

A Method for Assessing the Importance of Farm Level Capital Investment Decisions in the Analysis of Water Reforms

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Abstract:

Traditional approaches to estimating the potential benefits of water reform, including the introduction of water markets, have relied on short-run models which assume irrigation capital is either fixed or not a constraint on decision making. Other studies have incorporated a long-run decision framework, accounting for capital investment decisions but generally keeping short-run decisions relatively simple. This paper presents firstly an approach to modelling both long and short-run decision making on-farm. This approach conceptually separates long and short-run decisions and incorporates many of the advantages of both linear and dynamic programming. The paper then describes the application of this approach in an Integrated Assessment project focused on water allocation options in the Namoi river catchment. The project requires an integrated assessment model to allow analysis of policy options in terms of their trade-off between agricultural production, water supplies and other water uses. A limited sensitivity analysis of the integrated model is provided as well as results from the application of the model to a set of policy scenarios. Overall the paper demonstrates the ability of the model to account for the dependence of decision making on existing capital infrastructure and costs of future investment required to take advantage of 'new' water supplies.

Keywords: *water allocation, dynamic programming, linear programming, integrated modelling*

1. Introduction

Development pressures on water resources worldwide are leading to increased conflicts between environmental and economic users of water. Changes in water policies within catchments lead to complex and often unexpected impacts on industries, agricultural producers, urban users, catchment communities and environmental values.

Many economic models have been built to consider the issues of water trading and the impacts of water reforms internationally (eg. Cacho, 1998; McClintock and Gooday, 1998; Sappideen *et al.*, 1998; Voinov *et al.*, 1999; Hu *et al.*, 1997; McKinney *et al.*, 1999; Rosegrant *et al.*, 2000 Hall, 1999; Branson *et al.*, 1998). This work has both a disciplinary economics perspective, which generally focuses on optimising water allocation based on economic criteria, as well as an integrated assessment perspective. The latter uses simulation to generate impacts and trade-offs resulting from various water policy options. Integrated assessment models generally attempt to incorporate similar levels of system complexity across a range of disciplines (see for example Rotmans and Van Asselt, 1996, Risbey *et al.*, 1996, Jakeman and Letcher, in press). Regardless of the approach taken, a key issue for consideration when evaluating the likely impacts of water policy change is that of capital infrastructure. However the models developed for this purpose have 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, either to the farmer or 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, changes in the spatial distribution of access to irrigation water within a catchment will the construction and maintenance of additional channels. Programs implemented by the catchment manager to improve irrigation efficiency in 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 or unregulated water. Increasing efficiency and activation of 'sleeper' licences will in many cases incur costs of laying out additional areas to irrigation. Economic models

developed to consider water reform have generally ignored these longer term structural adjustment costs.

This paper discusses a framework for simulating farmer decision making in which capital investment decisions on-farm are explicitly incorporated. An application of this framework in an integrated assessment of water allocation options in the Namoi River Basin, Australia is also presented. The next section provides a brief review of a number of water allocation studies and the techniques they have used for considering farmer decision making and capital infrastructure.

2. Treatment of capital in the literature on farmer decision making and water allocation

Dynamic programming methods are generally used for problems of optimal reservoir management or for considering issues of optimal water use or storage under different water allocation policies at different scales, including farm, regional and catchment scale, over a long time period. A range of dynamic programming techniques has also been developed to consider problems where some of the physical processes, such as climate or streamflow, are stochastic. An example of this is the work of Dudley *et al.* (Dudley, 1988a; Dudley, 1988b; Dudley and Hearn, 1993; Dudley and Musgrave, 1988; Dudley and Scott, 1993) where stochastic dynamic programming is used to investigate the implications of capacity, contents and volume sharing regimes and reservoir management. These models are generally basin or catchment scale models. Dynamic programming models are often used in conjunction with biophysical simulation models, such as models of crop growth, or streamflow generation. Dudley and Scott (1993) used Muskingum routing of flow and soil water-plant growth simulation models in conjunction with stochastic dynamic programming models to maximise expected gross margins. This work followed on from previous studies such as Dudley (1972), Dudley *et al.* (1971a), Dudley *et al.* (1971b) and Dudley *et al.* (1972) where stochastic dynamic programming was used for intraseasonal water allocation problems in irrigation. State and decision variables in these models are discretised and the area to be irrigated is fixed. These models deal with uncertainty in weather by using a stochastic dynamic programming technique. State transition probabilities are calculated by simulating plant growth under historical conditions defined by rainfall and evaporation data. Mahendrarajah *et al.* (1992) used a dynamic

programming model to look at a different type of water allocation problem, that of optimal intraseasonal allocation of storage in small dams in Sri Lanka for irrigation purposes. The model was used to optimise aggregate net revenue for a village (corresponding to a single dam) using backward recursion and broke a single year into a number of subperiods of the wet and dry seasons.

Bryant *et al.* (1993) integrated a farm level dynamic programming model with the EPIC crop model to maximise the expected net returns of two competing crops under irrigation and stochastic climatic conditions. Epperson *et al.* (1993) also used a farm level dynamic programming model in conjunction with CERES-Maize to find optimal irrigation thresholds for several maize irrigation strategies, and Evers *et al.* (1998) used the PRMS rainfall-runoff model and the EPIC crop model in conjunction with dynamic programming and linear programming models to find an optimal irrigation strategy. Generally problems for which dynamic programming has been used involve time as a critical element in the optimisation. This includes temporal considerations such as scheduling or it may be that the optimisation is over a medium to long-term. Dynamic programming models are also sometimes used in conjunction with linear programming techniques. For example, Evers *et al.* (1998) used linear programming models to identify the combination of crop and irrigation strategy which maximised net revenue over various soil types, and then used dynamic programming to identify the sequence of alternatives which would maximise net revenue. Vedula and Kumar (1996) used a combination of linear programming and dynamic programming techniques at a farm level to consider optimal reservoir release policies and irrigation allocation to multiple crops in India. They used

linear programming to maximise the sum of relative yields of all crops for a given state of the system and stochastic dynamic programming to derive the steady state operating policy for the reservoir. The stochastic variables in this case are the seasonal inflow into the reservoir, seasonal rainfall and reservoir storage.

Dudley *et al.* (1971b) used a stochastic dynamic programming (SDP) approach to look at optimal intraseasonal irrigation water allocation. This marks the beginning of a substantial body of work on the part of various of the authors, looking at the use of stochastic dynamic programming approaches for considering water allocation problems. In Dudley *et al.* (1971a) this short-run stochastic programming model was

used as a simulation model to consider the problem of optimal cropping acreages within a season when the operation of the reservoir and the area to be planted is under the control of a single decision maker. The SDP model was used to produce curves of gross margin versus cropping acreage under different reservoir levels from which the optimal acreage choice could be determined. This SDP model was also used in a further paper, Dudley *et al.* (1972), to look at the long-run problem of finding the optimal area to develop for irrigation given a certain reservoir size. The model used in this paper was also an approximating simulation model rather than a dynamic programming (DP) model. This model was chosen in preference to an additional DP model because of the smaller computation time required for its implementation. In Dudley (1972) these models were extended to consider the optimal interseasonal allocation of irrigation water when the value of water carried over from one season to another is recognised. This leads to significant differences in the estimated best acreages to develop for irrigation in the long-run and can considerably increase the estimate of the present value of benefits of the irrigation project. Saleem and Jacob (1971) also used stochastic dynamic programming to look at the optimal operation of a composite system of two coupled aquifers and a surface water subsystem in New Mexico, when the system is operated over a long time horizon. This model seeks to maximise the net value added to the basin over this long time period. The dimensionality of the model is reduced by not incorporating the surface water system as an independent state variable. This simplification was justified on the basis that surface water accounts for a small part of the water used for irrigation (~4%) in the region.

