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Where should out water go? Assessing trade-offs in water allocation in the Namoi River Catchment

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Abstract:

The Namoi river catchment in northern NSW is an important irrigation region. Water resources in this region are increasingly stressed. Both surface and groundwater supplies are overallocated in many areas of the catchment. Management options to reduce allocations in line with available supply and environmental requirements are expected to have long term social, economic and environmental implications. One water resource, off-allocation water, is currently unallocated. This means that no user is currently given a property right to this resource and it is available for re-allocation to alternative users, including the environment. This paper outlines an integrated economic-hydrologic modelling tool which has been developed to estimate regional scale economic and environmental trade-offs associated with alternative water allocation policies. A detailed description of the economic modelling component is provided. In particular the way in which capital investment decisions are treated in the model are described. The sensitivity of the model to assumptions about the cost of investing in additional capital is shown and results for the application of the model to a number of policy scenarios are presented.

Key words: water allocation, capital, economic model, dynamic programming, linear programming

1. Introduction

The Namoi River Catchment covers approximately 42,000 km^2 in northern NSW and is an important irrigation area. Groundwater and surface water supplies are overallocated in many areas of the catchment. Management options for dealing with this overallocation are likely to have significant social, economic and environmental impacts. Figure 1 shows the catchment. The major storages (Keepit, Chaffey and Split Rock dams) are shown, as well as the main towns of Tamworth, Gunnedah, Narrabri and Walgett. The Namoi river stretches for over 300km, flowing from east to west.

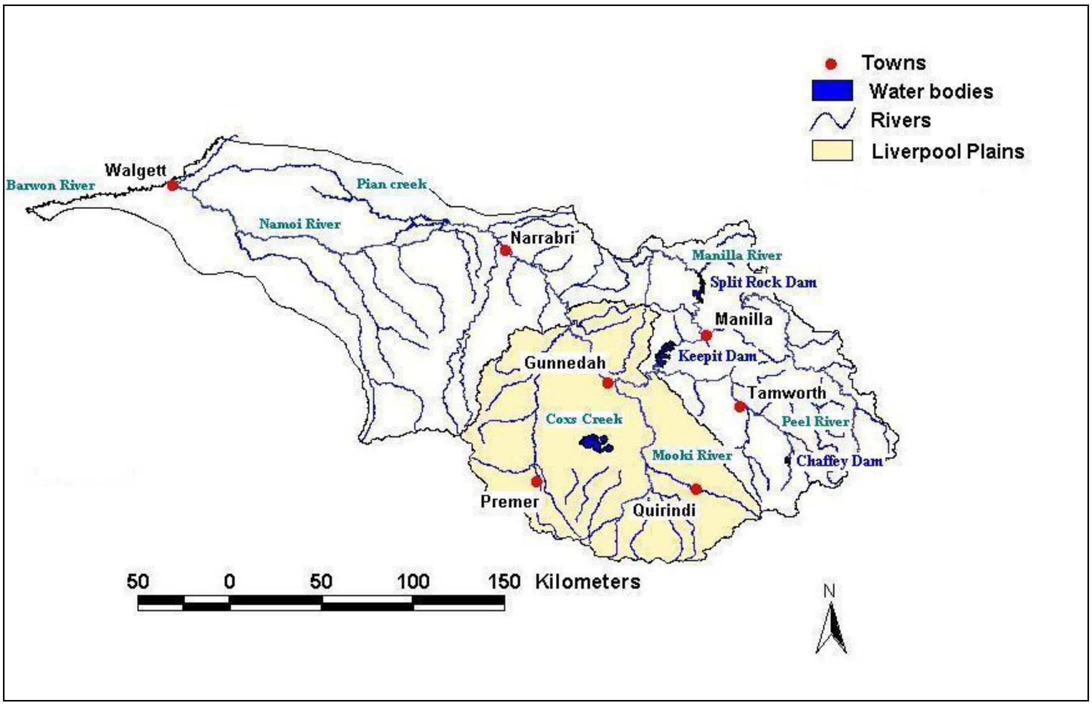

Figure 1. Namoi River Basin

Water management and use falls into three main areas in the catchment: unregulated and regulated system surface water, and groundwater. Groundwater allocations for extraction in many areas of the catchment currently exceed sustainable levels. Surface water resources in the Namoi catchment have been divided into two classes for the purposes of management: regulated and unregulated water. The unregulated system consists of those subcatchments of the Basin which are above the major dams (Keepit, Split Rock, and Chaffey dam). The regulated system consists of the river below these storages, including the Peel river below Chaffey Dam. Off-allocation water is water that spills from the dams, or that flows into the regulated system from the unregulated system. It is not currently allocated to any specific users by a licence or other type of property right. Currently, this off-allocation water may be extracted when it exceeds users' demands and identified environmental needs. These off-allocation extractions are not counted against the users' licensed allocations (see for example DLWC (1999)). Off-allocation water is usually made available during periods of high river flow (generally corresponding to the winter months in the Namoi catchment). Producers then store the water for the irrigation season in turkeys nest dams. Under current management, off-allocation may account for approximately one-third of surface water extracted in the catchment, with this proportion varying greatly between years with differences in climate (DPMS, 1996). In the past no property right has been given over this off-allocation water, with access being at the discretion of the NSW Department of Land and Water Conservation. The lack of such defined property rights or licences to this resource has resulted in off-allocation water being viewed as part of a solution to water allocation problems in the catchment.

This paper focuses on the economic modelling component of an integrated modelling tool capable of considering the following management question:

What are the trade-offs involved with different policies for water allocation in the Namoi catchment given:

- *overallocation of groundwater and the phase in of groundwater allocation reductions expected over a 5-10 year period in most groundwater zones in the catchment;*
- *expected activation of sleeper licences and further development of irrigation in the unregulated system, where the irrigation industry has historically been less developed than in the lower catchment;*
- *the dependence of traditional users of off-allocation water on this resource; and*
- *environmental flow requirements. The interim rules for off-allocation in the catchment includes a 50:50 sharing rule of off-allocation water with the environment.*

2. Treatment of capital in applied work on water allocation issues

Many economic models have been built to consider the issues of water trading and water reforms in Australia and more generally (eg. Hall (1999), McClintock and Gooday (1998), Branson *et al.* (1998)). However most of these models have been focused on the short term, ignoring the possibility of structural adjustment in the face of reform. Few models have considered the costs of additional infrastructure, both to the farmer and the catchment manager, of changing access to irrigation water. Changing access to irrigation water supplies will in many cases mean additional capital costs to both the farmer and the catchment manager. To the catchment manager, changing the spatial distribution of access to irrigation water within a catchment will mean additional channels may need to be constructed and maintained. Programs implemented by the catchment manager to improve irrigation efficiency within the catchment will also carry a cost to the catchment manager. Where a farmer chooses to adopt such efficiency improvements, costs to the farmer can also be expected to increase. Farmers may require additional storage capacity in order to capture less secure or differently timed water supplies, such as off-allocation water. Increasing efficiency and activation of sleeper licences will in many cases involve costs involved with laying out additional areas to irrigation. Economic models developed to consider water reform have generally ignored these longer term structural adjustment costs.

Hall *et al.* (1994) described a spatial equilibrium model developed to consider tradeable water entitlements in the Southern Murray-Darling Basin. While this model considered the running costs of the distribution system and the costs of renewals of capital assets, it did not consider capital adjustment. The model was able to indicate likely pressures for adjustment, but could not consider structural adjustment as a result of trade. Farm capital was considered through constraints on the area which could be irrigated in the model, while regional capital was considered through channel capacity constraints. Similarly Branson *et al.* (1998) describes a spatial equilibrium model using a number of regional linear programming models previously developed for areas in NSW and Victoria (Branson and Eigenraam, 1996b; Branson and Eigenraam, 1996a; Curthoys *et al.*, 1994; Gunaratne *et al.*, 1995a; Gunaratne *et al.*, 1995b; Gunaratne *et al.*, 1995c; Jones, 1991; Pagan *et al.*, 1996; Wall *et al.* (1994) from Branson *et al.* (1998)) in which channel capacity was used as a constraint. Farm adjustment was limited to changing the enterprise mix through the linear programming models.

McClintock and Gooday (1998) developed a model for investigating water demands within and between irrigation seasons. This model was used to explore the implications of water policy reforms and the efficiency costs of not using a water market to reallocate water. Short run production decisions were simulated at a farm level using a linear programming model. No consideration was given to the costs to the catchment manager of additional infrastructure needed for water markets (constraints of channel capacity on farm were used). The number of on-farm storages and pumps could be changed by the user, but the model did not consider the costs of this additional infrastructure. Maintenance costs for reuse, storage systems and groundwater pumps were included with other fixed costs outside the linear programming module, but have no impact on the production decision.

3. Conceptual Modelling Framework

The previous section provided a review of economic techniques used in the literature to consider water allocation and capital investment. This review has been used to focus on the key aspects of the modelling issue being considered and the most appropriate techniques for exploring these issues.

