Weighing Up the Cost: Economic Impact of Water Scarcity and Environmental Targets[1]

Lisa Yu-Ting Lee, Tihomir Ancev, and Willem Vervoort

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ABSTRACT

Over-allocation of irrigation water has led to widespread environmental degradation in the Murray-Darling Basin, prompting discussions of the water efficiency performance of irrigated industries, particularly cotton. There is increasing pressure for irrigators to adopt water efficient practices in line with ecologically sustainable principles, especially with current drought conditions. However, there is great uncertainty surrounding the available measures to improve irrigation efficiency from both ecological and economic standpoints. An integrated biophysical and economic modelling approach is used to determine the optimal allocation of water, irrigation system, source of water, and crop pattern, subject to various environmental and resource targets. Spatially referenced data are used to provide realistic results that are directly applicable to the case study basin in northern New South Wales (NSW). The results can assist in policy design and its implementation to achieve environmental objectives at least cost.

KEY WORDS

Deep drainage, water use efficiency, water reform, integrated modelling, Mooki Basin

1. Introduction

The ongoing drought has placed severe stress on the Australian landscape and river systems. The Murray-Darling Basin is under pressure from a myriad of environmental problems arising from diminishing water resources and the proliferation of irrigated agriculture. The over-extraction of water can be attributed to current underpricing of water, which only reflects the cost of supply rather than its true cost to society in terms of its scarcity rent. This has lead to an inefficient level of water extraction and overinvestment in the irrigation industry. While it is important to limit the environmental degradation resulting from this market failure, it is equally

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important that moves towards water conservation generate maximum net social benefits, by shifting inefficiently used resources from irrigation to where it has greater value. The intention of the ongoing water reforms is to provide an efficient avenue for water allocation, primarily through water trading, so that water is allocated to its highest value use, which may be in other sectors of the economy or in the environment. Water reforms are also intended to be an instrument for farmers to minimise the impact of water shortages on farm income.

In this paper, a framework which allows efficient irrigators to maintain profitability, but at the same time conform to water sustainability targets and environmental objectives of the community, is presented. The framework involves a combined economic and hydrologic modelling of production activities on a catchment level, explicitly taking into account the volume of water diverted for agriculture and the quantity of deep drainage (deep percolation) resulting from irrigation. Deep drainage has serious environmental consequences in terms of increased groundwater and soil salinity, and potential water logging. While it is important to reduce deep drainage occurrence, it is equally important deep drainage targets are achieved efficiently; i.e. at least cost.

These issues are investigated based on the case study of the Mooki sub-catchment in northern NSW. Using an integrated biophysical and economic modelling approach, information generated from a computer based biophysical simulation model, the Soil and Water Assessment Tool (SWAT), will form the basis of an economic optimisation model constrained by environmental targets and water supply limits. This interdisciplinary framework will help assess the economic and ecological impact of catchment management policies, and to guide Mooki irrigators' production decisions and government policy direction.

2. Background

A wide range of water reforms have since been introduced in NSW with recognition given to the environment as a legitimate user of water. All NSW river systems are required to have a Water Sharing Plan (WSP) in place to establish the rules for sharing water between the environment and extractive users. However, it is difficult to establish and enforce water sharing rules in unregulated systems due to the lack of monitoring of river flow and compliance. As a result, unregulated systems have a greater propensity for environmental problems which must be urgently addressed through catchment policies.

The Mooki River sub-catchment is an unregulated tributary of the Namoi River located in northern NSW. The production of irrigated agriculture in the catchment is valued at AUD$2,072 million and is considered to be an important contribution to the regional economy. Cotton is the dominant irrigated crop in the catchment, making up about 70 percent of the irrigated areas (NSW Agriculture, 2001). Flows in the Mooki River can be extremely variable, and irrigators make the most of passing flows by pumping as much water as possible whenever the opportunity arises. As a result, large on-farm storages are common in the Mooki River basin and extraction occurs all year round. Without strict rules constraining individual irrigators' extraction level, there is the tendency for inefficient levels of water being extracted. WSPs that are properly enforced become necessary to ensure the needs of all users in the catchment are met, including the environment.