Linear programming (LP) models are another common tool used to assess the impacts of various water reforms and to indicate optimal water management options. LP models are often used for problems where time is not so critical, but where spatial aspects of the problem may dominate. However, it is possible to use a series of LP models to represent the system over a longer time period. The spatial scales of LP models used for water allocation problems vary depending on the aspect of the problem on which the model builders are focussed. These models may be used for plot or field scale, up to farm or even catchment or basin scale. The scale of resolution depends critically on the types of adjustment and impacts being considered. LP modelling applications are normally short-run in nature, assuming either fixed capital

or that capital is not a constraint on decision making. McClintock and Gooday (1998) used a farm scale linear programming model to estimate the changes in demand for irrigation water on a seasonal basis taking into account variability in volumetric allocations and climatic conditions in the Murrumbidgee Irrigation Area (MIA). Brennan (1997) used a farm scale linear programming model to consider the impact of minimum flow restrictions in the Williams River catchment on dairy farms.

Nieswand and Granstrom (1971) developed a number of linear programming models for conjunctive use planning in an aquifer in the USA. The models developed were for a single year at a monthly time step, optimising different functions of quantity of water drawn from both sources. BAE (1987) used linear programming models of representative farms in the Murrumbidgee Irrigation Area (MIA) to estimate the short-run demand for irrigation water in the MIA. These models were short-run models, where the objective was to maximise total gross margin for the whole region for a given year subject to a number of restrictions. This model was based largely on the earlier model of Clark *et al.* (1986).

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) describe 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.

Models developed at the farm level may be aggregated to a larger catchment or basin scale. For example, Adams and Cho (1998) used four farm level linear programming models to explore the trade-offs between lake levels for fish protection in the Klamath Basin in Oregon, and the profits of farmers under a range of lake levels and farmer adaptations. Each of these farm level models was used to maximise profit subject to the availability of water and other fixed resources of each farm type, and these models were then aggregated to the catchment scale. Beaulieu *et al.* (1998) used 96 farm level linear programming models to represent an entire catchment in Southern Illinois to investigate non-point source pollution management options in the catchment.

Quiggin (1986, 1988, 1991) used a combination of linear and dynamic programming to consider the costs of salinity and current production practices in the Murray River system under irrigation. These models consisted of six representative farm models along river stages, and a downstream urban use model. These representative farm models were used with linear programming to determine the 'open' solution to the problem, where upstream farmers maximised their own profit without concern for costs imposed on downstream users. The system was then reconstructed as a dynamic programming problem, where each of the river stages replaced the time periods traditionally used in dynamic programming. This system was then solved to see find the new optimum, considering externality costs to downstream water users. The difference between these two solutions then provided an estimate of the institutional costs of salinity.

McKinney *et al.* (1999) developed a model called SWIM to consider water allocation. This model was designed to account for the interactions between water allocation, farmer input choice, agricultural productivity, non-agricultural water demand, and resource degradation to estimate the social and economic gains from the allocation and efficiency of water use (McKinney *et al.*, 1999; Rosegrant *et al.*, 2000). It is intended to estimate the economic benefits of water use for different demand management instruments, including markets for tradeable water rights based on production and benefit functions with respect to the agricultural, urban and industrial sectors. The economic modelling component includes an optimisation model to estimate returns to water use. Both instream and offstream uses are modelled. Instream uses include flows for waste dilution and hydropower. Offstream uses

include diversions for agriculture and municipal and industrial uses. Agricultural water use decisions in the model are made using a fixed level of capital infrastructure.

3. Decision model formulation

Conceptually decision making on-farm can be divided into two separate sets of decisions: long-run decisions relating to investment in on-farm capital infrastructure; and, short-run crop planting decisions based on resource availability. Most economic models of farmer decision making effectively simulate decision making under a single economic assumption: that farmers aim to maximise profit over the period of simulation given constraints on resource availability. The majority of models that consider the impacts of changing water allocation policies, such as the implementation of water markets or changed access conditions generally, focus on either long-run decisions, in which case a fixed set of crop combinations is generally considered, or short-run decisions where access to capital infrastructure is either fixed or considered not to be a constraint on decision making. While the first approach emphasises the importance of structural adjustment, it generally does not consider changes to the crop mix by farmers resulting from factors such as interseasonal climatic variability. Where such short-run decisions are simulated by a dynamic programming algorithm, they must often be divided into a relatively small number of discrete decision options in order to reduce problems of dimensionality. This limits the complexity of short-run decisions able to be considered by such models. The second approach, that of focusing solely on short-run decisions, does not allow for the impacts of structural adjustment on agriculture. It assumes either that water can be costlessly transferred between users without development of expensive capital infrastructure or that there is no capacity for farmers to adjust their behaviour through uptake of new technologies and capital investments. This generally leads to an under and over estimation of impacts respectively.

The approach discussed in this paper to overcome these problems nests linear programming formulations within a dynamic programming framework. Conceptually, the dynamic programming optimisation procedure is used to simulate long-run capital investment decisions, while the linear programming models simulate short-run planting decisions at each capital investment state in each period. This approach builds on concepts developed by Evers *et al.* (1998), Vedula and Kumar (1996) and

Yaron and Dinar (1982). These authors used a combination of linear programming and dynamic programming to model decision making. But these authors did not explicitly consider capital investment on-farm using the dynamic programming component. Instead this was used to simulate irrigation scheduling. The mathematical formulation of the approach applied in this paper is described below.

4.1. Long-run decisions

Long-run decisions are simulated using the following dynamic programming formulation.

Maximise

$$f_{t+1}(\underline{k}) = \frac{1}{(1+r)^{t+1}} (\pi_t(\underline{k}) - C_t(\underline{k})) + f_t(\underline{k})$$
$$f_0(\underline{k}) \equiv 0 \tag{1}$$

where r is the interest rate (discount factor), $\Pi_t(\underline{k})$ is the short-run profit for the production decision in year, t , given the state space option (ie. vector of capital states), $\underline{k}$, and $C_t(\underline{k})$ are the capital costs of moving from $(\underline{k}_0)$ in time $t-1$ to $(\underline{k}_1)$ in time t .

4.2. Short-run decisions

Short-run profit in time t is modelled as the solution of a linear programming problem. That is,

Objective Function

$$\text{Maximise } \Pi_t = \sum_{i=1}^n d_i a_{i,t} \tag{2}$$

Constraints

$$\sum_{i=1}^n a_i \leq A$$
$$\sum_{i=1}^n w_i a_i \leq W$$

where d_i is the gross margin returned from a hectare of crop activity i , $a_{i,t}$ for $i=1, \dots, n$ is the decision variable, representing the area of land devoted to crop i in time t , A is

the total area of land available, W is the total volume of water available for irrigation and w_i is the per hectare water use of crop activity i . Note that the resource constraints are dependent on the state of capital investment. For example the area laid out to irrigation affects the overall land constraint for irrigated production, while irrigation efficiency and on-farm storage capacity will both affect the volume of water available for irrigation. The short-run model described here is very simple. In practice a more complicated model structure considering other resource constraints, such as labour or monthly or other water constraints could also be included.