The management issue for which the integrative modelling framework in this paper was developed was outlined in Section 1. This question has two key characteristics. Firstly it is essentially spatial in nature, considering trade-offs between upstream and downstream users and the environment. The types of users and returns from production vary within the catchment. Significant levels of infrastructure are also required to take advantage of this resource, with incumbent users being highly adapted to utilising this water. Secondly the question is intrinsically dynamic or intertemporal in nature. Off-allocation water supplies and their importance to irrigated agriculture in any year depend critically on climatic conditions in the catchment. In the Namoi, off-allocation water is usually made available during periods of high river flow (generally in the winter months) and producers store the water for the irrigation season in turkeys nest dams. In some years there is no off-allocation water to be accessed, whereas in other years off-allocation water can account for one third of all irrigation water used in the regulated river system. Additionally, groundwater allocation reductions will be phased in over 5-10 years in most zones. The year in which constraints become binding differs between zones depending on current active use and the amount by which the zone is overallocated. Also changes to the allocation of off-allocation water will involve significant structural adjustment, including the development of considerable levels of capital infrastructure. The management question becomes a trade-off between incumbent users who are already extremely specialised towards the use of this water and new users who will require significant levels of investment in infrastructure if they are to take advantage of the resource.

Given the nature of the management question being asked and the type of trade-offs being considered it was decided that a regional scale economic model was most appropriate for considering the off-allocation management issue. The intertemporal nature of the management issue suggested a 'long run' model structure in which structural adjustment could be taken into account. It was decided that in order to capture both the spatial and temporal nature of the off-allocation management issue, a regional scale model, linking regional scale dynamic programming models and streamflow models should be developed.

3.1. Decoupling decision making in the model

The management issue described above is affected by two levels of decision making: 'catchment manager' and 'regional farmer'. The catchment manager introduces policies into the catchment so that the well-being of the catchment as a whole is optimised. This well-being may be measured in purely economic terms or may also include environmental and social goals. Once a policy has been implemented by the catchment manager, regional farmers are free to adjust their individual production decisions in response to this change. This adjustment will affect the optimal policy for the catchment as a whole. In particular, changing water use by upstream users can be expected to affect the water available to downstream users, as well as the income of the whole catchment. The model separates these two levels of decision making in the catchment.

3.2. Regional Model Structure

Irrigators have different access to surface and groundwater sources throughout the catchment, with different types of licences and different levels of security of access. This means that the question of where to provide access to off-allocation water involves a trade-off between upstream and downstream users, and is intrinsically spatial in nature. Thus to address this issue a framework that accounts for the important spatial variability of this management problem is required. For the consideration of this off-allocation problem, this has meant that the catchment has been mapped into a number of relatively homogenous regions. The term ‘relatively homogenous’ is with respect to important economic and social scales for water allocation in the catchment. In the case of off-allocation access, this means that regions are chosen to be relatively homogenous in terms of groundwater policy, surface water policy and production type. The development of these regional boundaries has involved an iterative process with stakeholder input into each stage of model framework development. A first cut of regions was developed by overlaying groundwater zones and subcatchment areas, and was further refined on the basis of advice on regional production differences provided by various stakeholders. The final regions developed in this framework are shown in Figure 2.

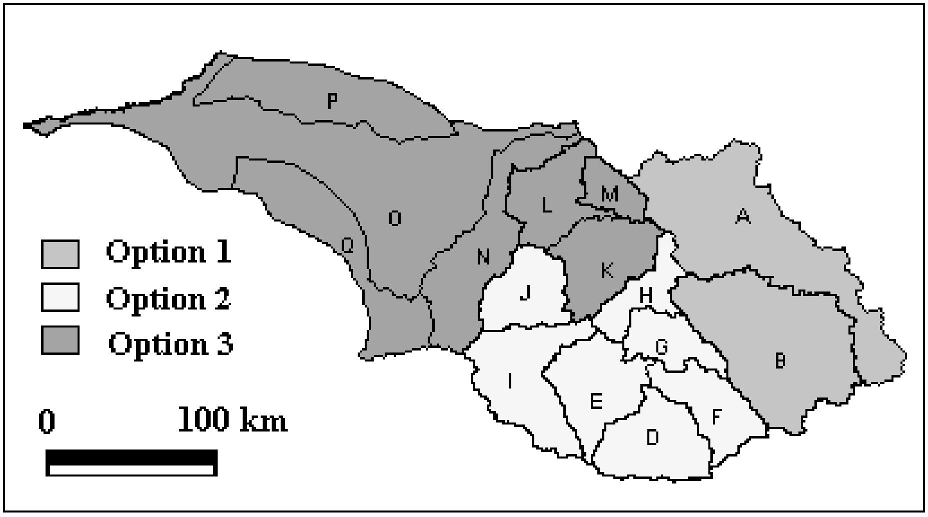

Figure 2. Model Regions in the Namoi Catchment

A summary of the major features of these regions is given in Table 1. A set of alternative cropping activities has been developed for each region. These activities have been developed to be representative of those likely to be undertaken in each region on potentially irrigable land. As can be seen in Table 1, each region also corresponds to a hydrological node (Regions E and F share a hydrological node, other regions have a unique node). This structure forms the basis of the links between hydrological and economic components of the model.

Table 1. Major Regional Features

Region	Description	Stream Gauge	Activities*
A	Above Keepit	419022	Option 1
B	Peel River	419006	Option 1
D	Mooki River catchment to Caroona	419034	Option 2
E	Western side of Mooki River catchment from Caroona to Breeza	419027	Option 2
F	Eastern side of Mooki catchment from Caroona to Breeza	419027	Option 2
G	Mooki River from Breeza to Gunnedah	419084	Option 2
H	Namoi from Carroll Gap to Gunnedah	419001	Option 2
I	Cox's Creek above Mullaley	419052	Option 2
J	Cox's Creek Mullaley to Boggabri	419032	Option 2
K	Namoi River from Gunnedah to Boggabri	419012	Option 3
L	Namoi River from Boggabri to Narrabri	419002	Option 3
M	Maules Creek	419051	Option 3
N	Namoi River from Narrabri to Mollee	419039	Option 3
O	Namoi River from Mollee to Walgett	419026	Option 3
P	Pian Creek	419049	Option 3
Q	Barradine Creek	419072	Option 3

*Activity Options:

Option 1
1. Irrigated Lucerne
2. Dryland Wheat

Option 2
1. Irrigated wheat/ cotton rotation
2. Dryland wheat/ sorghum rotation
3. Dryland wheat/cotton rotation

Option 3
1. Irrigated cotton/ wheat rotation
2. Irrigated continuous cotton
3. Irrigated cotton/ faba bean rotation
4. Dryland cotton/ wheat rotation
5. Dryland sorghum/ wheat rotation

Regional farmer level decisions are simulated through a set of dynamic programming modules. These modules make long term capital investment decisions given a policy option for off-allocation water, constraints on available water and land, and levels of irrigation efficiency. Short run production decisions in these modules are made by a series of nested linear programming models (i.e. for a given 'capital state', production choices for the year are given as the solution of a linear programming problem). Regional farmers are constrained by land and water availability and are assumed to be profit maximising. A scenario based approach is used to investigate trade-offs in the decision of the catchment manager. Impacts on river health of various scenario combinations can be signalled through links with the hydrological model previously discussed. Economic impacts on regions and on the entire catchment are also considered. The user may decide what trade-offs they are willing to accept and investigate likely outcomes of management options.

3.3. Capital and off-allocation water use in the Namoi catchment

Irrigated agriculture in the Namoi catchment is largely dependent on intensive levels of capital infrastructure. In the Namoi catchment, the water supply system consists of several large dams (Keepit, Chaffey and Split Rock) and the river system, with producers managing their own off-river diversion. Canals and weirs are used in some areas to supply water to producers. In the lower catchment the use of turkeys nest dams is common among irrigators, with producers pumping water directly from the river into their dam for storage until the water is required for irrigation. These producers experience costs associated with fuel and the capital costs of pumps as well as having to provide on-farm reticulation systems to distribute the water from these dams to their fields. Some users also have formal drainage systems consisting of channels linking back to the river system, in which excess water from their fields is transported back to the river system. Furrow or flood irrigation systems are the most common in the lower catchment. In the upper catchment some areas have spray irrigation. In many cases producers pump direct from the river to the sprinkler rather than storing the water on-farm. Groundwater users in the catchment are unlikely to pump into an on-farm storage, rather they are more likely to pump directly to their crops. Capital associated with groundwater usage consists of pumps, bores and on-farm reticulation systems.

Off-allocation water usage in the catchment is largely dependent on on-farm storage capacity. The timing of off-allocation flows is such that they must be extracted and stored for several months before being used for irrigation. This means that for non-traditional users of off-allocation water, significant levels of infrastructure must be developed for them to make use of this resource.

The other types of capital investment required for irrigated agriculture consist of investment in laying areas out to irrigation and the types of infrastructure improvements which could increase irrigation efficiency on-farm. These capital works could include the cost of regular laser levelling, storage and channel compaction or lining, investment in subsurface drip irrigation systems, covering storages or piping channels.

3.4. Treatment of capital in the model

Changes to capital in the model arise largely in response to the policy scenarios or decisions undertaken by the catchment manager. However the costs of these changes are felt mainly at the regional farmer level. This section describes the types of capital changes considered by the model and the way in which the costs of these changes have been incorporated into the model.

3.4.1. Irrigation technology options (k)

Irrigation technology options differ by region. It has been suggested by various people involved with water reform that decreases in allocation would not be required if irrigation efficiencies were to be improved. The model considers the possibility for regional farmers to increase their irrigation efficiency through improvements to their irrigation technology or capital. Regions A and B (see Figure 2) have only one option: current spray irrigation. All other regions are modelled to allow three irrigation technology options: current flood irrigation; 10-15% improvement; and, 15-20% improvement. Regional farmers are able to choose whether or not to increase their irrigation efficiency, depending on the returns they are likely to experience. Once irrigation efficiency has been increased in the model, the regional farmer may not return to the lower efficiency level. The level of irrigation technology or efficiency is a state variable in the dynamic programming module. The costs of improving irrigation efficiency are included in the objective function of the dynamic programming module.