The way in which water allocations are determined is similar for regulated and unregulated rivers. The predicted river supplies for the year are estimated based on hydrological models and allocated according to irrigator's licensed entitlement. In this study, the SWAT model (Arnold et al. 1998) is used to generate biophysical information pertaining to river flow, landuse, and other physical parameters. SWAT is a basin scale model that, based on Geographic Information Systems (GIS) data, divides the basin into sub-basins containing hydrological response units (HRU). These HRUs are 'managed' under various activities to generate agronomic and hydrologic information (Arnold et al., 1998). The biophysical information generated from SWAT are then used as an input into a catchment level mathematical programming model with the objective to maximise net social benefit from the HRUs, subject to environmental constraints and constraints on water availability. The value of these constraints is then varied (parameterised) to observe its associated economic outcome. The results then provide a useful management framework that is based on actual catchment information and can be used to determine the optimal policy mix to achieve environmental targets at least cost.

2.1 Previous Studies

Irrigated cotton has been treated quite substantially in the economic literature, both on its own right and as exemplification of other, more general problems of the economics of irrigation. In an influential paper, Caswell et al. (1990) developed a comprehensive theoretical model, incorporating the choice of irrigation technology, efficiency of water use, land quality and deep drainage. The model was based on the cotton producing San Joaquin Valley in California. More recently, Varega-Ortega et al. (1998) formulated a mathematical programming model incorporating crop choice, soil quality and irrigation technique choice, to analyse the responsiveness of irrigation water demand to various policy scenarios intended to increase water use efficiency. The literature on the economics or irrigation in Australia has gained momentum recently, in the wake of the drought conditions and water policy reform (Freebairn, 2003). Economics of irrigated cotton in Australia was featured in a recent paper by Ritchie et al. (2004) in the context of managing risk of climate variability. Treating broader issues of irrigated agriculture, Abawi et al. (2001), discussed improving water use efficiency in the Northern Murray-Darling Basin.

Models have been developed for the optimal allocation of irrigation water in the Namoi river valley under limited water supply, using an integrated approach involving the combined use of biophysical simulation and economic programming (Aluwihare et al. 2005; Ancev et al. 2004; Letcher and Jakeman, 2002). The farm-based model developed in Aluwihare et al. (1998) integrates the existence of on-farm storages (an important feature on farms in unregulated rives). However, the water losses to deep drainage in conveyance, storage and application, which are significant sources of water loss at various points in the farm, are not considered. A catchment level approach is used by Ancev et al. (2004), which define the relationship between upstream-downstream water uses through the connection between deep drainage and return flows. The model is spatially referenced which makes the results location-specific and forms the basis of this paper. Environmental constraints pertaining to deep drainage are also imposed to study the effect of policies targeting the level of deep drainage. A similar method of analysing the effect of pollution targets is conducted in Tanaka and Wu (2004), using SWAT to simulate the changes in crop production associated with various nitrogen reduction targets.

Following this methodology, profit loss curves could be obtained for the desired environmental constraints set in the model described in this paper.

Modelling at a catchment scale allows for an analysis that readily incorporates the social values of water, as well as the environmental problems associated with irrigated agriculture. The treatment of water related issues at a catchment level allows the optimal spatial locations for agricultural activities to be determined, and implicitly an optimal spatial allocation of irrigation water quantities. Furthermore, the use of average parameters, with respect to deep drainage coefficients, crop yield, irrigation etc, to analyse inherently heterogenous landscapes can result in misleading conclusions. Using a biophysical computerized simulation model, the present paper treats these parameters on a site specific basis and at a high level of spatial detail. This allows for more precise estimation of the optimal choices on the site-specific basis and can be used as a valuable input in policy design and implementation.

