure 8.5: Scenario 1.1 production activities.

Under Treatment One, the area of irrigated cotton HRUs is almost at par with the number of HRUs suited to dryland crops (Figure 8.5). Dryland cotton and wheat makes up around half the area of the basin, and the other half of the catchment produce furrow irrigated cotton equally sourcing either surface (activity 1) or groundwater (activity 2). This could suggest that, where there are no alternative irrigation systems (AIS) or water trade, much of the HRUs which are currently under irrigated production may be more profitable under dryland production. This may reflect an overdevelopment of irrigation enterprises in the Mooki currently, and that some areas could be retired from irrigation at relatively low economic cost.

Disaggregating production activities by irrigation areas shows that at the optimum irrigated cotton has the highest prevalence in Ruvigne, followed by Caroona and Breeza (Figure 8.6). This suggests that, under the status quo optimum solution, irrigation should occur mostly in the downstream region of Ruvigne, which has a heavy reliance on groundwater (activity 2). With regards to surface water, however, Caroona appears to be the main user considering it has the greatest area under activity 1 (furrow irrigation sourcing surface water). Breeza seems to be the least suited to irrigation, since it has the smallest proportion of its area under irrigated cotton. The relatively large areas under dryland cotton in all irrigation areas implies that the distribution of water according to area – the way area-based licences were issued to irrigators in unregulated systems – was not efficient. There is scope to reallocate water and improve allocative efficiency and basin profit.

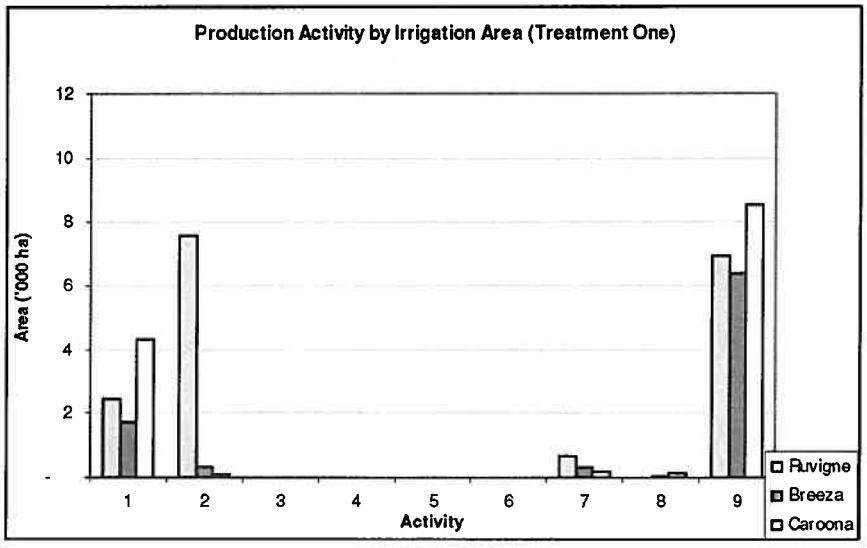

Figure 8.6: Production activity by irrigation area, Treatment One Base Case.

8.3.1.2 Scenario 1.2 – Water Caps

Under scenarios with water caps, the outcomes where surface water supply is capped at 55,000ML, 40,000ML and 20,000ML are presented. This is compared to the base case where the full season's surface water supply, of 59,000ML, is available.

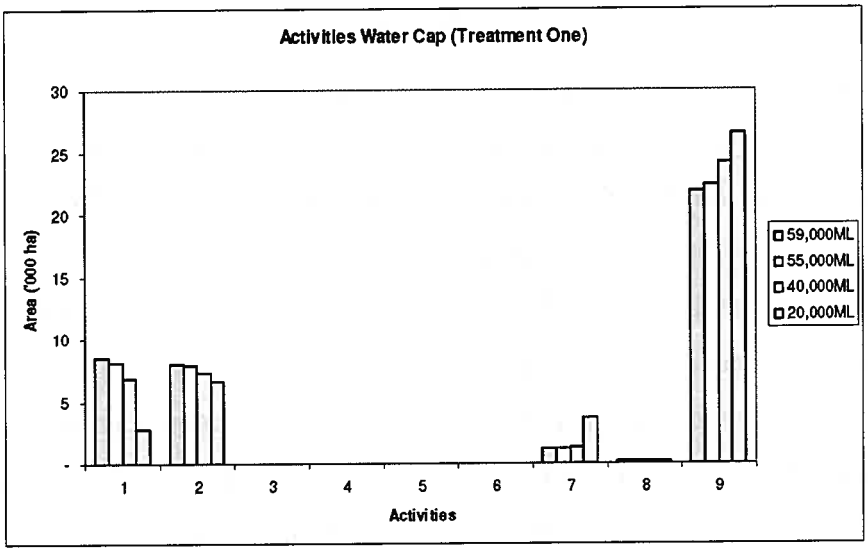

Figure 8.7: Scenario 1.2 production activities.

The impact of water caps on production activities, at the aggregate scale, is shown in Figure 8.7. As expected, where water caps are imposed, the area under surface irrigated cotton (activity 1) is reduced successively with a corresponding increase in the area under dryland production. Since groundwater is unaffected by the water caps, the total groundwater used remains unchanged for all constraints.