3.4.2. Area laid out to irrigation (Ω)

The model assumes that where cuts to groundwater do not reduce allocation to below current active use, and sleeper licences are being allowed to activate, it is possible that additional areas may be developed for irrigation. The decision to increase area laid out to irrigation will depend on the cost. The area laid out to irrigation is a state in the dynamic programming module for a region. Farmers may choose to increase their area laid out to irrigation. However such an increase incurs a fixed cost of in the model. These costs are included in the objective function of the dynamic programming module.

3.4.3. On-farm storage capacity (d)

In order for off-allocation water to be used by a regional farmer, sufficient farm dam capacity must exist for the farmer to store off-allocation water until it is required. Where off-allocation water is being reallocated to traditional groundwater licence holders or where sleeper licences are activating in the unregulated sections of the catchment, additional dam capacity will be required for farmers to use this water. The cost of increasing dam capacity must be weighed in their decision on what areas to irrigate. The model includes on-farm storage capacity as a state in the dynamic programming module for each region in which changes in capacity would be required. The costs of increasing on-farm storage capacity are included in the objective function of the dynamic programming module.

3.5. Hydrological Network

Figure 3 shows the flow network being modelled in this integrated model. Each of the regions which were illustrated in Figure 2 corresponds to a node in this flow network.

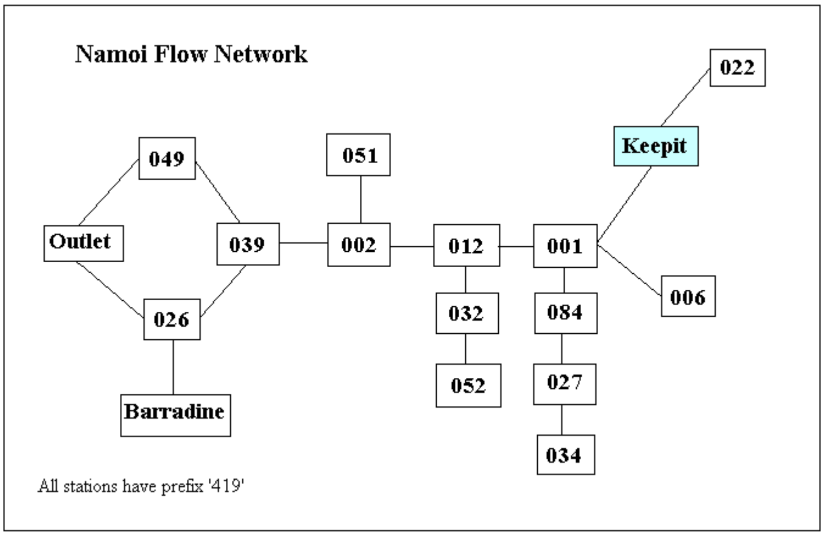

Figure 3. Flow network

Streamflow models and calibration results for this case study are described in detail in Letcher *et al.* (in preparation). This flow network provides the limits of surface water extraction and allocation in each of the regions, and thus provides the surface water availability constraints in the regional economic dynamic programming models. Additionally any extraction decision made in each region is fed through the hydrologic network in order to determine the impacts of different allocation decisions on catchment discharge. This is the main link or point of integration between the economic and hydrological models.

3.6. Policy Scenarios

Initially the model has been developed to consider six main policy scenarios. The way in which these are enacted in each region depends on the groundwater situation in each region, as well as whether the region is in a regulated or unregulated subcatchment. These are:

1. Surface water allocation limited to active use. Off-allocation access is dictated by a first in rule, with no off-allocation water being transferred to groundwater users. This is the 'current' situation.

2. Surface water allocation is limited to active use plus half of the sleeper licences activating. In the unregulated system these activations occur at the volumetric conversion rate for sleeper licences. In the regulated system they occur at allocation. Off-allocation access is dictated by a first in rule, with no off-allocation water being transferred to groundwater users.

3. Surface water allocation is limited to active use plus all sleeper licences activating. In the unregulated system these activations occur at the volumetric conversion rate for sleeper licences. In the regulated system they occur at allocation. Off-allocation access is dictated by a first in rule, with no off-allocation water being transferred to groundwater users.

4. Surface water allocation is limited to active use. Available off-allocation (or additional allocation water in the unregulated system) is allocated to groundwater users in zones where current active use is greater than future allocation.

5. Surface water allocation is limited to active use plus half of the sleeper licences activating. In the unregulated system these activations occur at the volumetric conversion rate for sleeper licences. In the regulated system they occur at allocation. Available off-allocation (or additional allocation water in the unregulated system) is allocated to groundwater users in zones where current active use is greater than future allocation.

6. Surface water allocation is limited to active use plus all sleeper licences activating. In the unregulated system these activations occur at the volumetric conversion rate for sleeper licences. In the regulated system they occur at allocation. Available off-allocation (or additional allocation water in the unregulated system) is allocated to groundwater users in zones where current active use is greater than future allocation.

3.7. Conceptual Framework

The conceptual framework for the integrative model which was developed is shown in Figure 4. Model components shown inside the smaller box correspond to individual models which were developed for each of the regions (α) in the catchment. A flow model is used to simulate daily flows at a node or point within the catchment given a set of climatic time series inputs (temperature and rainfall). This daily flow is fed through policy model which calculates yearly volumes of water available in a region to the economic model based on policy scenario and allocation. Output from this policy model is fed to a regional farm level dynamic programming model. This model optimises choices of investment in improved irrigation efficiency, the areas laid out to irrigation to be increased, and on-farm storage capacity over the long run. Regional farmer level production choices for each year given constraints of land and water available are also determined given these capital choices. Water use decisions from the economic model are fed to a daily extraction model which translates yearly use into a daily water use time series. This daily water use is then extracted from the simulated flow time series and the resulting 'extracted flow' routed to the next node downstream.

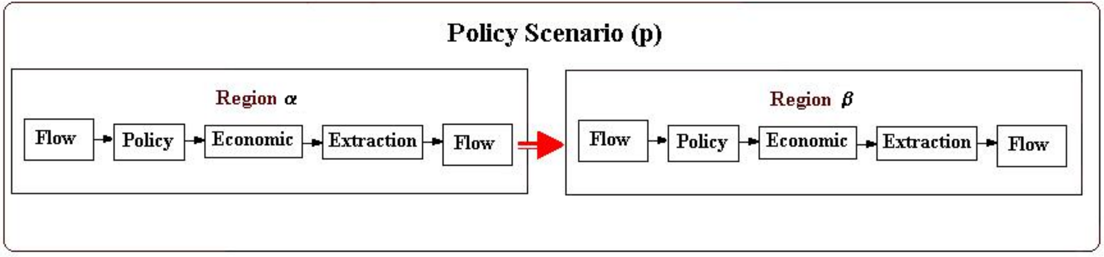

Figure 4. Conceptual Framework of the Namoi Integrated Model

Indicators of stream health, as well as regional farm profit, are calculated at each node of the system. This allows the user to investigate the environmental and economic costs and benefits of a change in policy to the catchment as a whole, as well as to individual regions. It would be possible to optimise policy using a multi-objective function approach with this model structure. However it was decided that a scenario based approach should be used instead. This approach allows users to investigate trade-offs between the environment and economy of the catchment without requiring complex assumptions about the relationship between these different systems and their desired levels of health to be made and built into an objective function.

4. Economic model structure

4.1 General regional structure

Each region in the model (see Section 3.2) is assumed to represent a single profit maximising farmer. This farmer is assumed to be maximising long-term profits, that is, it is assumed that the farmer's access to capital is not fixed and that they may invest in additional capital as described in Section 3.4. A dynamic programming algorithm is used in each region to model this behaviour. This model chooses the optimal level of irrigation efficiency (k), on-farm storage capacity (d), and area laid out to irrigation (Ω) in each year (stage) given returns for each year for these states, and capital costs for moving from one state to another. This model can be described by the following set of equations for each region:

Maximise

$$f_{t+1}(k,d,\Omega,) = \frac{1}{(1+r)^{t+1}}\left(\pi_{\alpha,t}(k,p,d,\Omega) - C_{\alpha,t}(d,p,k,\Omega)\right) + f_t(k,d,\Omega)$$

$$f_0(k,d,\Omega) \equiv 0 \qquad (1)$$

where p is the policy scenario being considered, r is the interest rate (discount factor), $\Pi_{\alpha,t}$ is the short run profit for the production decision in a region (α) in a year (t) given a policy scenario and state space option (k,d,Ω) and $C_{\alpha,t}$ is the capital costs of moving from (k_0,d_0,Ω_0) in time t to (k_1,d_1,Ω_1) in time t+1.

Forward recursion has been used to solve the dynamic programming problem in this model as it was found to be more applicable to the nature of the problem being considered. Computational efficiency of the Namoi model was not limited by the efficiency of the dynamic programming solution method.

4.2 State variables for each region

The number of state variables which are considered by the dynamic programming model differs between regions. These differences arise from constraints which have been placed on producers' choices in each region due to individual characteristics of the region. For example, if in a region no increases in access to unregulated or off-allocation water is allowed (either through increase in allowed licensed extractions or activation of sleeper licences) then no change in on-farm storage capacity is considered to be feasible in the model. This is because it is assumed that producers have sufficient on-farm storage capacity for current unregulated water availability and would only increase their storage capacity if additional unregulated water became available.