The interaction between the DP and LP components described above is illustrated in Figure 1.

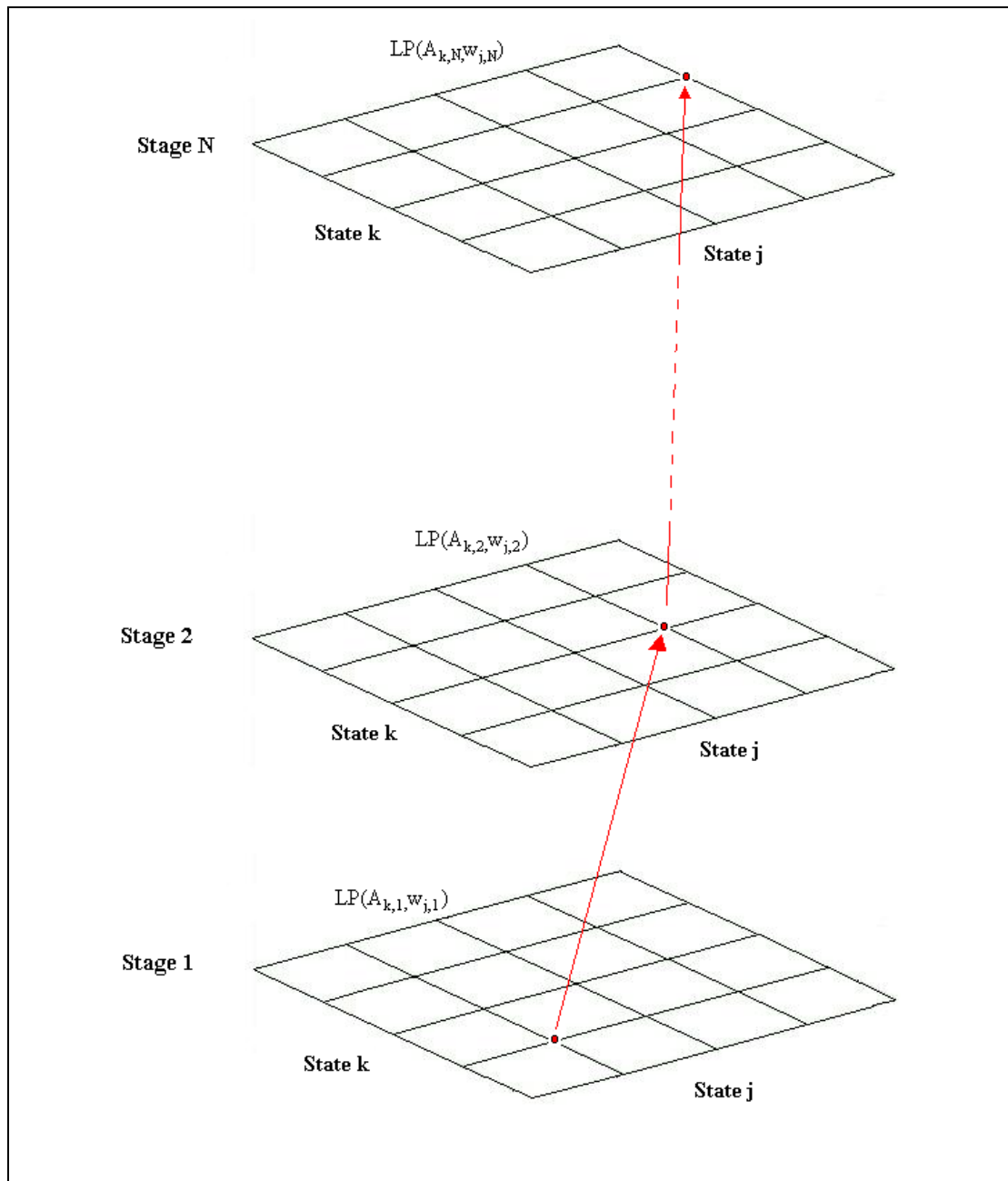


Figure 1. Interaction between DP and LP

It indicates that for each discrete point in the state space of the DP, a linear programming algorithm is used to define the short-run return at that state in that time period. As was shown above, this total return for that state also depends on the cost of capital investment.

This approach has several advantages over other approaches that have been applied to this problem:

- the short-run cropping decision can remain 'continuous' and can be very complex without affecting the efficiency of the model solution. This uses one major advantage of linear programming: that robust algorithms providing very fast solutions to linear programming problems are readily available. Considering short-run decisions with an LP formulation effectively reduces the dimensionality of the DP problem. Discrete states for capital investment are arguably less problematic than using discrete states for crop decisions as capital tends to be 'lumpy' or discrete in nature.
- conceptually this approach provides a good separation between long and short-run decisions on-farm. Conceptual separation of these components makes it clearer where alternative short-run decision models, such as decision tree approaches or other mathematical programming approaches, can be incorporated within this framework.
- outputs from the LP such as shadow prices are able to be derived and analysed not only for one point in time and state of capital investment but for many different resource constraints. This should allow a better understanding of water demands being simulated by the model, and their response to capital costs.

4. Case Study: the Namoi River Catchment

The decision model structure described in Section 3 has been applied in an integrated assessment of water allocation options in the Namoi River catchment, Australia. This section briefly outlines the water management issue in this catchment. The integrated model structure is then presented and the links between the agricultural production decision models and other model components are discussed. The decision models used in this application are then specified.

4.1. Catchment and Irrigation System

The Namoi River Catchment covers approximately 43,000 km² in northern NSW and is an important irrigation area. Groundwater and surface water supplies are overallocated in many areas. Management options for dealing with this overallocation are likely to have significant social, economic and environmental impacts. Figure 2 captures relevant features of 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.