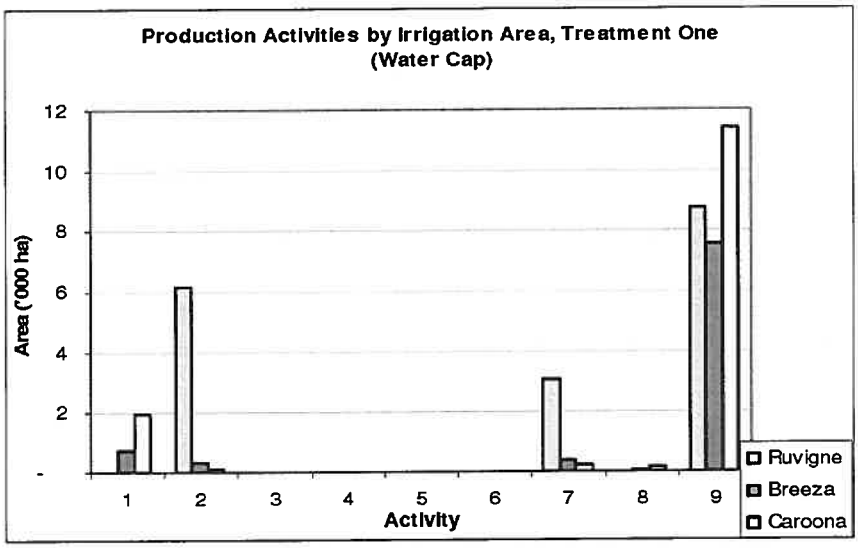

Figure 8.8: Production activities by irrigation area, Treatment One under Water Cap.

The change in production patterns, by irrigation area, is considered under a water cap of 20,000ML (Figure 8.8). Irrigated cotton under activity 1 (surface furrow irrigation) is

reduced significantly in all irrigation areas, particularly in Ruvigne where all surface irrigated cotton is eliminated. However, Ruvigne still has the largest irrigated cotton production, under activity 2 (groundwater furrow irrigation). This suggests that cotton production in Ruvigne is relatively less affected by surface water caps since it is reliant on groundwater sources. On the other hand, Breeza and Caroona, which rely on surface water as its primary water source, experience comparatively greater impact from reductions in surface water allocations. It can be expected that, if environmental flow requirements are increased, the upstream irrigation areas would bear greater economic losses than Ruvigne. It will be seen later that the overall opportunity cost of meeting environmental flow targets is also greater than necessary, since surface water resources have not been distributed efficiently.

8.3.1.3 Scenario 1.3 – Deep Drainage Caps

Under scenarios with DD caps, the outcomes where drainage is capped at 20,000ML, 14,000ML and 10,000ML are presented. This is compared to the base case where DD is unconstrained, at 25,000ML.

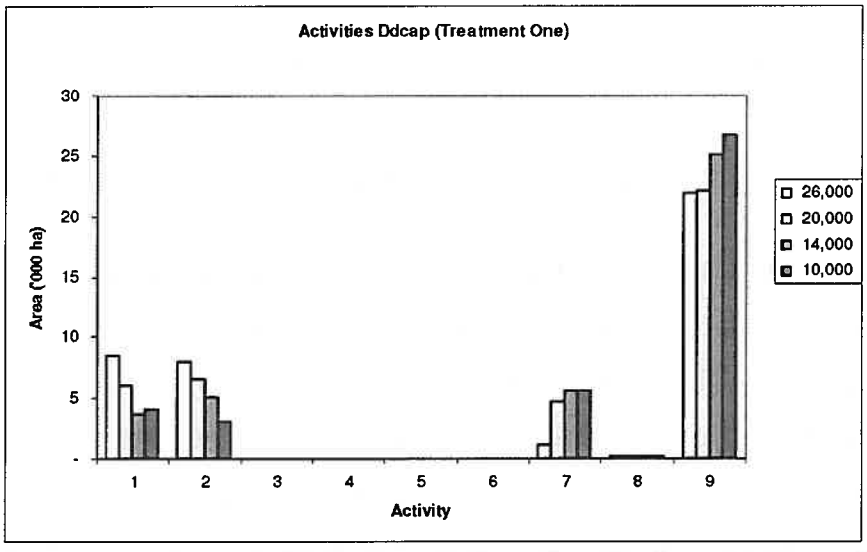

Figure 8.9: Scenario 1.3 production activities.

Where DD caps are imposed, the area under irrigated cotton sourcing both surface (activity 1) and groundwater (activity 2) are reduced as the DD target becomes stringent (Figure 8.9). There is a distinct drop in irrigation areas under activity 2, compared to

where water caps were imposed. This is because a constraint on DD affects all irrigators – ground or surface water users – rather than just irrigators reliant on surface water. While this means that only the least efficient irrigators switch to dryland production, DD caps also affect the level of groundwater use, which has been set to the estimated 'sustainable' recharge rate according to the groundwater Water Sharing Plan (WSP). Assuming this recharge rate is correct and can be maintained indefinitely, reducing groundwater extractions below this level would result in a sub-optimal outcome since the full capacity of groundwater resources is not utilised. This is a common trend under each treatment where DD caps are imposed.

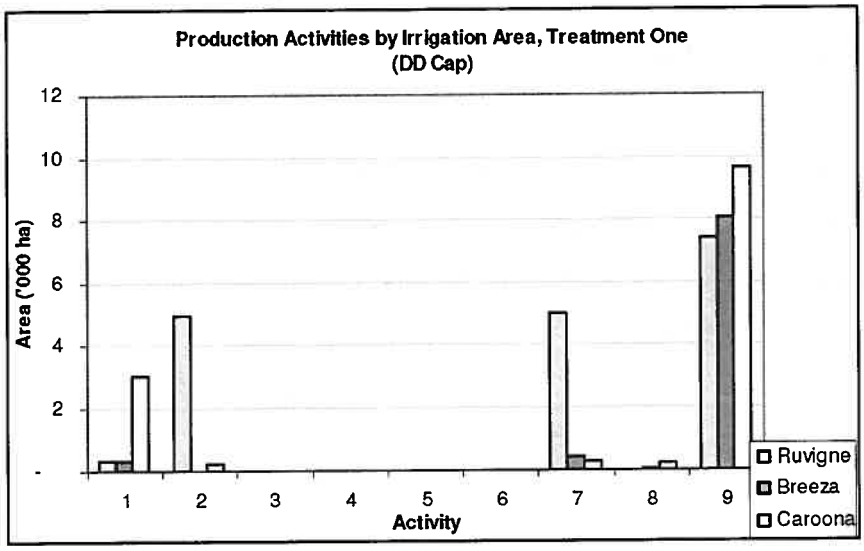

Figure 8.10: Production activities by irrigation area, Treatment One under DD Cap.