The number and type of states considered by the dynamic programming model for each region are given in Table 2. All regions except regions A and B are allowed by the model to improve their irrigation efficiency. Regions A and B have predominantly spray irrigation, as opposed to furrow irrigation which is most common in other areas. Users in region A face no cuts in any type of water and so are assumed to have chosen their current form of irrigation because it is most profitable for them to do so. It has been suggested by various local stakeholders that users in Region B would be more likely to sell allocation rather than invest in further irrigation capital because the relative value of their irrigated production is so low, further increases in their capital stock to enable increased irrigation would not be profitable.

In general, only regions where additional water (summed across all types of water: activation of sleepers, access to additional off-allocation water, or increase in water available due to improvements of irrigation efficiency within the region) is expected to be supplied to the region by a scenario are able to increase their area laid out to irrigation. This reflects the assumption that it is more profitable to use water on areas already laid out rather than investing in additional capital infrastructure where there is currently unused capital.

Table 2. Capital options considered by region for the economic model

Region	No. of k options	No. of d options	No. of Ω options	Total number of states in DP
Region A	1	1	1	1
Region B	1	1	1	1
Region D	3	1	1	3
Region E	3	1	1	3
Region F	3	3	1	9
Region G	3	3	1	9
Region H	3	3	1	9
Region I	3	3	3	27
Region J	3	3	1	27
Region K	3	3	1	9
Region L	3	1	1	3
Region M	3	3	3	27
Region N	3	1	1	3
Region O	3	1	1	3
Region P	3	3	1	9
Region Q	3	3	3	27

Other decision variables, such as areas to plant to different crop activities in each year, were not used as state variables in the dynamic programming model formulation. These decisions were instead made in each year at each possible state (ie. combination of k, d and Ω) using a series of nested linear programming models. Two advantages of this approach should be mentioned. Firstly, the state space for these decisions would need to be discretised to fit within the current dynamic programming formulation in the model. Whilst discretisation of capital investment (which generally occurs in "lumps") is reasonable, it could be argued that planting decisions on a regional scale occur on a much more continuous basis. Secondly simple linear programming problems can be solved extremely efficiently and quickly. Reductions in the dimensionality of the dynamic programming formulation, from hundreds or thousands of state variable options, down to at most 27 (as is the case in the dynamic programming formulation used) result in much larger computational efficiency gains than the cost of solving the nested linear programming problems.

4.3 Linear programming formulation for short run decisions

A separate linear programming (LP) model structure exists for each of the regions considered by the model. A different LP is run for each year (time step/stage) and for each state of the dynamic programming model valid for that region (ie. different values of k, d, Ω, G and R). The link between the dynamic programming component and the linear programming models are illustrated for two state variables in Figure 5.

This Figure shows the overarching structure of the economic model for each region. The dynamic programming algorithm is used to find the optimal path through time given discrete state space options (note that for simplicity only two states are shown). A linear programming model runs at each point on the state space grids for each stage (or time period). The state space option (or grid point) implies a particular constraint on land and water available for production. These constraints are used to solve the linear programming model at this point on the grid. The solution of this LP gives the short run profit for that state space option (or grid point in the diagram). This is used as a part of the objective function which is being maximised by the DP.

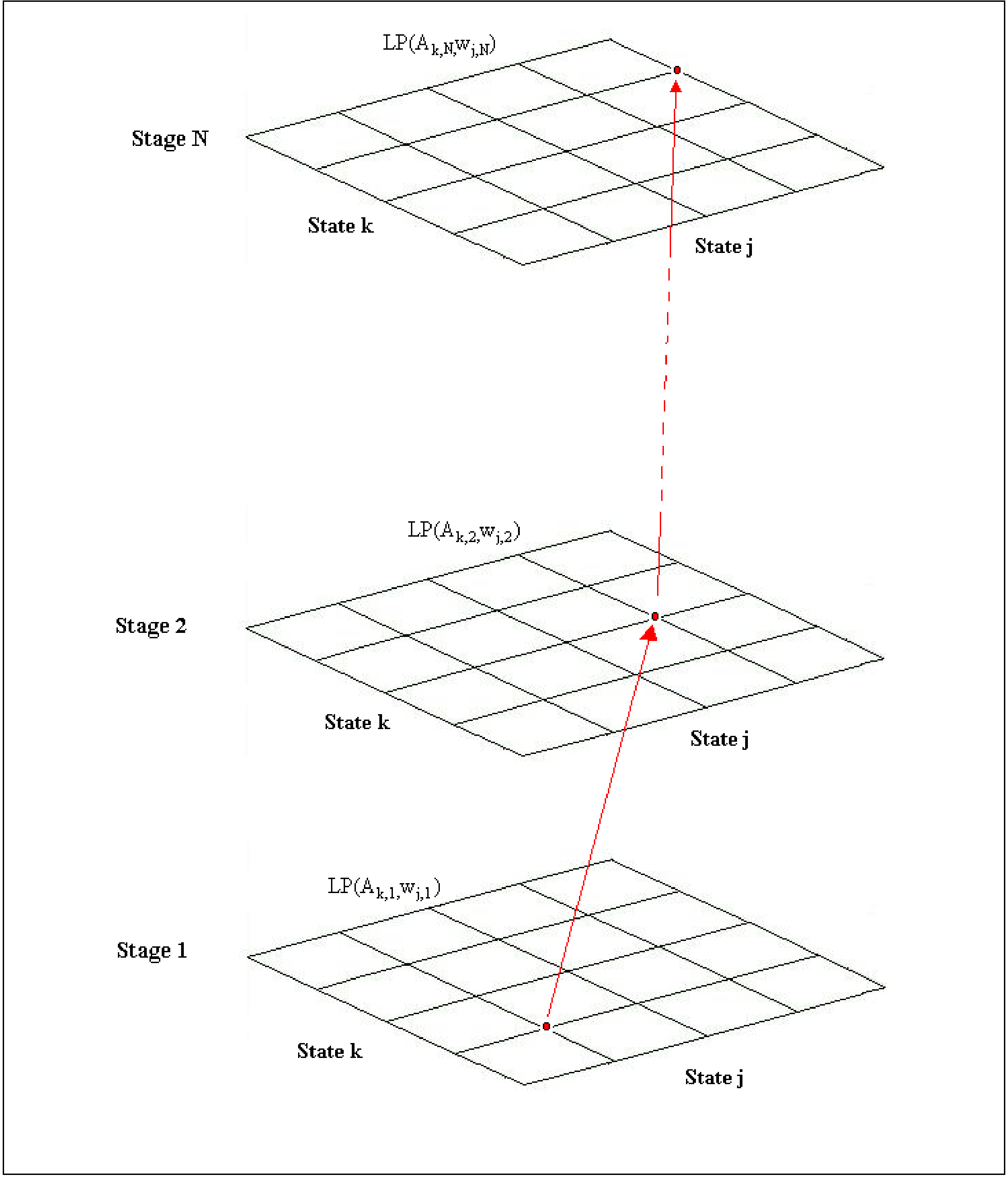

Figure 5. Link between LP's and DP in the Namoi model for each region

The specifications for the linear programming models used for each of the regions in the model is given below. For simplicity subscripts and superscripts denoting the dependence of each of the variables in the equations have been mostly left off. However the dependence of the variables can be summarised in all cases as follows:
G = groundwater limit = G(d,p,t)
R = regulated surface water limit = R(d,p,t)
U = unregulated or off-allocation water extraction limit = U(d,p,t)
u = efficiency of unregulated water use = u(k,t)
r = efficiency of regulated water use = r(k,t)

g = efficiency of groundwater use = g(k,t)
A = area of land limit = A(Ω,t)
a_i = area of land devoted to crop activity i = $a_i(t)$
P_{ij} = price of product j from crop activity i
p_{ij} = crop rotation proportion for product j of crop activity i
w_{ij} = water use per ha of product j from crop activity i

This summary shows the dependence of the model on the scenario option chosen and the state variable at each stage in the dynamic programming model.

Regions A and B

Objective Function

$$\text{Max } \Pi_{\alpha,t} = \sum_{i=1}^{2}\sum_{j=1}^{k_i}\left(P_{ij}y_{ij} - c_{ij}\right)a_i p_{ij} \tag{2}$$

Constraints

$$\sum_{i=1}^{2} a_i \leq A$$

$$\sum_{i=1}^{2}\sum_{j=1}^{k_i} w_{ij}a_i p_{ij} \leq uU$$

Regions D, G, H, I, J

Objective Function

$$\text{Max } \Pi_{\alpha,t} = \sum_{i=1}^{3}\sum_{j=1}^{k_i}\left(P_{ij}y_{ij} - c_{ij}\right)a_i p_{ij} \tag{3}$$

Constraints

$$\sum_{i=1}^{3} a_i \leq A$$

$$\sum_{i=1}^{3}\sum_{j=1}^{k_i} w_{ij}a_i p_{ij} \leq uU + rR + gG + uO$$

where R=0 and O=0 if the region corresponds to an unregulated river section.

Regions E and F

Regions E and F are modelled with a single LP because they share a streamflow node (and therefore a surface water limit). It is assumed that surface water is transferable between these two regions but groundwater is not.