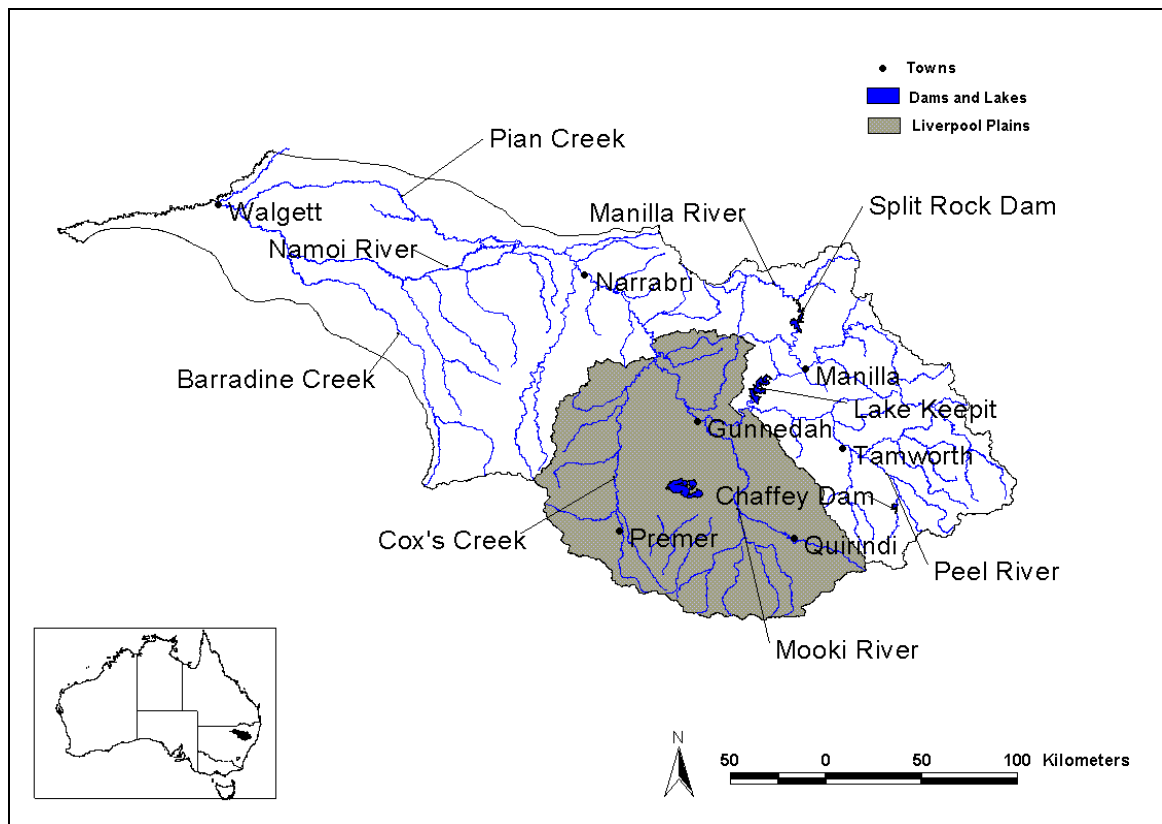


Figure 2. Namoi River Basin

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 which are above the major dams (Keepit, Split Rock, and Chaffey dams). 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 according to 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.

The integrated model discussed in this paper was developed to consider 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.*

It should be noted that this question implies the use of a simulation based approach where 'what if' type questions can be asked of various policy options, rather than an optimising approach, which defines an optimal access regime for the catchment given particular criteria.

4.2. Capital and water use in the Namoi catchment

Irrigated agriculture in the Namoi catchment is largely dependent on intensive levels of capital infrastructure. The water supply system consists of the three 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 largely associated with fuel and the capital costs of pumps and 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 area have spray irrigation. In many cases producers pump directly 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 and unregulated water usage in the catchment is largely dependent on on-farm storage capacity. The timing of off-allocation or unregulated 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 or unregulated 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 that 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.

4.3. Model framework

The spatial nature of the water allocation problem in the catchment, as outlined in Section 4.1, requires that a regional model structure capable of considering spatial

trade-offs. The integrated model developed consists of a regional scale agricultural production model underlaid by a hydrologic network. This requires that the catchment be 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 water access in the Namoi, 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. Further detail on the stakeholder interaction in this project can be found in Letcher and Jakeman (in press). The final regions developed in this framework are shown in Figure 3.

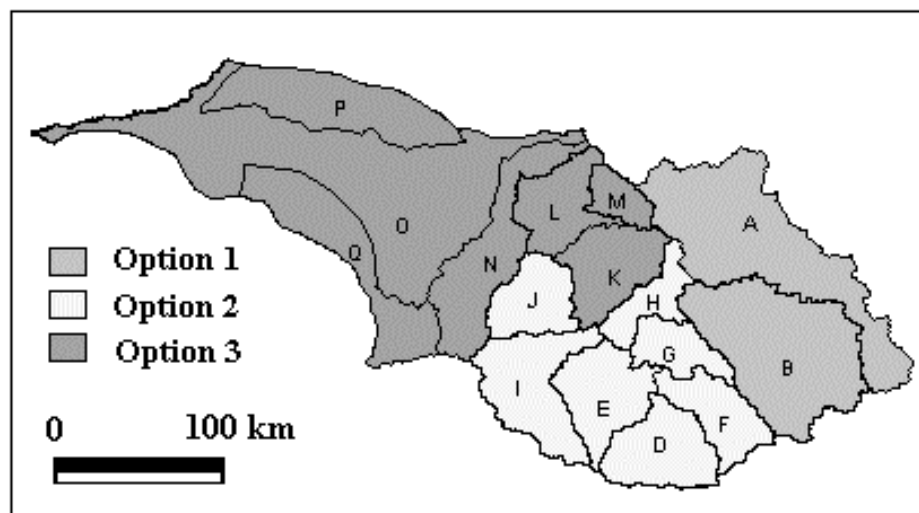


Figure 3. Model Regions in the Namoi Catchment

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 were 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 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. Note that in this way the model differs from traditional economic approaches, using a simulation approach to consider trade-offs under given policy scenarios, rather than 'optimising' access across the basin.

4.3.1. Nodal structure

Figure 3 shows the flow network being modelled in this integrated model. Each of the regions that were illustrated in Figure 4 corresponds to a node in this flow network.

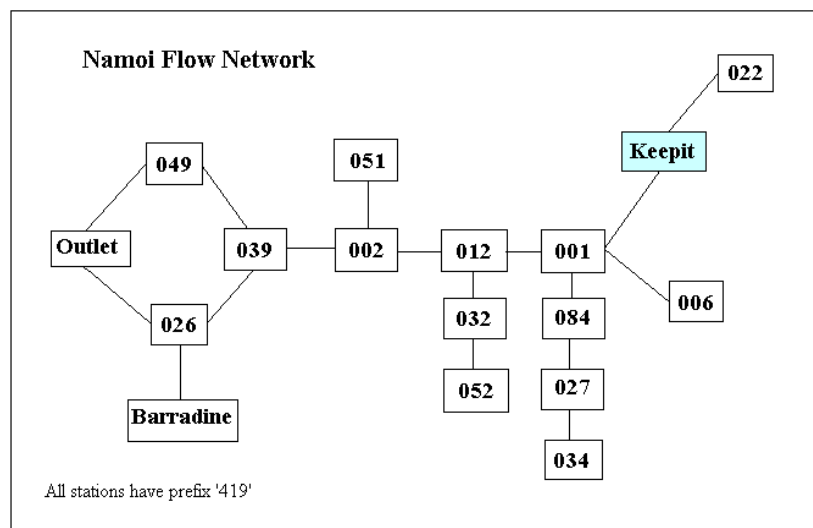


Figure 4. Flow network

Streamflow models and calibration results for this case study are described in detail in Letcher (2002) and Letcher *et al.* (under review). 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 agricultural production 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.

4.3.2. Conceptual Framework

Sequential steps in the conceptual framework for the integrated model that was developed are shown in Figure 5. 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 in the catchment given a set of climatic time series inputs (temperature and rainfall). This daily flow is fed through the policy model. This model 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 dam 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. This model 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.

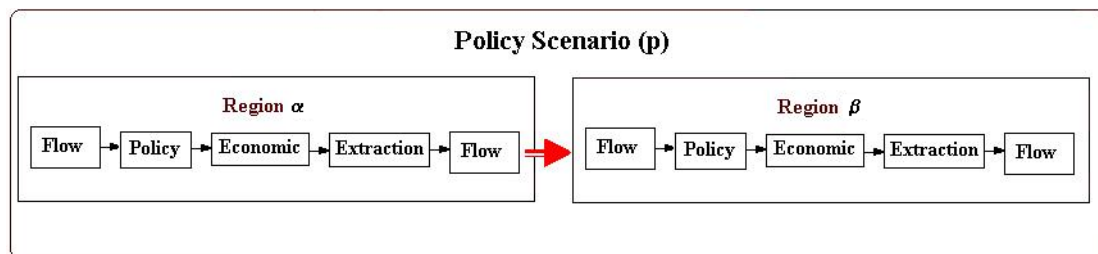


Figure 5. Sequential Steps in the Framework of the Integrated Water Allocation Model

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.