3. Conceptual Framework

The fundamental theory behind this framework is rational producer behaviour, subject to resource constraints. This theory corresponds to the producers' need to make production decisions such that profit is maximised using scarce resources. At the catchment level, the objective is to find the profit maximising distribution of water for the Mooki Basin, given water supply constraints and flexibilities in crop choice, source of water, irrigation rate, and irrigation systems. A hypothetical catchment manager would therefore make optimal choices with respect to these decision variables in such a way that maximises the net social benefits from agricultural activities, but at the same time takes into account resulting environmental impacts. The environmental impacts are predominantly caused by extractive water use and deep drainage, resulting in increased groundwater and soil salinity, and potential for water logging. There is also the externality of reduced return flows from improved irrigation efficiency. These effects enter explicitly into the manager's decision problem.

Modelling from a catchment perspective allows for the least-cost way of meeting environmental targets and water constraints to be determined at the basin scale, which would also generate the greatest social benefit in the long-run. The optimisation process involves maximising the net benefit generated from the production of a variety of crops across *n* HRUs over T periods, through the decision variables surface water use (S_{ijt}), groundwater use (G_{ijt}), crop choice (J_{it}), and irrigation system choice (Z_{it}). The objective function is given by:

$$\underset{S_{ijt},G_{ijt},J_{it},Z_{it}}{Max} F(S,G,J,Z) = \sum_{n=1}^{N}\sum_{t=1}^{T}\frac{1}{(1+r)^t}\pi_R(t)\cdot A_i \tag{1}$$

$$\begin{aligned}\pi_R(t) &= \sum_{j=1}^{J}\left(P_jY_{ijt} - C_{ijt}\right)\cdot J_{it} \\ &= \sum_{j=1}^{J}\left(P_j\cdot f_{ijt}\left(W_{ijt}\right) - \left(\sum_{z}^{Z} FCI_{iz} + WA_{ijt}\cdot a_{ijz} + P_sS_{ijt} + P_pG_{ijt} + OtherCosts_j\right)\right)\cdot J_{it}\end{aligned} \tag{2}$$

Where

$\pi_R(t)$ is profit per hectare in the i[th] HRU in period *t*, expressed as the sum of net revenue per hectare of *J* crops produced in the i[th] HRU in period *t*;

A_i is the acreage in hectares of the i[th] HRU;

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

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

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

$$J_{it} = \begin{cases} 1 & if \quad crop = j \\ 0 & otherwise \end{cases} \tag{3}$$

Z refers to the irrigation system used for irrigation;

r is the discount rate;

P_j is the price of crop *j*;

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

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

WA_{ijt} is the water applied per hectare to crop j in the i[th] HRU in period *t* ;

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

P_s is the per unit cost of using surface water, including the pumping cost from the river, annualised storage costs including construction (of both existing and new storages), and maintenance costs;

P_p is the per unit cost of pumping groundwater.

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

The irrigation water can either be diverted from surface water bodies, S_{ijt}, or pumped from groundwater, G_{ijt}. Both fixed and application costs are higher when using the groundwater source for each individual irrigation technology (because of pumping equipment and fuel). However groundwater is a more reliable source than the surface water, and is therefore the marginal source used whenever there is shortage of surface water. A distinction is made between effective water consumed by crop *j* (W_{ijt}) and applied water (WA_{ijt}) because the value for WA_{ijt} is likely to be greater due to losses in conveyance and application. The variable WA_{ijt} is contingent on the irrigation requirement per hectare for the target yield, limited by the volume of surface and ground water available to the farm. Due to the ephemeral nature of river flow in the Mooki, all surface water must be pumped into the storage before it can be used for irrigation, so the total volume of water for crops *J* produced across A_i hectares of the ith HRU in time *t* must be less than or equal to what is available in the storage at time *t*, X_{it}, plus groundwater, G_{it}. The total volume of water used for irrigating crops *J* in the ith HRU in period *t* is subject to the following constraint:

$$0 \leq \sum_{j=1}^{J} WA_{ijt} \cdot A_i \cdot J_{it} \leq X_{it} + G_{it} \tag{4}$$