Objective Function

$$\text{Max } \Pi_{E+F} = \sum_{\alpha\in\{E,F\}}\sum_{i=1}^{3}\sum_{j=1}^{k_i}\left(P_{ij}y_{ij} - c_{ij}\right)a_{i,\alpha} p_{ij} \tag{4}$$

Constraints

$$\sum_{i=1}^{3} a_{i,E} \leq A_E$$

$$\sum_{i=1}^{3} a_{i,F} \leq A_F$$

$$\sum_{i=1}^{3}\sum_{j=1}^{k_i} a_{i,E} w_{ij} p_{ij} + \sum_{i=1}^{3}\sum_{j=1}^{k_i} a_{i,F} w_{ij} p_{ij} \leq uU + g(G_E + G_F)$$

$$\sum_{i=1}^{3}\sum_{j=1}^{k_i} a_{i,E} w_{ij} p_{ij} \leq uU + gG_E$$

$$\sum_{i=1}^{3}\sum_{j=1}^{k_i} a_{i,F} w_{ij} p_{ij} \leq uU + gG_F$$

Regions K to Q

Objective Function

$$\text{Max } \Pi_{\alpha,t} = \sum_{i=1}^{5}\sum_{j=1}^{k_i} (P_{ij} y_{ij} - c_{ij}) a_i p_{ij} \qquad (5)$$

Constraints

$$\sum_{i=1}^{5} a_i \leq A$$

$$\sum_{i=1}^{5}\sum_{j=1}^{k_i} a_i w_{ij} p_{ij} \leq uU + rR + gG + uO$$

where R=0 and O=0 if the region corresponds to an unregulated river section.

4.4 Model parameterisation

Parameter values in the economic modelling component came from a range of sources. The parameters for which values had to be obtained in this module included:

- Crop yields and water uses for different regions of the Namoi;
- Crop prices and short run production costs (i.e. information on gross margins for various crop rotations);
- Information on surface and groundwater licenses by region;
- Current areas laid out to irrigation in each region, assumptions of possible additional areas to lay out and costs of increases in area laid out t irrigation;
- Current on-farm storage capacity, assumptions of possible additions in each regions and costs of increases in on-farm storage capacity;
- Current irrigation efficiency and costs associated with likely improvements in irrigation efficiency; and
- Costs of increasing catchment scale capital (channels to farm gate).

Information on these parameters came from a wide variety of sources. The process by which values were obtained for this module included a validation exercise for model assumptions. The main sources of data used to create a first cut of model assumptions were:

- Farm budget information provided by NSW Department of Agriculture (Scott, 2001; Scott, 2000).
- Gross margins information on experimental cotton rotations provided by NSW Department of Agriculture from work they performed for the Australian Cotton Research Institute;
- Original survey information on farm capital, yields and water use from a Murray-Darling Basin Commission survey of farmers in the Liverpool Plains area provided by NSW Department of Agriculture (Bennett and Bray, 2001);
- Original farm survey data from various farmers in the Namoi region obtained and provided by NSW Department of Agriculture;
- ABARE cluster data on farms in two clusters in the Namoi region (Wee Waa and Gunnedah);
- GIS data layers of remotely sensed data on areas laid out to irrigation and on-farm storages provided by NSW Department of Agriculture;
- GIS layers of land use, land capability, surface and groundwater licences, groundwater zones, soils and cotton survey data provided by NSW Department of Land and Water Conservation;
- Information on irrigation efficiency and costs of improvement provided by NSW Department of Agriculture;
- Information on the costs per ha of laying out additional areas to irrigation provided by NSW Department of Land and Water Conservation;
- Collated surface water license information provided by the NSW Department of Land and Water Conservation;
- Information from survey of agriculture performed on Liverpool plains (Flavel and McLeish, 1996);
- Published information on crop yields used in previous modelling efforts undertaken within the catchment (Greiner, 1997);
- Results of survey on irrigation practices of unregulated water users in the Namoi Valley (Hassell and Associates, 1999).

These data sets were used as the basis of initial assumptions about parameter values in the economic modelling component. A set of model assumptions and parameter values was then collated and presented to various stakeholders including many of the original providers of the information sets outlined above, members of the catchment management committees and staff at local state government agency offices. These assumptions and parameter values were then refined on the basis of suggestions from this group of stakeholders. The broad range of sources for the data and the cross validation of assumptions with local stakeholder knowledge forms an important part of the validation of this component of the model.

5. Model sensitivity

In order to test the sensitivity of the model to assumed costs of capital investment, as well as to the level of discretisation used in the dynamic programming component, the model was run over a uniformly sampled grid of assumed costs for irrigation efficiency improvements and on-farm storage capacity. The costs per ML of increasing on-farm storage capacity was varied between $300 and $1000, at $50 intervals. Table 3 shows the grid of capital investment costs of increasing irrigation efficiency. All values were moved through from the lower bound to the upper bound on their respective steps simultaneously (ie. seven options were considered not 7^4). These options are collectively referred to in the following results by the per hectare costs of changing from Irrigation Option 1 to Irrigation Option 2. The irrigation efficiency options considered by the model were summarised in Section 3.4.1 as:

- Irrigation Option 1 - current flood irrigation.
- Irrigation Option 2 - 10-15% improvement in efficiency.
- Irrigation Option 3 - 15-20% improvement in efficiency.

The sensitivity of the model to the discretised values of on-farm storage capacity considered by the model was also tested. A finer grid of values (at 1% of current capacity, until 10%) was used for all regions where additional investment was considered feasible (see Table 2).

Table 3. Grid for costs of increasing irrigation efficiency

Cost	Lower bound	Upper Bound	Grid Step
Cost per hectare of area laid out to irrigation			
Option 1 to 2	$400	$1000	$100
Option 2 to 3	$800	$2000	$200
Cost per ML of on-farm storage			
Option 1 to 2	$200	$500	$50
Option 2 to 3	$400	$1000	$100

The effect of allowing for a smaller discretisation of on-farm storage investment choices on total farm profit for the total catchment and on each of the regions in the model is captured in Table 4. This Table shows that, for the Base Case scenario, total farm profit does not depend on the level of discretisation in most regions. The exceptions to this are Regions M and Q. Due to the non-linear nature of interactions in the model however, this does not mean that the model is never sensitive to this factor in the majority of regions as is the case under the Base Case assumptions. It is reassuring however that the model does not usually depend on this for the Base Case.

Table 4. Total farm profit for Base Case Scenario under different levels of discretisation

	11 options	3 options
Region A	$23,914,853	$23,914,853
Region B	$30,549,153	$30,549,153
Region D	$22,433,471	$22,433,471
Regions E and F	$66,535,379	$66,535,379
Region G	$89,394,682	$89,394,682
Region H	$28,126,572	$28,126,572
Region I	$34,348,440	$34,348,440
Region J	$65,645,204	$65,645,204
Region K	$79,890,089	$79,890,089
Region L	$90,219,155	$90,219,155
Region M	$503,381	$502,191
Region N	$35,473,076	$35,473,076
Region O	$652,738,702	$652,738,702
Region P	$419,452,581	$419,452,581
Region Q	$347,168	$271,805

The impact of changing these costs of capital on total farm profit is illustrated in Figure 6. This Figure shows that as the cost of increasing irrigation efficiency decreases, total farm profit for the catchment increases. Once the per hectare cost of increasing from efficiency Option 1 to 2 falls to $300 per ha, profit for the catchment has changed by approximately 2%. The percent change in total farm profit for the entire catchment for different costs of investing in increased irrigation efficiency only is shown in Figure 7. This Figure shows that total farm profit increases slowly until the cost is reduced and then linearly at a higher rate across the range of options until the cost is $300 per ha. This chart looks identical for all assumed costs of increasing on-farm storage capacity. Thus it appears that $800 is a critical threshold in assumed costs of increasing irrigation efficiency for the catchment.

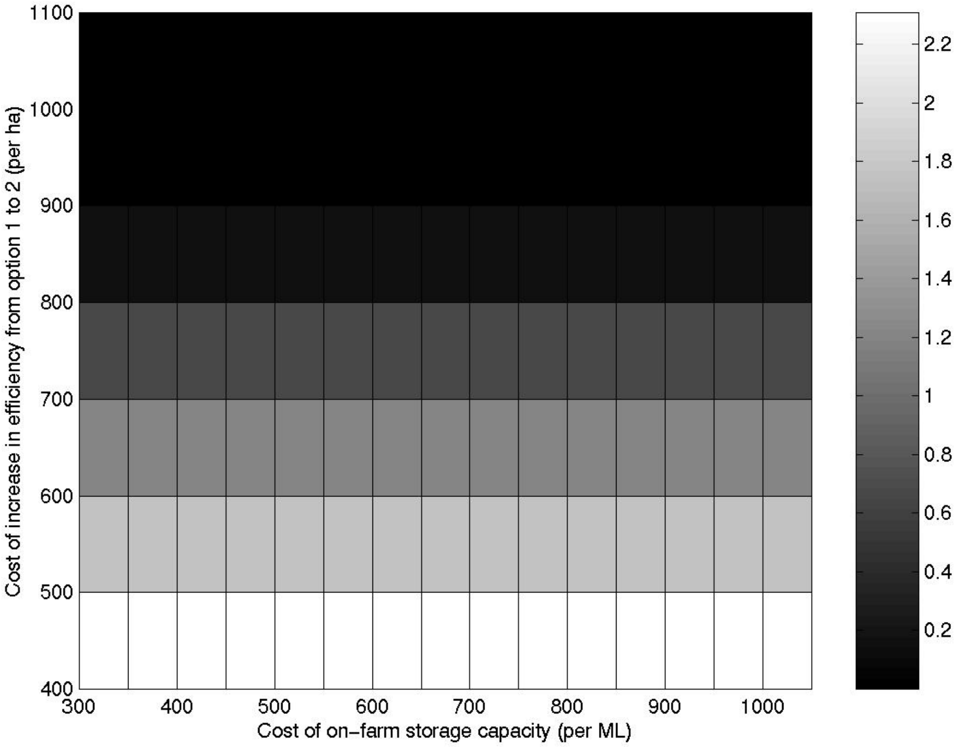

Figure 6. Change in total farm profit by capital costs (irrigation efficiency and storage) from Base Case