4.4. Decision model specification

This section describes in detail the agricultural production models used in the integrated model.

4.4.1. 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. Three types of capital investment decisions are considered for each region: irrigation technology; area laid out to irrigation; and on-farm storage capacity.

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 3) have only one option: current spray irrigation. All other regions have been 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. The value of costs depends on both the area laid out to irrigation and the on-farm storage capacity.

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 this area. However such an increase incurs a fixed cost per hectare developed in the model. These costs are included in the objective function of the dynamic programming module.

3. On-farm storage capacity (d)

In order for off-allocation or unregulated 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 which 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 and depend on the ML of storage developed.

4.4.2. State variables

The number of state variables that are considered by the dynamic programming model differs between regions. These differences arise from constraints that have been placed on producers' choices in each region due to individual characteristics of the region. For example, if in a region no increase 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. These assumptions are easily changed in the model by varying the input data files.

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 that 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 in 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.

4.4.3. 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). The link between the dynamic programming component and the linear programming models was illustrated for two state variables in Figure 2.

The specifications for the linear programming formulations used for each of the regions in the model are given below. For simplicity subscripts and superscripts denoting the dependence of each of the variables in the equations have been largely omitted. 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 water extraction limit = $U(d,p,t)$

O = off-allocation water extraction limit = $O(d,p,t)$

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 = $A(\Omega,t)$

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

$$\text{Max } \Pi_{\alpha,t} = \sum_{i=1}^2 \sum_{j=1}^{k_i} (P_{ij} y_{ij} - c_{ij}) a_i p_{ij} \quad (3)$$

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

$$\text{Max } \Pi_{\alpha,t} = \sum_{i=1}^3 \sum_{j=1}^{k_i} (P_{ij} y_{ij} - c_{ij}) a_i p_{ij} \quad (4)$$

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

$$\text{Max } \Pi_{E+F} = \sum_{\alpha \in \{E, F\}} \sum_{i=1}^3 \sum_{j=1}^{k_i} (P_{ij} y_{ij} - c_{ij}) a_{i,\alpha} p_{ij} \quad (5)$$

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

$$\text{Max } \Pi_{\alpha,t} = \sum_{i=1}^5 \sum_{j=1}^{k_i} (P_{ij} y_{ij} - c_{ij}) a_i p_{ij} \quad (6)$$

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.

4.4.4. Model parameterisation

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

- 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 licences 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 to irrigation;
- Current on-farm storage capacity, assumptions of possible additions in each region 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 was derived a wide variety of sources. The process by which values were obtained included a validation exercise for model assumptions.

The main sources of data used to create a first set 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 a 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 agricultural modelling component. A set of model assumptions and parameter values was then collated and discussed with various stakeholders including many of the original providers of the information sets outlined above, members of the catchment management committees and a group of district agronomists employed by the NSW Department of Agriculture. 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. Further information on the collaboration of stakeholder groups in the development of this model is given in Letcher and Jakeman (in press). A full description of all parameter values used in the model is given in Letcher (2002).

5. Results

Due to the complexity of the model developed in this paper, a comprehensive testing and analysis of model runs and their responsiveness to all input parameter assumptions and policy scenarios is not able to be presented. This section describes and analyses two sets of model results. This analysis is provided to demonstrate the capacity of the model to consider the sensitivity of decisions to capital costs as well as its ability to show spatial economic and environmental trade-offs resulting from a set of policy scenarios. The sensitivity of the model outcome to the costs of improving irrigation efficiency and increasing on-farm storage capacity is shown in Section 5.1. Section 5.2 then provides an analysis of results from applying the model to consider the issue of sleeper licence activation in the catchment.

5.1. Model Sensitivity to Capital Investment Costs

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 cost 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 7⁴). 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 5.2.1 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 (ie. the 'current' policy situation), total farm profit does not depend on the level of discretisation in most regions. The exceptions to this are Regions M and Q. The differences in these regions are very small. Due to the non-linear nature of interactions in the model however, this result 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 (NPV over 20 years) for Base Case Scenario under different levels of discretisation

Region	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 to \$800 per ha and then linearly at a much 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.

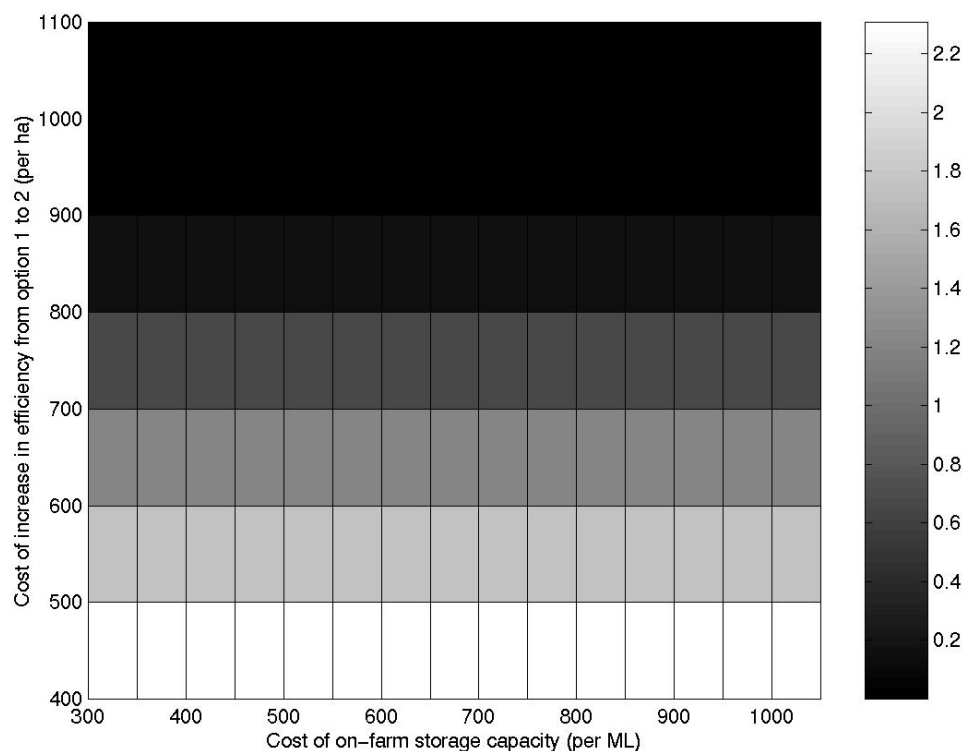


Figure 6. Change in total farm profit by capital costs (irrigation efficiency and storage) from Base Case