In Figure 8.10, the change in production activities under a DD cap of 20,000ML is disaggregated into irrigation areas. The impact of a DD target is more evenly spread between production under groundwater irrigation (activity 2) and surface water irrigation (activity 1), compared to a water cap. It can be inferred that DD targets aimed at reducing salinity would affect all irrigation areas, since both surface and groundwater use are affected by a cap on drainage. This suggests that the economic impact on irrigators located in Ruvigne irrigation zone would be relatively higher, while those located in Caroona and Breeza zones would experience lower economic impacts under a DD cap, relative to a water cap. However, the effect of DD caps on groundwater would be additional to the substantial reductions in groundwater entitlements that have already

occurred in the Mooki. This may inflict unjustified costs on irrigators reliant on groundwater resources in downstream Ruvigne.

8.3.2 Treatment Two – with Alternative Irrigation Systems (AIS)

8.3.2.1 Scenario 2.1 – Base Case

Under Treatment Two, it is assumed that irrigators are given the option to invest in pivot irrigation systems (activities 3 and 4) or drip irrigation systems (activities 5 and 6) where it is profitable. Otherwise, irrigation could remain under the traditional furrow irrigation (activities 1 and 2). Water trading is still not possible, such that irrigators must produce only with the initial water allocations given.

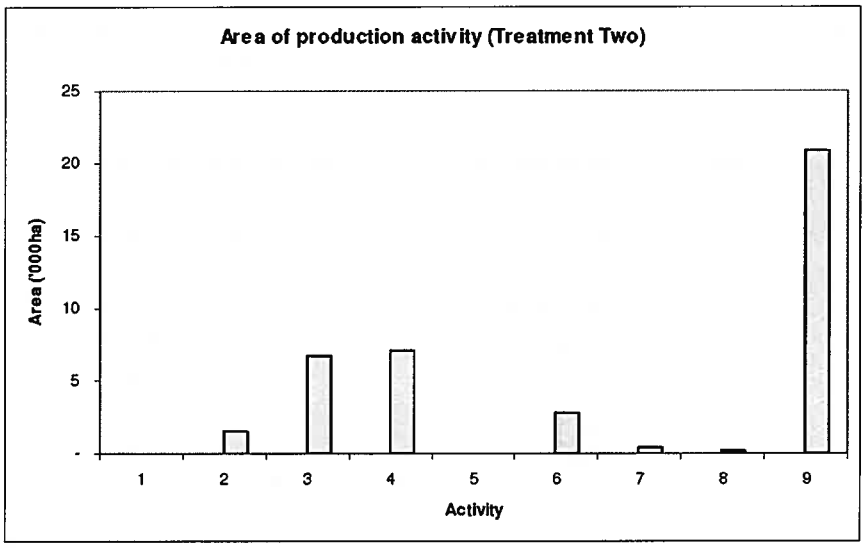

Figure 8.11: Scenario 2.1 production activities.

In Figure 8.11, it can be seen that most irrigators would opt for pivot irrigation systems, with almost equal areas sourcing surface (activity 3) and groundwater (activity 4). In fact, almost all surface water is used conjunctively with pivot systems. Only a handful of irrigation areas remain under furrow irrigation, sourcing groundwater (activity 2). This is rational because pivot systems allow for greater yields for the same level of water use as furrow irrigation. Some HRUs adopt drip irrigation conjunctively with groundwater (activity 6). This could be explained by the reliability of groundwater, which allows greater crop yields to be achieved since irrigation could occur regularly, and ensures the capital investments in drip systems (which have higher capital costs than pivot) are

recouped. Dryland cotton (activity 9) still dominates the catchment, with a small portion producing dryland wheat (activity 7). Given the areas under dryland cotton and wheat are relatively unchanged compared to Treatment One, it can be inferred that many HRUs may in fact be more suitable to dryland crops. Environmental flows may be sourced from these areas at relatively low cost to the basin, since they are more profitable under dryland production.

Considering the activities by irrigation area, the most irrigation still occurs in Ruvigne which remains heavily reliant on groundwater (Figure 8.12). The difference is that pivot systems have become the most profitable irrigation technology, followed by drip irrigation systems and by furrow irrigation.