The volume of available storage water, X_{it}, must be less than or equal to the capacity of the storage, $\overline{X}_{it}$, and similarly the volume of groundwater pumped, G_{it}, must be less than the groundwater entitlement, $\overline{G}_{ijt}$, as licensed by DNR. The volume of surface and groundwater water that can be extracted is therefore subject to constraints (5) and (6):

$$X_{it} \leq \overline{X}_{it} \tag{5}$$

$$G_{it} \leq \overline{G}_{it} \tag{6}$$

The total volume of storage water available for irrigating crops in the ith HRU in period t is given by:

$$X_{it} = \overline{S}_{it} - AL_{it} \tag{7}$$

$$\overline{S}_{it} \leq \overline{S}max_{it} \tag{8}$$

where AL_{it} refers to all combined storage losses through evaporation and deep drainage, $\overline{S}_{it}$ is the volume of water pumped from the river, and $\overline{S}max_{it}$ refers to the individual irrigators' maximum extraction limit over period t, which is in turn determined by the basin's total available river flow in period t.

Other constraints in the model include the environmental constraints pertaining to deep drainage (which has implications for the occurrence of salinity) and environmental flow targets. These are defined as:

$$\alpha AL_{it} + \sum_{j=1}^{J} (WA_{ijt} - W_{ijt}) \leq DD_{it} \tag{9}$$

$$\overline{S}max_{it} \leq \overline{FL}_{it} - CTP_t \tag{10}$$

where α is the portion of AL_{it} that becomes deep drainage and the second term is the water lost to deep drainage in application, given by the difference between applied and effectively consumed water for all crops in the i[th] HRU, $\sum_{j=1}^{J}(WA_{ijt} - W_{ijt})$. The sum of deep drainage in storage and application must be less than or equal to a set deep drainage limit for the i[th] HRU in period *t*, DD_{it}. Constraint (10) specifies that $\overline{S}max_{it}$ must not exceed the river flow at the i[th] HRU in period *t*, $\overline{FL}_{it}$, less the Commence-To-Pump limit, CTP_t (the level that in-river flow must reach before extractions can begin). The CTP_t is analogous to environmental flow rules, so by varying the value of CTP_t the effect of different environmental flow levels on basin profit can be parameterised. Similarly, the economic impact of deep drainage targets can be parameterised by varying DD_{it} for the deep drainage constraint. In this way, the relationship between these environmental constraints and its associated economic impact can be derived, and used as a guide for policy making.

3.1 Water Allocation and Crop Choice

The optimal allocation of water from a social perspective is such that the marginal value product (MVP) of the last unit of water used for each crop is equated with all private and social costs associated with the crop produced. It is assumed that the primary irrigation water demand would be sourced from storage until the cost of using surface water, P_s, outweighs the cost of groundwater, P_p, or if surface water is limiting (Zilberman and Lipper, 2002). The producer has the option of growing dryland crops in response to water shortages if it becomes the most profitable option. Where the farmer decides to switch to dryland production, the operation cost associated with irrigation is eliminated from the objective function for that period. The fixed costs of the irrigation technology, however, would be sustained regardless because the investment had already been made. An additional condition may be included to represent the dryland production option, whereby if *J*=*k* and *k* is a dryland crop then production costs becomes the fixed costs of the irrigation system plus other dryland production costs, $C_{ijt} = \sum_{z}^{Z} FCI_{iz} + \{\text{dryland costs}\}$. The threshold prices, including water and crop prices (P_s, P_p, and, P_j), at which dryland production becomes more profitable than irrigated crops may be established accordingly. The impact water pricing, and crop prices, have on the distribution of water, water use, and choice of crop production in the catchment could then be analysed.