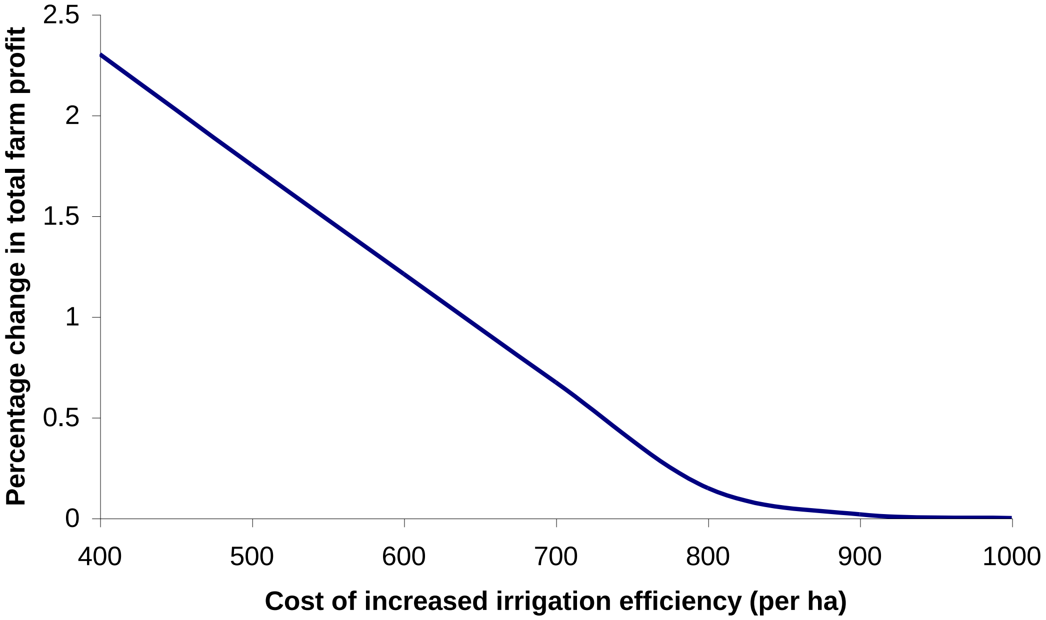

Figure 7. Percentage change in total farm profit by cost of efficiency improvements

By contrast Figure 6 reveals that, for the Base Case, decreasing the cost of increasing on-farm storage capacity has minimal effect on total farm profit for the catchment. Thus profit for the entire catchment is not sensitive under the Base Case to assumed costs of additional on-farm storage capacity. It does not follow that other scenarios would give the same results. The non-linear nature of interactions in the model mean that changing other assumptions, such as allocations or pumping limits, may result in total farm profit becoming sensitive to this factor. It does mean that for the Base Case, and likely for other scenarios that are not too far removed from this scenario, total farm profit for the entire catchment is not sensitive to assumed costs of increasing on-farm storage capacity. They are however sensitive to assumptions about the cost of increasing irrigation efficiency.

Sensitivity of the model in each region differs depending on water use, profitability of production, and land and water availability. For example, the regional farmer in Region H responds to changing capital costs by investing in both improved irrigation efficiency and additional on-farm storage capacity. Changes in investment in irrigation efficiency and additional on-farm storage capacity respectively are captured in Figures 8 and 9. Within the range investigated the decision to invest in irrigation efficiency improvements is independent of the cost of additional on-farm storage capacity. Once the cost per ha of changing from Option 1 to Option 2 has fallen to $500, the farmer will choose to improve their irrigation efficiency up to Option 2 (see Section 3.4). However the decision to invest in additional on-farm storage capacity is affected by the cost of investing in irrigation efficiency improvements within this range. Once the costs of improving efficiency falls sufficiently that the farmer will invest in additional irrigation efficiency, then a smaller change in the cost of additional on-farm storage capacity will induce additional investment in this asset. Also the level to which additional on-farm storage capacity costs must fall before investment occurs is lower than in Regions E and F. A smaller percentage change in capacity is also decided upon in this region. This indicates that land use decisions in Region H are more limited by access to water than in Regions E and F.

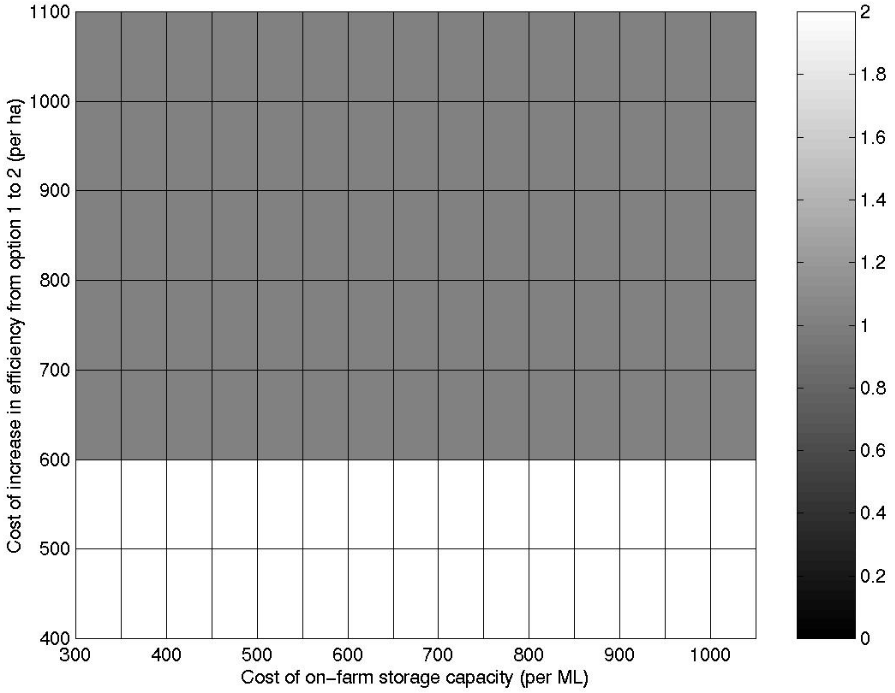

Figure 8. Investment level for efficiency given efficiency and storage costs in Region H

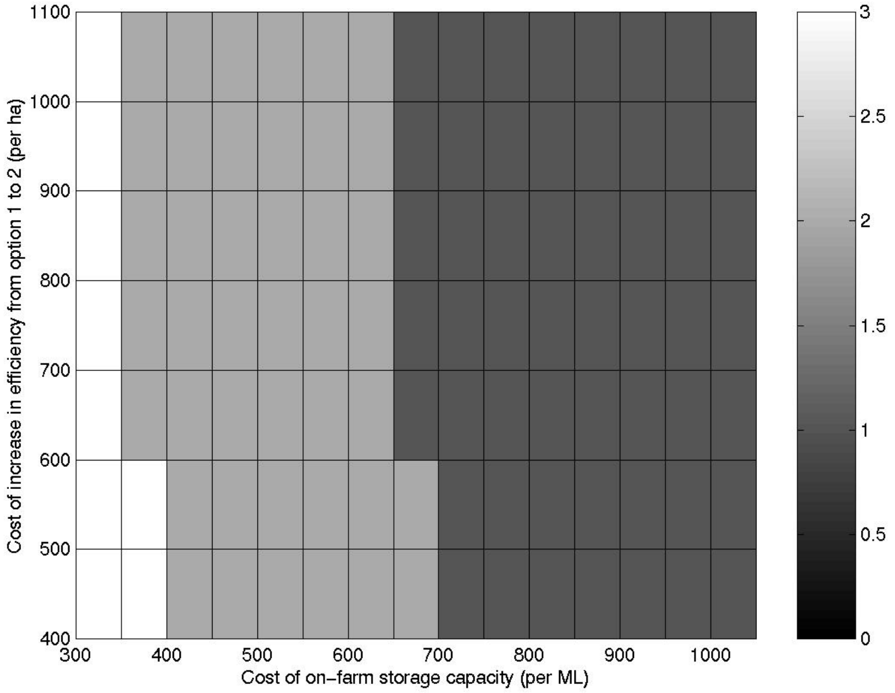

Figure 9. Investment level for on-farm storage given efficiency and storage costs in Region H

Table 5 summarise the thresholds for changing capital investment decisions in each region.