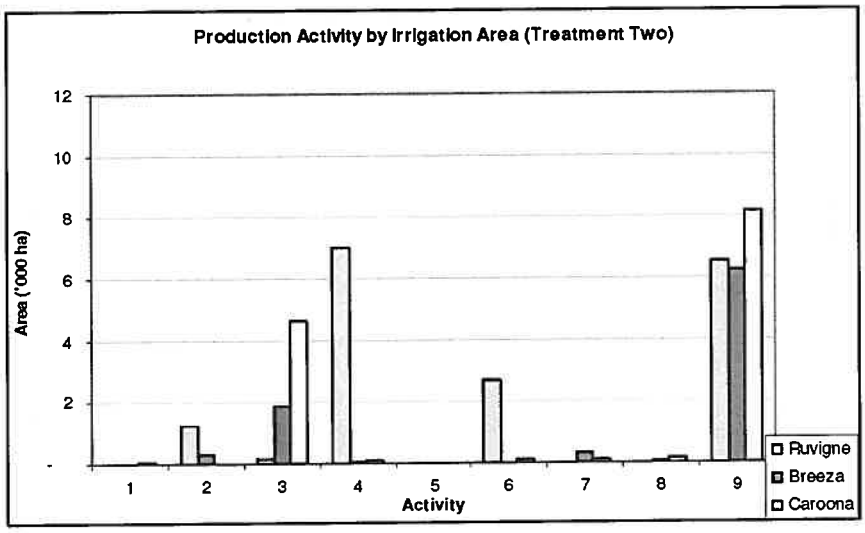

Figure 8.12: Production activities by irrigation area, Treatment Two Base Case.

It can be seen that, where AIS is used, the primary source of water in all irrigation areas does not change. However, it is almost always optimal to switch to water efficient technologies. The area under dryland cotton still dominates a significant portion of each irrigation area, which is similar to Treatment One. This reiterates the notion that water has not been efficiently distributed in such a way that reflects its highest value use. The use of AIS can improve the productivity of water; but this improvement is confined to the farm-level.

8.3.2.2 *Scenario 2.2 – Water Caps*

In Figure 8.13, the aggregate effect of water caps, under Treatment Two are presented. Water caps are again imposed at 55,000ML, 40,000ML and 20,000ML. The outcomes are compared to the base case surface water supply of 59,000ML.

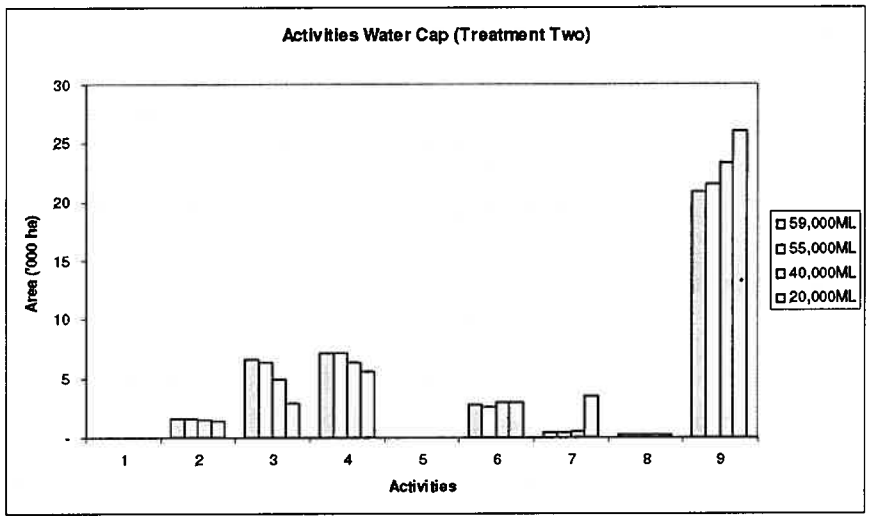

Figure 8.13: Scenario 2.2 production activities.

It can be seen that, where water caps are imposed, most of the HRUs that sourced surface water (activity 3) switch to dryland crops, while irrigated production sourcing groundwater (activities 2, 4 and 6) is again relatively unaffected. This result is logical since water caps only affect surface water users, and is a consistent trend under each treatment.

The impact of water caps by irrigation area is presented in Figure 8.14. Since almost no surface water is used in Ruvigne, much of the water reductions occur in Caroona and Breeza. The main impact of water caps is therefore inflicted on Caroona and Breeza irrigators, while Ruvigne is relatively unaffected. Similarly to Treatment One, where greater environmental flows requirements are imposed on the Mooki irrigators, the most economic impact would occur in the upstream irrigation areas.

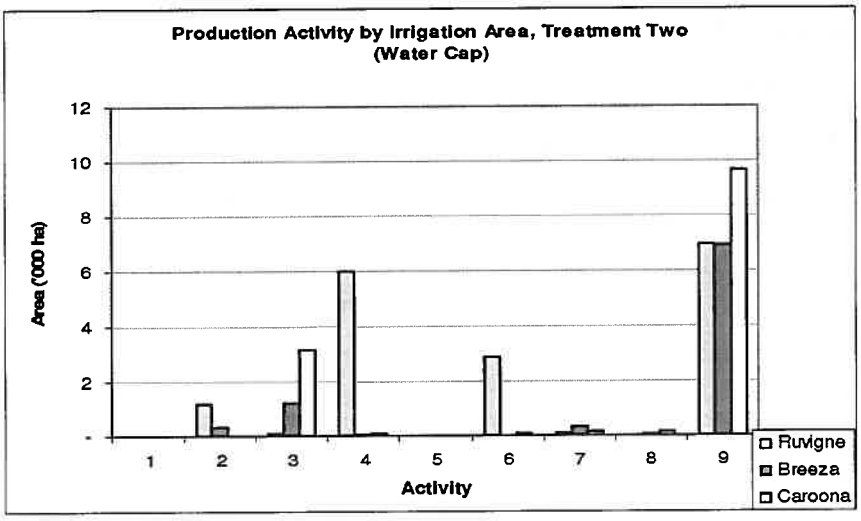

Figure 8.14: Production activities by irrigation area, Treatment Two under Water Cap.

8.3.2.3 Scenario 2.3 – Deep Drainage Caps

In Figure 8.15, the changes in production activities as DD caps are imposed at 20,000ML, 14,000ML and 10,000ML are presented. This is compared to the outcome under the unconstrained scenario with a DD of 25,000ML.