4. Data and Methodology

The described theoretical approach was applied in the case study of Mooki catchment in the Northern NSW. This catchment is characterized with intensive agricultural activities. The Soil and Water Assessment Tool (SWAT) hydrological model was used to model the Mooki catchment (Arnold et al., 1998). Available geographic information systems (GIS), remotely sensed spatially referenced data and weather data were used in the SWAT model: Digital Elevation Model (DEM) data (Geosciences Australia) and soil data layer (University of Sydney Database and DNR), agricultural management data (NSW Agriculture), precipitation data and other climatic data (Commonwealth Bureau of Meteorology – BOM), and stream flow data (DNR). Land use data were developed from a land use survey by DNR.

The size of the catchment is about 836km^2. The catchment was partitioned into 32 sub-basins, defined within the SWAT model as a unique collection of streams that drain to a single outlet. Together, the 32 sub-basins contain 608 hydrologic response units (HRUs), which is a homogeneous land unit with respect to soil type and land use. GIS image of the modelled catchment is given in Figure 2. The total number of irrigated cotton HRUs referenced is 53, making up total area of 397km^2.

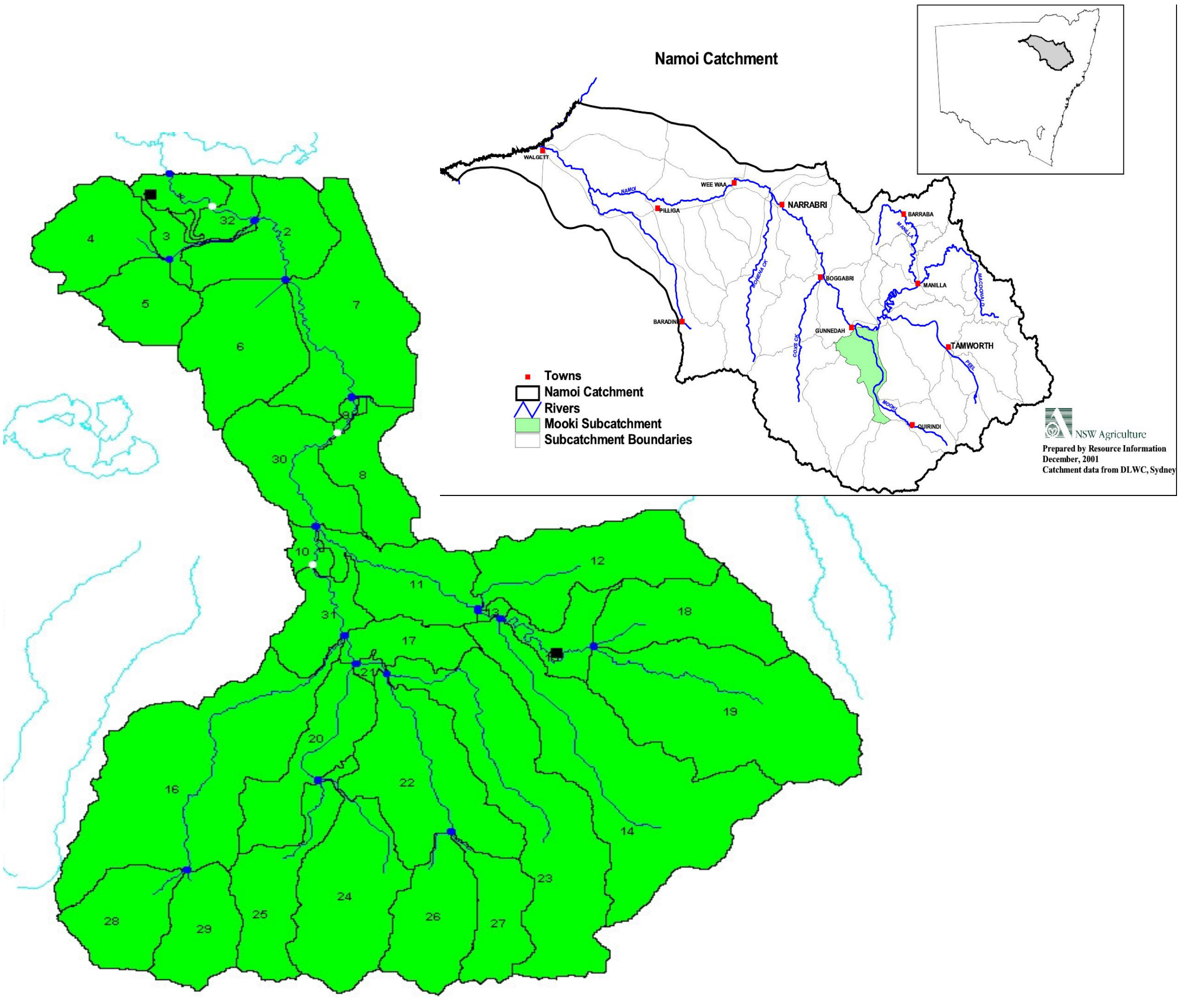


Figure 1: GIS delineation of the Mooki in Sub-basins (Aluwihare et al. 2005; Vervoort, pers.comm 2005).

The modelling is a two-stage process. The first stage involves simulating crop production using the agronomic model, the SWAT, and the second stage involves using an economic optimisation tool, “What’s Best!”, to determine the profit-maximising combination of landuse for HRUs in the basin given resource constraints. The biophysical information generated from SWAT are used as an input into a catchment level mathematical programming model with an objective to maximise net social benefit from the HRUs, subject to environmental constraints and constraints on water availability. The value of these constraints is then varied (parameterised) to observe its associated economic outcome. At this stage, hydrological