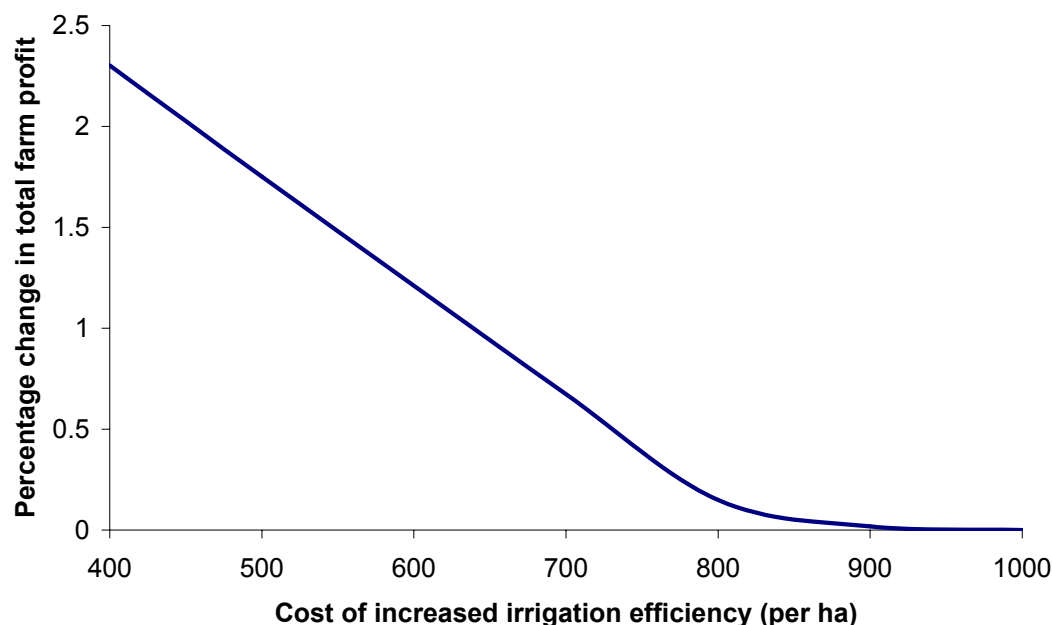


Figure 7. Percentage change in total farm profit by cost of efficiency improvements

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. These results can also be used to estimate the amount of subsidy required to induce substantial investment in irrigation efficiency improvement.

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. 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 on 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.

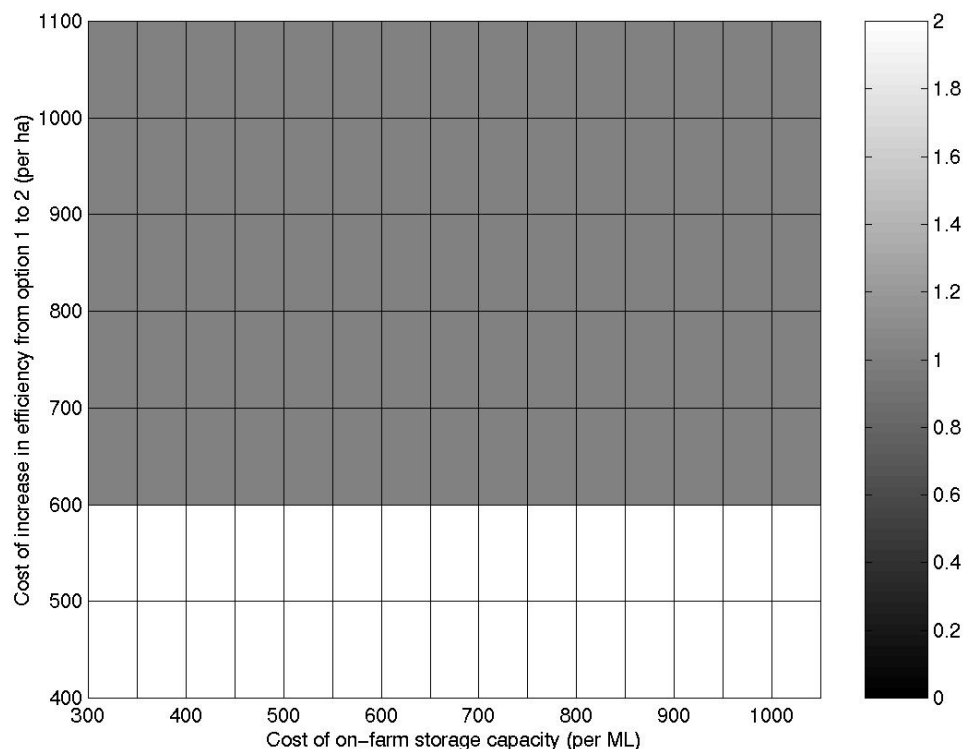


Figure 8. Investment level for efficiency given efficiency and storage costs in Region H

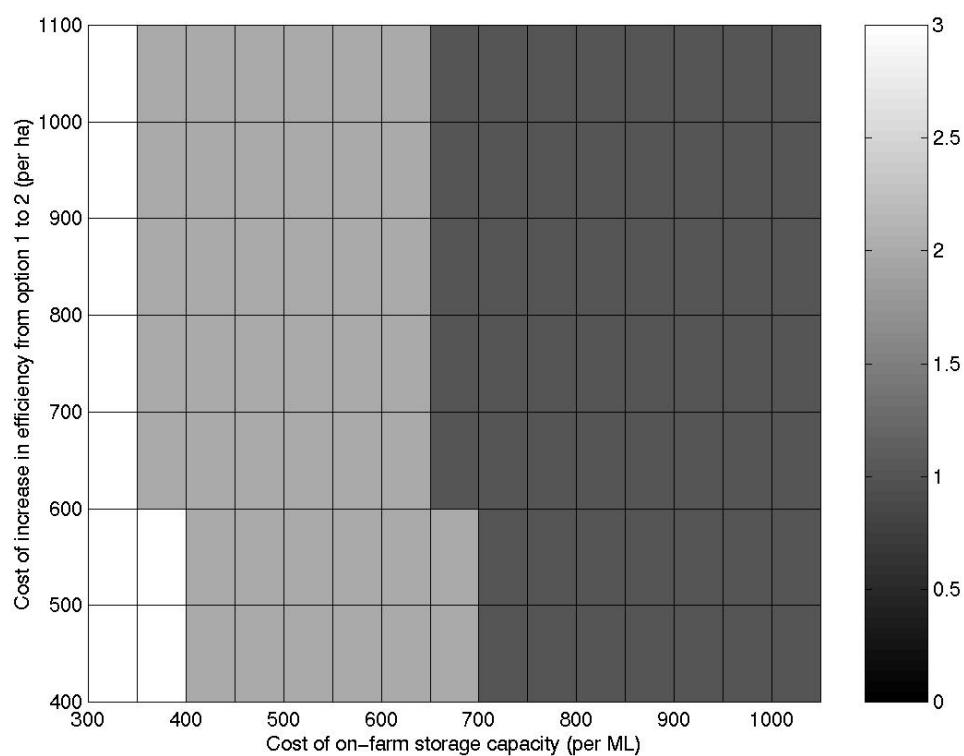


Figure 9. Investment level for on-farm storage given efficiency and storage costs in Region H

Table 5 summarises 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 system 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 (which corresponds to approximately 40 hours of computer time to run and many more to analyse). The model has many other such assumed values that 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 integrated models.

5.2. Results from the application of the model to a policy scenario

This section describes results from applying the model to consider sleeper licence activation in the catchment. Sleeper licences are those which have been allocated to users in the past but which have remained allocated in the past but which have remained unused. Activation of these licences is expected to put significant pressures on the water resources of the catchment.

5.2.1. Policy Scenario description

In order to explore the impact of increased sleeper licence activation a grid of sleeper licence activation scenarios was considered with all other policies constant (i.e. same as Base Case). In total eleven sleeper licence scenarios were considered, based on the percentage of sleeper licences which were activated uniformly across all regions, ranging from none to all sleeper licences. The sleeper licence activation scenarios used as model inputs are summarised in Table 6.