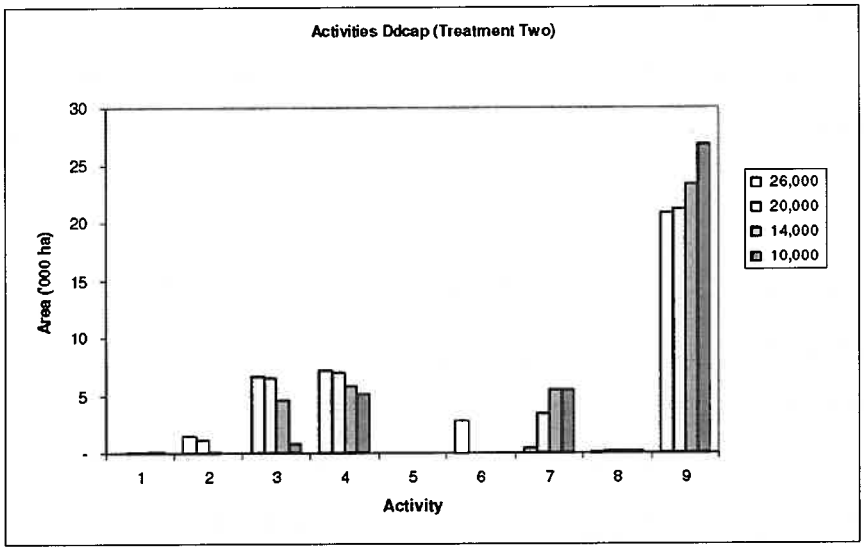

Figure 8.15: Scenario 2.3 production activities.

A considerable reduction in both surface and groundwater use is observed where DD caps are imposed. A distinctive change is the area under pivot irrigation sourcing surface water (activity 3), which falls significantly at stringent DD targets. While groundwater

use (activities 4 and 6) is not reduced as dramatically as observed under Treatment One (Scenario 1.3), its extraction level nevertheless drops below the sustainable extraction rate for all DD constraints.

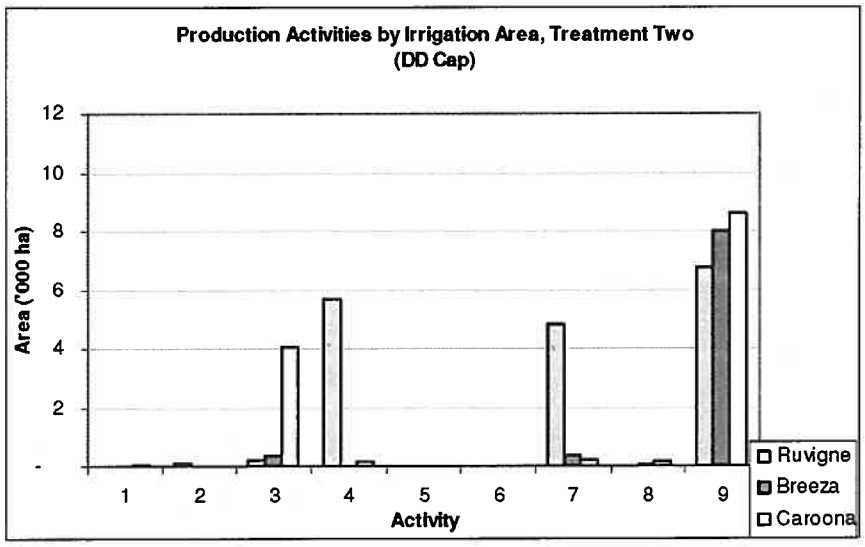

Figure 8.16: Production activities by irrigation area, Treatment Two under DD Cap.

The impact of DD caps according to irrigation area is shown in Figure 8.16. Much of the reduction in water use occurs in Ruvigne, where groundwater use is reduced significantly under activity 4 (pivot system) and activity 6 (drip system). Again, the economic impact of DD caps on groundwater may lead to excessive costs on irrigators reliant on groundwater resources, particularly in Ruvigne, due to the substantial cuts in groundwater entitlements that have already occurred.

8.3.3 Treatment Three – with Water Trade and Alternative Irrigation Systems (AIS)

8.3.3.1 Scenario 3.1 – Base Case

Under Treatment Three, water trading is introduced and irrigators have the choice to use AIS. Given the option to trade water and use water efficient technology, the area under dryland cotton (activity 9) falls considerably, with a corresponding increase in the area that under irrigated cotton. This is distinctly different to previous treatments without water trade, under which a significant portion of the landscape is under dryland crops (Figure 8.17).

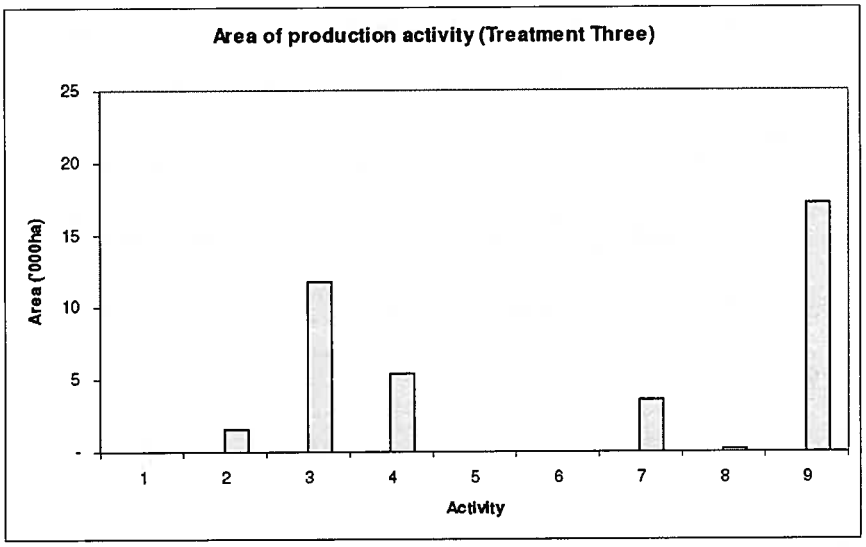

Figure 8.17: Scenario 3.1 production activities.