interconnections are not modelled so the impact on return flows from landuse is not considered. The water availability constraint is set according to equation (4), and the deep drainage constraint is set according to equation (9). For now, no condition is set on where the water is drawn or where deep drainage occurs, so long as the total does not exceed the constraint. The environmental flow constraint, CTP_i, is imposed by setting a command in SWAT which requires a minimum river flow level before extraction can begin. This is set according to the Water Sharing Plan for the Mooki River Water Source, Phillips Creek Water Source, Quirindi Creek Water Source, and Warra Creek Water Source, depending where the HRU is located (DNR, 2004).

The scope of the analysis is narrowed to the 53 irrigated cotton HRUs, across one period (one season). Around half of these HRUs are accumulated in the most upstream area of Mooki (sub-basins 22-27) and the remainder are in the most downstream area (sub-basins 2-5, 7, and 32) (Figure 2). Each HRU has a choice of 4 crops to grow (irrigated cotton, dryland cotton, dryland wheat, or grain sorghum), 2 sources of water (surface or ground), and 3 irrigation rates per irrigation event (100mm/100m^2, 50mm/100m^2, or no irrigation)[2]. For the present paper, there are no alternative irrigation systems and all irrigation activities are under furrow irrigation. This results in 7 possible production activities for every HRU (Table 1).

Table 1: Choice of production activities for each HRU.

Activity number	Source of water	Crop production	Irrigation
1	Surface	Cotton	100mm/100m2
2	Surface	Cotton	50mm/100m2
3	None (Dryland)	Dryland Cotton	None
4	Ground	Cotton	100mm/100m2
5	Ground	Cotton	50mm/100m2
6	None (Dryland)	Wheat	None
7	None (Dryland)	Grain/Sorghum	None

The actual volume of water applied is the lesser of what is available in the water source or application rate specified. Irrigation is also limited by the maximum field capacity; if field capacity is reached the excess is returned to the source. No water trading is permitted between the HRUs at this stage, so there is no market value placed on the excess water.