Table 5. Summary of thresholds of costs for changing capital investment decisions

Region	On-farm storage cost threshold	Change induced in on-farm storage	Corresponding efficiency cost level	Efficiency cost threshold	Change induced in irrigation efficiency
A	-	-	-	-	-
B	-	-	-	-	-
D	-	-	-	-	-
E and F	$750	1 → 11	-	-	-
G	-	-	-	-	-
H	$600 $300 $650 $350	1 → 2 2 → 3 1 → 2 2 → 3	>$500 >$500 <$500 <$500	$500	1 → 2
I	$500	1 → 2	-	-	-
J	-	-	-	-	-
K	$700 $350	1 → 2 2 → 3	-	-	-
L	-	-	-	$900	1 → 2
M	$750 $300	2 → 3 3 → 5	-	-	-
N	-	-	-	$700	1 → 2
O	-	-	-	$800	1 → 2
P	-	-	-	-	-
Q	$650 $300	2 → 3 3 → 5	-	-	-

These results show that it is possible for the decision to invest in one type of capital to be dependent on the cost of another type of capital (as was seen in Region H). This type of interdependence would be expected in such a complex non-linear model and means that it is not always possible to interpolate between individual outcomes to find a result. In most cases it was seen that these decisions were independent, at least for the Base Case scenario. It is likely that for scenarios around the Base Case this result will still hold. Another important feature of these results is that the critical cost thresholds for investing in different types of capital differ by region, depending on production, available land and water, and profits which can be made from these resources. Consequently, trade-off questions will often be difficult to answer absolutely because results will depend on assumed cost and other variables in each region. Therefore, in order to fully understand the model it is not sufficient to change individual parameter values in isolation. Rather a more detailed sensitivity or uncertainty analysis would be required where interdependence of parameters is considered. One problem with this is the large computational time required for such detailed testing. Changing only these two values over a limited grid resulted in 105 runs of the model having to be undertaken. The model has many other such assumed values which would ideally be tested: these include crop prices; short run costs; initial values for storage, efficiency and area; and, crop yields. This means that many thousands of runs would be required for testing of all these assumptions, not a simple task for a model such as this. Techniques to narrow down or bound the ranges over which values should be tested are required to fully test these types of complex integrative models.

6. Policy scenario results

6.1 Scenario and climate option descriptions

The off-allocation policy scenario options described in this paper have been run for five different climate options to test the sensitivity of the policy scenario results to these climatic assumptions. The five climate options which have been used are:

1. Historic rainfall over twenty years from 1970 to 1989.
2. A random rearrangement of individual years of rainfall data from the twenty years of historic rainfall from 1970 to 1989. This option maintains volumes of rainfall over the entire period but changes the order of drought and flood years experienced by the regional farmer.
3. As for option 2 this is a different random arrangement of individual years from 1970 to 1989.
4. Rainfall from 1970 to 1989 is used in the same order of years, but rainfall for each day in each year is multiplied by a factor randomly chosen between 0.5 and 2 (ie. a different factor for each year). This maintains the sequence of events but changes the volume of rainfall in these events (and thus over the entire twenty year period).
5. As for option 4, this uses a different randomly chosen multiplicative factor between 0.5 and 2 applied to rainfall during each year.

Off-allocation policy scenarios were described in Section 3.6. The relationship between these scenarios is summarised in Table 6. Note that Scenario 1 represents the 'base case' or current situation.

Table 6. Off-allocation Policy Scenarios

	Active surface water only	Half surface water sleepers activate	All surface water sleepers activate
No transfer of off-allocation water to groundwater users	Scenario 1 (Current situation)	Scenario 2	Scenario 3
Transfer of off-allocation water to groundwater users	Scenario 4	Scenario 5	Scenario 6

6.2 Model results

The model was run for the six scenarios using the five separate climate series outlined above. The impact of changing scenarios from the base case (Scenario 1) on both economic and environmental indicators was analysed. Results are analysed using two indicators of streamflow variability: percentage change in median non-zero flows, and in the number of zero flow days (from the base case), as well as in total discounted farm profit for the entire catchment and by region. These indicators easily show major differences between scenario outcomes. Trade-offs, both between regions and between economic performance and impacts on ecology (signalled through impacts on flow), are able to be shown using the indicators. The range of total farm profit and percentage change from the base case over all climate options for the entire simulation period for the whole catchment is given in Table 7.

Table 7. Total Farm Profit by Scenario ($'000)

Climate	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
1	1,639,536	1,641,462	1,641,687	1,547,298	1,549,271	1,549,551
2	1,592,538	1,594,149	1,593,944	1,516,054	1,517,713	1,517,550
3	1,635,858	1,637,890	1,638,016	1,545,696	1,547,779	1,547,953
4	1,655,549	1,659,485	1,661,260	1,554,599	1,558,580	1,560,399
5	1,660,960	1,664,466	1,666,064	1,557,406	1,560,963	1,562,611
% change	-	0.1 - 0.2%	0.1 - 0.3%	-6.2 - -4.8%	-6 - -4.7%	-5.9 - -4.7%

Table 7 shows that it is more profitable for the catchment as a whole if no off-allocation water is transferred to groundwater users who are to receive cuts to their groundwater allocation (ie. scenarios 4 to 6). The highest total catchment profit for each climate series option is achieved for the scenario where no off-allocation water is transferred to groundwater users but all sleeper licence activation takes place. However, the economic benefits for the entire catchment from sleeper licence activation are quite small, at 0.1% to 0.3% (up to a NPV of $6 million over a 20 year period) depending on climate series option.

The impact of changing scenarios on total farm profit by region is given in Table 8. The impact on median non-zero flows and the number of zero flow days at each node is given in Tables 9 and 10 respectively.

Table 8. Range of percentage change in total farm profit over five climate scenarios

Region	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
A	0	0	0	0	0
B	1.7 - 7.5	1.8 - 12.5	0	1.7 - 7.5	1.8 - 12.5
D	0.6 - 0.6	1.1 - 1.3	0	0.6 - 0.6	1.1 - 1.3
E and F	0	0	0	0	0
G	1.1 - 1.5	0.7 - 1.5	0	1.1 - 1.5	0.7 - 1.5
H	0	0	0	0	0
I	0	0	0	0	0
J	0	0	0	0	0
K	0	0	-4.4 - -4.1	-4.4 - -4	-4.3 - -4
L	0	0	-4.3 - -3.9	-4.3 - -3.9	-4.3 - -3.9
M	0	0	0	0	0
N	0	-0.2 - 0	-16 - -13.5	-16 - -13.5	-16 - -13.5
O	0	0	-9.6 - -8.6	-9.6 - -8.6	-9.6 - -8.6
P	0	0	-6.9 - -2.6	-6.9 - -2.6	-6.9 - -2.6
Q	0	0	0	0	0
Total	0.1 - 0.2	0.1 - 0.3	-6.2 - -4.8	-6 - -4.7	-5.9 - -4.7

The range of economic impact by region of the various scenarios across all climate series options (as a percentage change from the base case) is given in Table 8. This shows that the decrease in profit under scenarios 4 to 6 is not uniform across the catchment. However no region is better off under scenarios 4 to 6 than they would have been under the equivalent level of sleeper activation (scenarios 1 to 3), without changed access to off-allocation water. Substantial reductions in profit are also faced in several regions in the lower catchment under scenarios 4 to 6. When economic impact is considered by region, scenario 3 is still clearly optimal.

The impact on total farm profit of changing scenario from the base case can also be seen to be largely insensitive to the different climatic series. The direction of the change in total profit under each of these scenarios is the same across climate options, however the magnitude of that change differs slightly according to climate. The order of magnitude is the same in all regions except Region B, where the greatest range of change is 1.8%-12.5%. Region B is modelled as an unregulated region (ignoring Chaffey Dam). It is likely that greater licensed entitlement (through sleeper licence activation) is allowing more access to water in this region in the model than would be the case otherwise. Results for this region should be treated very cautiously, as they are unlikely to be affecting outcomes at the whole of catchment scale, but are not considered to be accurate when considering the Peel subcatchment (Region B) in isolation.

Table 9. Range of percentage change in median non-zero flows over five climate scenarios

Region	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
A	-1.6 - 0	-2.6 - 0	0	-1.6 - 0	-2.6 - 0
B	0	0	0	0	0
D	-6.3 - 0	-6.3 - 0	0	-6.3 - 0	-6.3 - 0
E and F	-4.8 - 3.7	-7.8 - 2.9	0	-4.8 - 3.7	-7.8 - 2.9
G	-9.2 - 6.6	-12.7 - 17.5	0	-9.2 - 6.6	-12.7 - 17.5
H	0	0	0	0	0
I	0	0	0	0	0
J	0	0	0	0	0
K	0	0	0 - 0.3	0 - 0.3	0 - 0.3
L	0	0	0 - 0.3	0 - 0.3	0 - 0.3
M	0	0	0	0	0
N	0	0	0 - 0.6	0 - 0.6	0 - 0.6
O	0	0	1.3 - 3.2	1.3 - 3.2	1.3 - 3.2
P	0	0	-0.1 - 0	-0.1 - 0	-0.1 - 0
Q	0	0	0	0	0

Table 10. Range of percentage change in number of zero flow days over five climate scenarios

Region	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
A	0	0	0	0	0
B	0	0	0	0	0
D	1.4 - 2.4	2.8 - 5	0	1.4 - 2.4	2.8 - 5
E and F	0.6 - 3	1.2 - 4.9	0	0.6 - 3	1.2 - 4.9
G	0.8 - 4.6	1.8 - 7.9	0	0.8 - 4.6	1.8 - 7.9
H	0	0	0	0	0
I	0	0	0	0	0
J	0	0	0	0	0
K	0	0	0	0	0
L	0	0	0	0	0
M	0	0	0	0	0
N	0	0	0	0	0
O	0	0	0	0	0
P	0	0	0	0	0
Q	0	0	0	0	0

For flow, where the number of zero flow days remains constant, the median non-zero flow changes in the same direction for all climate series options. Where the number of zero flow days increases, median non-zero flows may increase or decrease. Both of these cases are indicative of the policy scenario drying out the catchment to some extent. Where median non-zero flows increase, then the impact has been to reduce low flows to zero on a number of days (it is possible that high flows are simultaneously being reduced) to the extent that this loss of low flow days outweighs the impact of the decrease in flow on high flow days on median non-zero flows. Where the median of non-zero flows decreases and the number of zero flow days increases, then low flow days are becoming zero flow days under the policy scenario and high flows are being reduced sufficiently to decrease median non-zero flows. In either case the policy scenario has had the effect of drying out the catchment to some extent. This means that while the exact magnitude of the impact of changing scenario from the base case depends on climate, the direction of these changes is largely insensitive to the climate option used. Therefore policy recommendations from the model involving these policy scenarios are robust to changes in climate.