Based on the changes in production observed, it appears that under previous treatments, a significant area of the catchment was forced to produce dryland crops due to limited access to water. Therefore, where surface water could be obtained through the water market, these HRUs switch to irrigated cotton under pivot irrigation systems (activity 3). Pivot irrigation sourcing groundwater (activity 4) remains a prominent production activity, although drip systems (activity 6) become unfavourable, and are not used. Given the possibility of purchasing surface water, the HRUs that were using drip irrigation (activity 6) in previous treatments, appear to find more profitable to invest in pivot systems and source surface water instead. That is, where it was not possible to purchase water through the water market, these HRUs were limited by the availability of surface water and were confined to irrigating with groundwater under drip systems. This also implies that these HRUs had higher values for surface water than other HRUs that initially had a greater allocation of surface water.

Closer inspection of the production activities by irrigation area shows that much of the surface water is traded to downstream Ruvigne, such that almost all irrigation occurs in this area (Figure 8.18). While Caroona remains the second largest area under irrigated cotton, the proportion under irrigation has shrunk significantly compared to previous treatments.

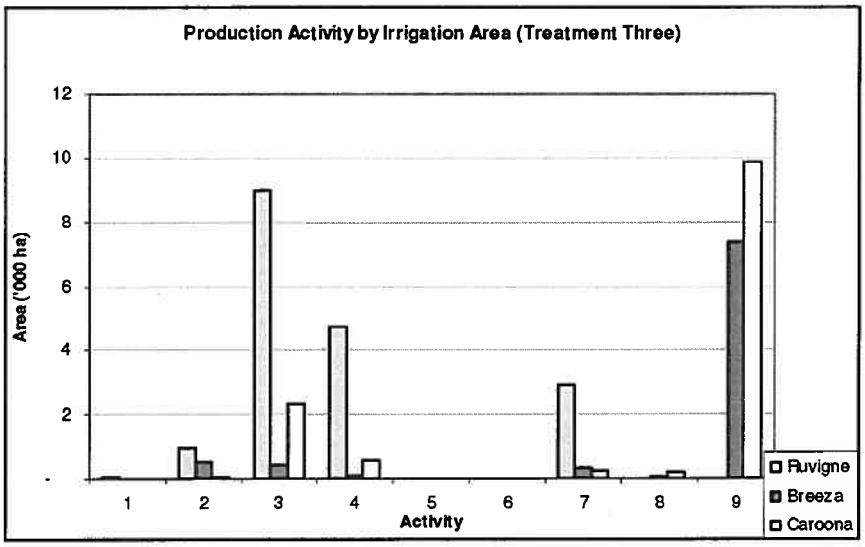

Figure 8.18: Production activities by irrigation area, Treatment Three Base Case.

This change in production pattern between Treatment Three and previous treatments can be explained by the location of Caroona and Breeza, which are the upstream-most irrigation areas with first access to surface water. Where no water trade is possible, surface water is extracted by these upstream irrigation areas, despite Ruvigne having the highest value for surface water. With water trade, surface water is almost completely traded downstream. This suggests that Ruvigne is the most productive irrigation area in the Mooki basin, and that basin profit can be maximised by establishing a system of water trade in this region. Since Upper Namoi is thought to have the highest conservation value, the trade of water downstream would result in a socially optimal outcome. Not only would the profitability of the basin be enhanced, the upstream environment could also be protected.

8.3.3.2 Scenario 3.2 – Water Caps

As per previous treatments, as water supply is reduced, the irrigated areas sourcing surface water (activity 3) fall and areas under dryland cotton (activity 9) rise. This is while areas reliant on groundwater (activities 2 and 4) remain relatively unchanged. Compared to treatments without water trade, however, surface water is distributed efficiently under Treatment Three such that its full value is realised, and only the least efficient surface water irrigators forego water use. This leads to lower overall opportunity

costs compared to where water has not been distributed efficiently under previous treatments.

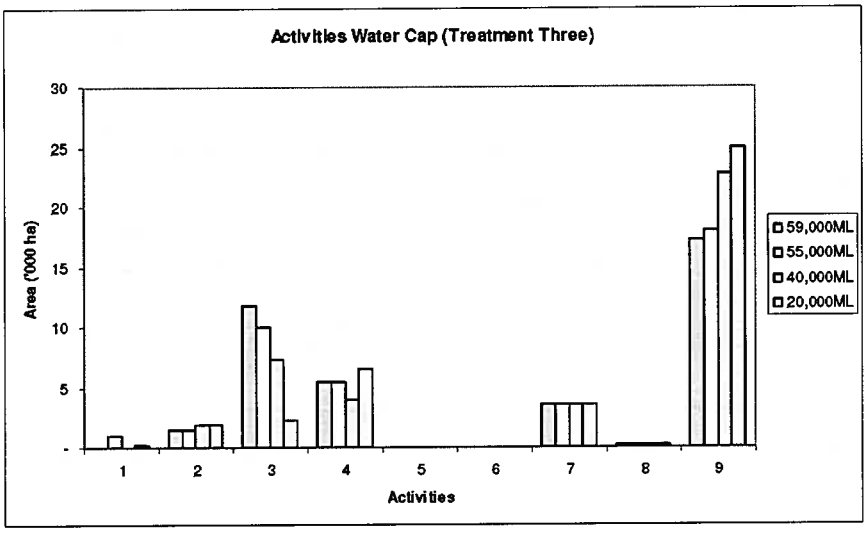

Figure 8.19: Scenario 3.2 production activities.