Table 6. Sleeper licence activation scenarios

<i>Scenario</i>	<i>Percentage of sleepers activated</i>
Sl. 1	0
Sl. 2	10
Sl. 3	20
Sl. 4	30
Sl. 5	40
Sl. 6	50
Sl. 7	60
Sl. 8	70
Sl. 9	80
Sl. 10	90
Sl. 11	100

5.2.2. Climate options

All policy scenarios described in this Section have been run for five different climate options to test the sensitivity of the policy scenario results to these climatic assumptions. The five climate scenarios that have been used are:

1. Historic rainfall over 20 years from 1970 to 1989.
2. A random rearrangement of individual years of rainfall data from the 20 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 20-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.

5.2.3. Indicators

The impact of changing scenarios from the Base Case (Scenario 1) on both economic and environmental indicators was analysed for all scenarios. 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 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. It was necessary to consider two indicators of flow since in many subcatchments of the Namoi river the most commonly used measurement of flow magnitude, the median flow, is generally zero (due to the ephemeral nature of the catchment). The way in which the interaction between these two flow indicators can be understood is described in Table 7.

Table 7. Interaction between flow indicators

Number of zero flow days	Median non-zero flow		
		Increase	Decrease
	Increase	Low flows are being dried out. Other flows may be increasing or decreasing	Catchment is drier overall
	Decrease	Catchment is wetter overall	Increases number of low flow events (by increasing flows on previously dry days)

5.2.4. Model Results

The model was run for each of the eleven sleeper licence activation scenarios outlined above, using all five climate options. The impact of each of these scenarios on total farm profit across all regions was calculated. The total farm profit for the entire catchment under each of these scenarios and climate options is given in Table 8. This table also shows the range of percentage change from the base case (Scenario 1).

Table 8. Total farm profit by sleeper licence activation scenario and climate series option (\$'000,000)

	Sl. 1	Sl. 2	Sl. 3	Sl. 4	Sl. 5	Sl. 6	Sl. 7	Sl. 8	Sl. 9	Sl. 10	Sl. 11
C. 1	1,640	1,640	1,641	1,641	1,641	1,641	1,642	1,642	1,642	1,642	1,642
C. 2	1,593	1,593	1,594	1,594	1,594	1,594	1,594	1,594	1,595	1,594	1,594
C. 3	1,636	1,636	1,637	1,638	1,638	1,638	1,638	1,638	1,638	1,638	1,638
C. 4	1,656	1,657	1,658	1,658	1,659	1,659	1,660	1,660	1,661	1,661	1,661
C. 5	1,661	1,662	1,663	1,664	1,664	1,664	1,665	1,665	1,666	1,666	1,666
% change	-	0% - 0.1	0.1% - 0.1	0.1% - 0.2	0.1% - 0.2	0.1% - 0.2	0.1% - 0.3	0.1% - 0.3	0.1% - 0.3	0.1% - 0.3	0.1% - 0.3

Total profit for the entire catchment increases across sleeper licence activation scenarios. Each 10% increase in sleeper licence activation has a very small effect on total profit however (less than 0.1%). Closer examination of the results shows that the maximum total profit does not always occur when all sleeper licences are activated (Sl. 11). For climate series Options 1 to 3 the maximum profit occurs for Sl. 9, when 80% of all sleepers are activated. In these cases it appears that sleeper licence activation is having some effects on downstream uses that are of a higher financial value by limiting their available water, however this impact is very small. This implies that further development beyond licensed allocation in the upper catchment would be expected to have further impacts on these downstream users, and depending on the relative marginal values of these uses, could significantly impact on total profit in the catchment. To have significant negative impacts on profit, however, these increases in use would have to be quite large, and be for low value uses. For climate series Options 4 and 5 the maximum total profit occurs when all sleepers are activated.

Table 9. Range of percentage change in farm profit by region over five climate series options

Region	Sl. 2	Sl. 3	Sl. 4	Sl. 5	Sl. 6	Sl. 7	Sl. 8	Sl. 9	Sl. 10	Sl. 11
A	0	0	0	0	0	0	0	0	0	0
B	0.5 - 1.7	1 - 3.3	1.4 - 4.9	1.6 - 6.3	1.7 - 7.5	1.8 - 8.8	1.8 - 9.8	1.8 - 10.8	1.8 - 11.6	1.8 - 12.5
D	0.1 - 0.1	0.2 - 0.3	0.3 - 0.4	0.5	0.6	0.7 - 0.8	0.8 - 0.9	0.9 - 1	1 - 1.1	1.1 - 1.3
E and F	0	0	0	0	0	0	0	0	0	0
G	0.4 - 0.5	0.8 - 1	1.2 - 1.5	1.2 - 1.5	1.1 - 1.5	1 - 1.5	0.9 - 1.5	1.4 - 1.5	0.8 - 1.5	0.7 - 1.5
H	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0	-0.2 - 0	-0.2 - 0
O	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0
Q	0	0	0	0	0	0	0	0	0	0
Total	0 - 0.1	0.1 - 0.1	0.1 - 0.2	0.1 - 0.2	0.1 - 0.2	0.1 - 0.3	0.1 - 0.3	0.1 - 0.3	0.1 - 0.3	0.1 - 0.3