Flow magnitude is substantially reduced in many areas of the upper Namoi catchment when sleeper licence activation occurs. In particular, sleeper licence activation on the Mooki river (D, E, F and G) has the effect of drying out flows in these regions (up to a 12.7% decrease in median non-zero flows and a 8% increase in zero flow days). Changes to the access of off-allocation water lead to a slight increase or no change in median non-zero flows in the regulated system (ie. regions H,K,L,O,P). Interestingly, sleeper licence activation in the upper catchment is shown to have no significant impact on flows further down the Namoi River system

These results illustrate that there can be a substantial trade-off between economic and environmental performance where sleeper licence activation is expected to occur. Future economic development which involves the expansion of irrigation areas, especially in the unregulated system, can be expected to have significant impacts on flow magnitudes. The model results show that policies which provide access to off-allocation water as compensation for reduced groundwater allocation are likely to reduce the amount of off-allocation water extracted in the catchment. This would have positive environmental impacts (slight), but would reduce the total farm profit in the catchment. Importantly, this policy would not be expected to improve economic outcomes on average in affected regions of the catchment.

7. Discussion

The results shown in this paper demonstrate that the model developed is capable of being used to consider the economic and environmental trade-offs (and the spatio-temporal variation) of various water allocation scenarios in the catchment. The breadth of these scenarios illustrate some of the broad range of issues able to be considered by the model. This is important because the model was developed for a specific issue, however the timeframes involved with developing such an integrative framework are such that much of the relevance of the initial focus issue may be past by the time the model is at a stage of development capable of producing results. A key to the ongoing relevance of this model was the broad focus of the original off-allocation water issue, which was seen to encompass so many components of the water allocation system in the catchment. Being mindful of this broad focus has allowed the resulting model to be applicable to a wide range of situations.

Due to the complex, non-linear nature of the model, results from the model have been shown to be dependent on co-varying parameters, although in most cases results for policy options were found to be insensitive to the choice of input climate data. Climate series options were chosen to be representative of both historical conditions, and also a reasonable range of variation in the sequence of rainfall years and events and the magnitudes of rainfalls experienced in the catchment. The ability to fully understand the model and its sensitivity to small changes in a number of parameter values is limited by the many thousands of runs this would entail. The results demonstrated in this paper encapsulate the outcomes from 135 runs of the model (over 70 hours of computer time in total - and many more human hours to analyse the results). In these results only one to two variables were varied across a relatively coarse grid. Rapid analysis of the many runs required to complete a detailed uncertainty and sensitivity analysis of the model to extract relevant information would also be difficult with currently available tools. This indicates that the development of methods for completing such sensitivity analyses of complex integrative models should be a priority for researchers in Integrated Assessment.

The model has been developed to consider regional-scale trade-offs of water allocation options, not impacts on individual farmers. This means that it provides a generalised view of the trade-offs between "types" of farmers rather than impacts on specific households. When demonstrating results from the model to stakeholder groups this feature of this model has been stressed. It has been suggested that where such impacts are to be considered, use of the model in conjunction with farm level models (which have been developed by the NSW Department of Agriculture for the catchment) would be preferable. This would provide stakeholders with a fuller picture of both types of impacts.

One of the main limitations of the model and its use for investigating trade-offs of various water allocation policies has been the lack of a detailed groundwater modelling component. This component would need to encapsulate the interactions between the surface and groundwater systems, as well as the impacts of groundwater extractions on aquifer levels in the catchment. This limitation of the model has been acknowledged in discussions with stakeholder groups and development of such a component is regarded as a priority for future development of the model.

Another limitation of the current model is the lack of response of crop yields, especially dryland crop yields, to rainfall and temperature. This means that the model is likely to overestimate profit from dryland crops, especially in years of drought. This would likely further highlight the importance of available irrigation water during these years.

The model results in this paper also demonstrate that results in Region B are sensitive to the assumption that this region is unregulated, ignoring the presence of Chaffey Dam. While this is unlikely to be having significant effect on results for the rest of the catchment however, more realistic treatment of this region in future developments of the model may be desirable if results for this region are to be used on a stand-alone basis.

The results presented demonstrated the ability of such an integrated modelling tool to demonstrate economic and environmental trade-offs of changes in water allocation policies. This framework is flexible enough to allow for consideration of other issues, as well as for reapplication to other catchments. Further work on finalising the Namoi application and reapplying the framework to another catchment is currently being planned.

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9. References

Bennett, R., and Bray, S. (2001). “Summary of responses to Murray Darling Basin Commission (MDBC) project No. 19002, Irrigation Futures Framework Modelling, Breeza Plains Farmer Survey, March 2001.”, Prepared for Participating farmers, MDBC Project 19001 Project Team and the MDBC 19002 Breeza Plains Consultative Group by NSW Agriculture, Gunnedah.

Branson, J., and Eigenraam, M. (1996a). “Northern Irrigation Region Mixed Linear Program.”, Victorian Department of Natural Resources and Environment.

Branson, J., and Eigenraam, M. (1996b) “Water policy in Victoria - A regional perspective.” *Paper presented to the 40th Annual Conference of Australian Agricultural and Resource Economics Society*, Melbourne.

Branson, J., Eigraam, M., Stoneham, G., Crean, J., and Pagan, P. (1998). "Structural adjustment pressures in irrigated broadacre farming in the Southern Murray-Darling Basin." *MDBC I&E Project No. I6041*, Economic Services Unit, NSW Agriculture. Economic Branch, Dept. of Natural Resources and Environment (Vic).

Curthoys, C., Marshall, G., and Jones, R. (1994). "Economics of On-farm Proposals: A Report to the Community Working Group of the Coleambally Land and Water Management Plan.", Economic Services Unit, NSW Agriculture.

DLWC. (1999). "Guidelines for River, Groundwater and Water Management Committees, Namoi River Catchment.", NSW Department of Land and Water Conservation.

DPMS. (1996). "Namoi Community Catchment Plan Situation Statement.", prepared by Donaldson Planning and Management Services for the Namoi Catchment Planning Taskforce.

Flavel, N., and McLeish, R. (1996). "Managing the Liverpool Plains: Detailed Survey Data 1995.", Liverpool Plains Land Management Committee.

Greiner, R. (1997). "Integrated Catchment Management for Dryland Salinity control in the Liverpool Plains Catchment: A preliminary study from an economic perspective." *Occasional Paper No 12/97,* Land and Water Resources Research and Development Corporation.

Gunaratne, N., Wall, L., Marshall, G., and Jones, R. (1995a). "Economics of on-farm proposals: A report to the Community Working Group of the Cadell Land and Management Plan.", Economic Services Unit, NSW Agriculture.

Gunaratne, N., Wall, L., Marshall, G., and Jones, R. (1995b). "Economics of on-farm proposals: A report to the Community Working Group of the Denimein Land and Management Plan.", Economic Services Unit, NSW Agriculture.

Gunaratne, N., Wall, L., Marshall, G., and Jones, R. (1995c). "Economics of on-farm proposals: A report to the Community Working Group of the Wakool Land and Management Plan.", Economic Services Unit, NSW Agriculture.

Hall, N. (1999). "IMMS Model Update 1998.", Hall Resource Economic Modelling.

Hall, N., Poulter, D., and Curtotti, R. (1994). "ABARE model of irrigation farming in the Southern Murray Darling Basin." *94.4*, ABARE, Canberra.

Hassell, and Associates. (1999). "Irrigation practices of unregulated water users in the Namoi valley.", Department of Land and Water Conservation, Dubbo, NSW.

Jones, R. E. (1991). "Optimal irrigation water allocation and supply reliability in the Murrumbidgee Valley," M.Econ, University of New England, Armidale.

Letcher, R.A., Croke, B.F., Jakeman, A.J. (in preparation) "Hydrological model development for an integrated assessment of water allocation in the Namoi River Basin, Australia".

McClintock, A., and Gooday, J. (1998) "A method for assessing the impact of water policy reforms: A case study of irrigated broadacre farming." *Proceedings of the Bioeconomic Workshop*, Armidale, 77-94.

Pagan, P., Curthoys, C., Marshall, G., and Jones, R. (1996). "Economics of on-farm proposals: A report to the Community Working Group of the Murrumbidgee Irrigation Areas and Districts Land and Water Management Plan.", Economic Services Unit, NSW Agriculture.

Scott, F. (2000). "Farm Budget Handbook 2000, Northern NSW.", NSW Agriculture.

Scott, F. (2001). "Farm Budget Handbook 2001, Northern NSW.", NSW Agriculture.

Wall, L., Marshall, G., Jones, R., and Darvall, D. (1994). "Economics of on-farm proposals: A report to the Community Working Group of the Berriquin Land and Water Management Plan.", Economic Services Unit, NSW Agriculture.