Considering the impact of water caps by irrigation area, it can be seen that the economic burden has also shifted from Caroona and Breeza to downstream Ruvigne (Figure 8.20). Under previous treatments, much of the economic impact occurs in Caroona and Breeza, since these areas relied on surface water. With water trade, most surface water shifts to Ruvigne from upstream irrigation areas, such that surface water caps affect only irrigators in this region.

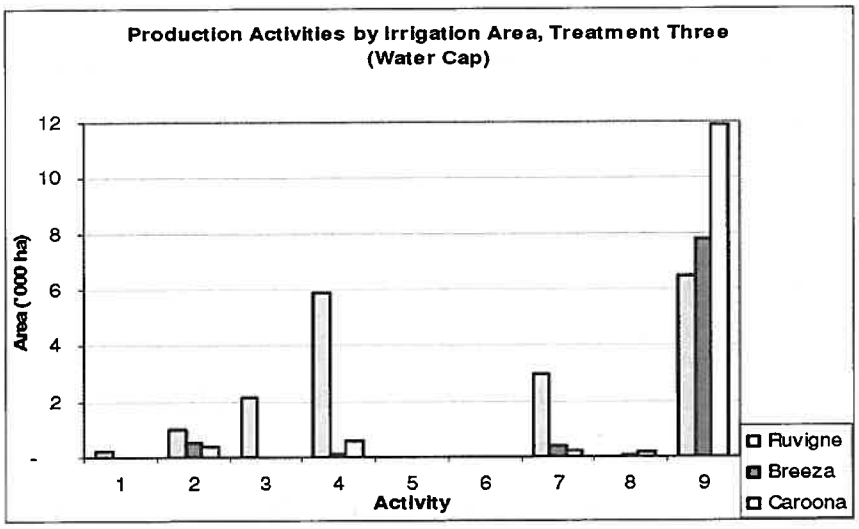

Figure 8.20: Production activities by irrigation area, Treatment Three under Water Cap.

While the economic impact is more pronounced in Ruvigne, irrigation still occurs in this region, while in Breeza and Caroona irrigation ceases completely. This suggests that, even where surface water allocations are cut significantly, Ruvigne remains the most productive irrigation area where much irrigated production would occur. This is while groundwater use (activities 2 and 4) is not affected.

8.3.3.3 Scenario 3.3 – Deep Drainage Caps

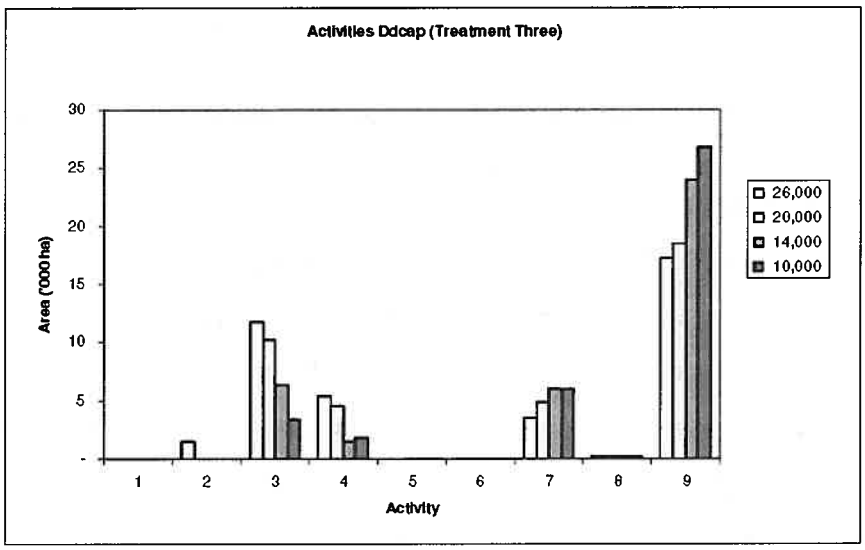

Figure 8.21: Scenario 3.3 production activities.

Where a DD cap is imposed under Treatment Three (Figure 8.21), a similar rate in water use reductions occur in pivot irrigation sourcing surface water (activity 3) and groundwater (activity 4). Compared to where water caps are imposed, however, it appears that the impact on groundwater use is more dramatic under a DD cap. Considering the changes in production by irrigation area (Figure 8.22), it can be seen that much of the impact of DD caps are also inflicted on Ruvigne since water is mostly used in this irrigation area.