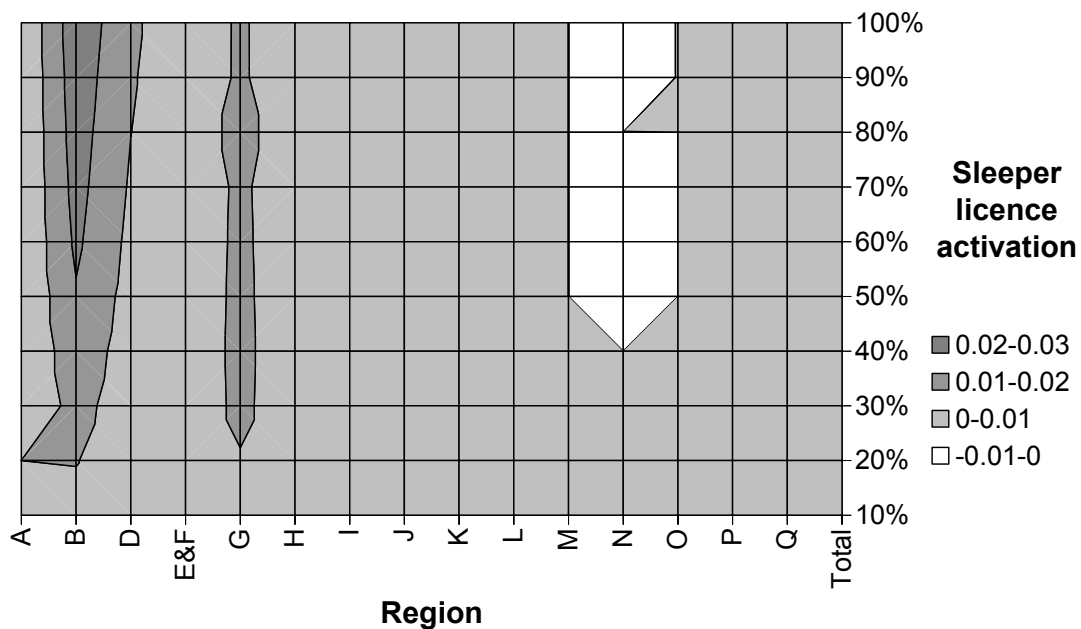


Figure 10. Change in farm profit by region for climate series Option 1

Table 9 gives the range of percentage change in regional farm profit for each of the eleven sleeper licence activation scenarios, under each climate option. Figure 10 illustrates the change in farm profit by region for these scenarios given by climate Option 1. It should be noted that these changes are similar for each region across climate options for each scenario, in both direction and magnitude, with Region B having the widest range of impacts (from 1.8% to 12.5%) for all sleeper licences activating. Region N shows a decrease in profit of up to 0.2% for scenarios 10 and 11. This decrease corroborates the discussion of total farm profits above, where it was noted that slight negative impacts on profit must be occurring in some downstream regions. This table also shows that all increases in profit are occurring in the upper catchment, specifically in the Peel River catchment and in regions on the Mooki River. This would be expected to have social and economic implications for these regions outside those considered by this model. In particular, the Peel River catchment has a significant dairy industry associated with irrigated lucerne production, which has recently been affected by dairy deregulation as well as water reforms. Benefits to these producers, either indirectly through increased production due to sleeper licence activation, or directly through the sale of this excess allocation to downstream users with higher valued uses, might be expected to have increase the flow-on of social benefits to this region, outside those measured directly by this model. Also these scenarios do not show the potential benefit to the catchment of these upper catchment users being able to sell their allocations to downstream users, and so these results represent the minimum economic benefit of activation of this water (as transfers of water to higher value uses downstream are more profitable for the catchment as a whole).

Table 10. Range of percentage change in median non-zero flows over five climate series options

Region	Sl. 2	Sl. 3	Sl. 4	Sl. 5	Sl. 6	Sl. 7	Sl. 8	Sl. 9	Sl. 10	Sl. 11
A	-0.4 - 0	-0.7 - 0	-0.9 - 0	-1.2 - 0	-1.6 - 0	-1.9 - 0	-2.1 - 0	-2.1 - 0	-2.3 - 0	-2.6 - 0
B	0	0	0	0	0	0	0	0	0	0
D	0	0	-6.3 - 0	-6.3 - 0	-6.3 - 0	-6.3 - 0	-6.3 - 0	-6.3 - 0	-6.3 - 0	-6.3 - 0
E and F	-2 - 2.1	-2 - 4.3	-3.4 - 4.9	-4.8 - 4.6	-4.8 - 3.7	-6.1 - 3	-8.2 - 3.4	0 - 3.1	-9.4 - 3	-7.8 - 2.9
G	-1.6 - 8.8	-2.9 - 5.5	-4.4 - 5.8	-7.3 - 9.5	-9.2 - 6.6	-11.7 - 8	-13.7 - 20.4	-8.6 - 8	-12.1 - 20.4	-12.7 - 17.5
H	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	-0.1 - 0	0	0
L	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0	0	0
O	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0
Q	0	0	0	0	0	0	0	0	0	0

Table 11. Range of percentage change in number of zero flow days over five climate series options

Region	Sl. 2	Sl. 3	Sl. 4	Sl. 5	Sl. 6	Sl. 7	Sl. 8	Sl. 9	Sl. 10	Sl. 11
A	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0	0
D	0.3 - 0.4	0.5 - 0.8	0.8 - 1.3	1.1 - 2	1.4 - 2.4	1.7 - 2.6	1.9 - 3.3	2.3 - 3.7	2.5 - 4.5	2.8 - 5
E and F	0.1 - 1.2	0.2 - 2.5	0.5 - 2.7	0.5 - 2.9	0.6 - 3	0.6 - 3.2	0.8 - 3.5	0.6 - 1.3	1.1 - 4.1	1.2 - 4.9
G	0.1 - 2.1	0.3 - 2.4	0.4 - 3	0.5 - 4.3	0.8 - 4.6	1 - 5	1.3 - 7.3	1 - 4.6	1.6 - 7.9	1.8 - 7.9
H	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0	0	0
O	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0
Q	0	0	0	0	0	0	0	0	0	0

Table 10 and 11 provide the range of percentage impact of each of the sleeper licence scenarios on median non-zero flows and the number of zero flow days across all regions, over all climate options. Sleeper licence activation decreases flows for many nodes, especially in the upper catchment (<21% median non-zero flows). A slight decrease in median non-zero flows is also observed in Region K (~0.1%) for Scenario 9. This means that some trade-offs are being made between upstream users and downstream users in terms of economic performance. However, sleeper licence activation does not appear to have significant impacts on streamflow in the regulated system (ie. regions H, K, L, N, O, P) under other initial conditions. What is clear from this result however, is that should other factors change concurrently (eg. increasing town water use in the upper catchment or less restrictive pumping conditions), then further negative impacts would be expected on these downstream users.

6. Discussion and conclusions

The success of water reform strategies in individual basins is dependent on the ability of water to move freely around the basin to higher values economic and environmental uses. The capacity of agricultural users to access water resources, particularly irregularly-timed flows, depends on their existing capital infrastructure and the costs involved in investing in additional capital. Additionally, those involved in water reforms often cite irrigation efficiency improvements as a potential 'win-win' for both agricultural users and the environment. This outcome depends critically on the cost of investing in these types of improvements compared to possible economic and environmental benefits of increased river flows. Traditional approaches to considering the impacts of water reforms have often ignored these capital infrastructure issues, considering the short-run benefits of trade and assuming either that infrastructure is not a constraint on water use or that it is a fixed constraint. While these approaches provide an estimate of the benefits of reform they do not allow for critical constraints in the water system and their impacts on farmer decisions.

This paper described a nested linear and dynamic programming approach for simulating both long and short-run decision making on-farm. The application of this approach in an integrated assessment project focused on water allocation options in the Namoi River catchment, Australia was also described. Results from a limited sensitivity analysis of this model to the costs of two types of capital investment (on-

farm storage capacity and irrigation efficiency improvements) were given. 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, at least for the sleeper licence policy scenarios, results were found to be relatively insensitive to the choice of input climate data. The inclusion of irrigation capital decisions in the model means that a better estimate of the long-term impacts of policy options can be made. The model framework discussed in this paper has the potential to be used to consider water trading in the catchment, and the implications of capital requirements for trading. This analysis has not yet been undertaken.

Results from the application of the model for a set of sleeper licence activation scenarios were also provided. These results demonstrate that the model developed is capable of being used to consider the economic and environmental trade-offs (and the spatio-temporal variation) of water allocation issues in the catchment. The model has already been applied to consider the trade-offs of a wide variety of surface and groundwater policies in the catchment (see Letcher (2002) for further details).

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 has been incorporated in a new project focused on further development of the model (Letcher and Aluwihare, 2003).

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. This is also to be included in future work.

The farm decision model framework provided in this paper is able to be modified to include more complicated short-run decision making algorithms, including other

mathematical programming formulations or decision-tree approaches. Additionally using the current range of modified dynamic programming algorithms, including stochastic DP, should allow for incorporation of uncertainty and risk preferences in the model structure.

Finally it is important to note that while optimisation algorithms were used in the modelling presented in this paper, the approach applied is a simulation approach. Optimisation is essentially used to simulate farmer behaviour under a single behavioural assumption: that the farmer acts to maximise their long-term profits given resource and other constraints on their decision. In this way the integrated model differs from more traditional economic modelling approaches to water allocation, attempting to estimate spatial impacts of varying policy from the current situation, rather than trying to provide an 'optimal' system outcome.

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