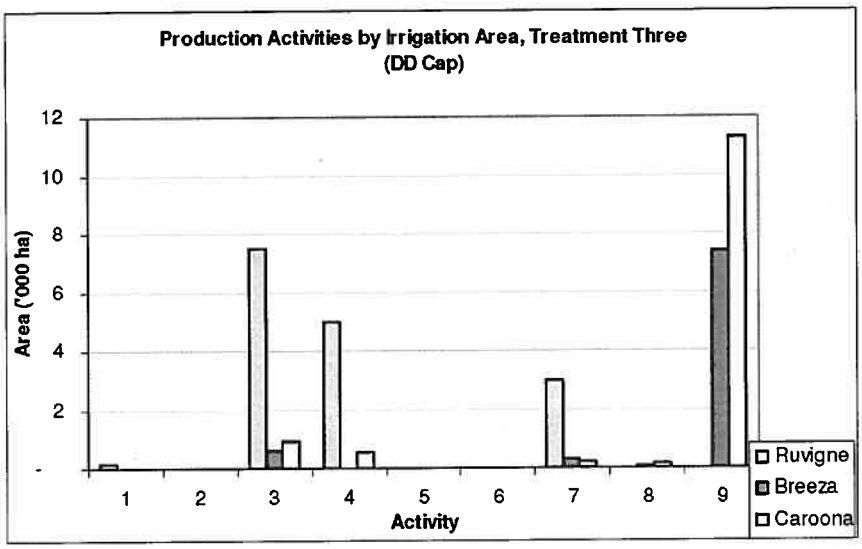

Figure 8.22: Production activities by irrigation area, Treatment Three under DD Cap.

As DD caps are tightened, groundwater use under furrow systems (activity 2) ceases in all irrigation areas. This is while pivot irrigation sourcing groundwater (activity 4) and surface water (activity 3) are also reduced considerably. Therefore, DD caps will affect both water sources, with the greatest impact being in Ruvigne. This is the case regardless if DD caps or water caps are imposed, since Ruvigne has the largest area under irrigation. This is in contrast to previous treatments where the upstream irrigation areas bear greater economic losses under water caps, because water has not been distributed efficiently. Where water trade is possible, the overall opportunity cost of meeting environmental targets would be much lower, because water has been shifted to its highest value use (in Ruvigne).

8.3.4 Shadow Prices for Water

The shadow values for surface water (Sw) and groundwater (Gw) were obtained for the Base Case scenario under each treatment for the HRUs in irrigation areas Ruvigne, Caroona and Breeza. The shadow price for each HRU within the irrigation area were summed then averaged for Treatments One and Two, since the value under non-trading treatments vary between HRUs. A single shadow price is reported for all irrigation areas under Treatment Three since it is the same for all HRUs in the presence of a water market. The shadow prices obtained in this section help shed light on the trends in

changes in production activities observed, and can assist in explaining results in the subsequent sections in this chapter.

It can be seen that under the status quo (Treatment One), Ruvigne has the highest shadow value for resources, followed by Caroona and then Breeza (Table 8-6). This corresponds to reality, since it is known that most cotton irrigators are located within Ruvigne, with fewer irrigators in the other areas (Smith 2006, pers. comm.). Considering the production activities in Figure 8.6, much of the surface water was initially used in the upstream Caroona and Breeza regions. This confirms the finding that at the outset surface water resource was not allocated efficiently to where it has the highest value. Groundwater appears to have the highest value in Caroona, although only slightly greater than Ruvigne.

Table 8-6: Shadow values under Treatment One Base Case.

Treatment One	Ave. Sw shadow value	Ave. Gw shadow value
Ruvigne	118.69	68.05
Breeza	73.19	49.70
Caroona	87.24	71.61

Under Treatment Two (no water trade, with AIS), the value of surface water is increased for all irrigation areas; with a significant rise observed in Ruvigne (Table 8-7). This is while the shadow price of groundwater is reduced (or unchanged) for all areas. This could suggest that, where AIS are available, the value of surface water is enhanced such that the relative value of groundwater falls.

Table 8-7: Shadow values under Treatment Two Base Case.

Treatment Two	Ave. Sw Shadow value	Ave. Gw shadow value
Ruvigne	129.79	47.51
Breeza	80.29	49.70
Caroona	89.28	64.26

As expected, where water trade is introduced under Treatment Three, the shadow value of surface water is equated across all irrigation areas (Table 8-8). Much of the water was traded to the downstream area of Ruvigne, where, in the absence of a water market, the

shadow value for surface water was highest. The equilibrium shadow price is $111.45/ML, which represents the market-clearing price in the water market. The equilibrium quantity traded is 37,500ML and much of the water is moved into downstream Ruvigne. This reflects the changes in production activity observed in Figure 8.18, which shows that almost all irrigated production occurs in this irrigation area. Under scenarios without water trade (Treatment One and Treatment Two), much of the surface water is used upstream, although it can be seen from the shadow price that it has the highest value in downstream Ruvigne.

Table 8-8: Shadow values under Treatment Three Base Case.

Treatment Three	Sw shadow value (with Gw)	Sw shadow value (w/o Gw)[9]	Ave. Gw shadow value
Ruvigne	111.45	148.91	62.27
Breeza			44.19
Caroona			70.48

The equilibrium shadow price obtained from the model reflects the empirical water market prices observed for the Namoi. From the WaterExchange website (WaterExchange 2007), the market price for temporary water trade in the regulated system in Namoi averages $100/ML, with a high of $120/ML over the last season. This market price seems to correspond well to the shadow value of $111.45/ML for the Mooki unregulated system. This validates the economic model, which generates a shadow value for water similar to that observed in the water markets in the Namoi region. Furthermore, it appears that there is scope for water trade to occur between the regulated (downstream) and unregulated (upstream) systems within the Namoi Valley, perhaps with more surface water flowing towards the regulated areas. This may result in an efficient outcome, due to the conservation value of Upper Namoi, given the presence of high value species and wetlands (Hudson 2005, pers. comm.; DLWC, 1998). However, the extent of trading may be limited since the marginal values are very similar. In addition, in the absence of groundwater, the shadow value of surface water grows to $148.91/ML. This has implications for future reductions in groundwater entitlements, which may create a

[9] Two shadow prices for surface water were calculated: one with full groundwater allocations available and one without (w/o) any groundwater supply available. This was to determine the value of surface water in the absence of an alternative water source.