[2] 100mm per 100m^2 = 1ML over 1 hectare

Simulations are run in SWAT to obtain production outcomes for each HRU under all seven activities. The yield obtained for the HRUs generated in SWAT is weighed against the average yield over the HRUs, to reflect its relative productivity. This relative yield is then fitted to a probability distribution of yields for corresponding northern NSW crops, based on the period 1965-2005 (Australian Commodities, 2005). The distributions for the crops under consideration – irrigated cotton, dryland cotton, winter wheat, and grain sorghum – are used. The revenue, variable and fixed costs, and profit are then calculated for these outcomes using price data obtained from NSW Agriculture Budget Sheets (NSW Agriculture, 2005). The revenue for cotton is given by its income from cotton lint and cotton seed, and the cost is given by a per hectare cost of production ($OtherCosts_j$ in equation (1)) plus variable costs associated with irrigation. These variable costs include usage charge per megalitre (ML), taken from the 2005-2006 Independent Pricing and Regulatory Tribunal price determination[3] (IPART, 2005), and pumping costs under furrow irrigation per megalitre according to figures from NSW Agriculture (NSW Agriculture, pers.comm). The pumping cost varies depending on the source of water used, with groundwater being more expensive due to higher pumping costs. Because alternative irrigation systems are not considered for now, fixed costs associated with switching to alternative irrigation systems are not included in cost calculations.

A matrix of net profit, irrigation water used, deep drainage incurred, and land area is then set up for economic optimisation. Using the mathematical optimisation program, 'What's Best!', the objective is to maximise the aggregate profit for the 53 HRUs by choosing the 'best' combination of activities that meets this objective. Various scenarios are run under various basin level water availability and deep drainage constraints, which have been parameterised in order to derive the economic impact of these constraints on basin profit. The economic outcome and production activities undertaken in the HRUs are used to assess the shadow price of deep drainage and water for the basin, as well as the change in landuses in the basin as constraints are tightened or relaxed.

[3] The current pricing arrangements do not take factor in the water scarcity rent in pricing water (an in situ price of water), and is priced only for cost-recovery of water services.

5. Results

The results are presented according to the constraint set. In section 5.1, the changes in production activity are presented, for 1) with water constraints only, and 2) with both water and deep drainage constraints. In section 5.2, the changes in basin profit are presented, for 1) with water constraints only, and 2) with both water and deep drainage constraints. Preceding these sections is a brief overview of the value of the seven production activities for the HRUs. It is important to note that the accuracy of economic analysis is highly dependent on the accuracy of the GIS data, and the assumptions made with respect to the biophysical parameters in SWAT. The assumption for parameter values e.g. percolation and soil conductivity or crop growth will have crucial implications for the reliability of the outcome. For this reason, it is important the results are used as an indicator for policy direction and that less emphasis is placed on the absolute value of the results. Instead, attention should be focused on the magnitude and direction of change.

Between the seven possible activities, irrigated cotton, using either surface or ground water, is the most profitable crop, averaging $1,384/ha. Irrigation rates of 50mm/m2 (0.5ML/ha) have only slightly lower profit than an irrigation rate of 120mm/ha (1.2ML/ha). This is on account of similar yields despite a lower irrigation rate, so there are cost-savings due to less irrigation water requirement. This suggests that applying less than conventional rates might not lead to significant falls in profit. While dryland cotton is only a third as profitable as irrigated cotton, with an average of $448/ha, it is the most profitable dryland production amongst alternatives wheat (average $209/ha) and sorghum (average $347/ha).

5.1 Production Activity Changes

5.1.1 *With Water Constraints Only*:

Without any constraints on water, all HRUs produce irrigated cotton (being the most profitable crop). As expected, as water constraints tighten, water is reallocated towards its highest value use, and the least profitable or water intensive HRUs substitute for dryland crops. Some of these HRUs have water requirements three-times greater than other equally productive HRUs. This might suggest that these areas might are more suited to dryland cropping, given its water use inefficiency and the relative profitability of dryland production. Some HRUs also generate much greater profit sourcing from groundwater than relying on surface water, suggesting that these HRUs do not receive enough surface water, perhaps limited by its position in the basin. This necessitates pumping from a more expensive, but reliable, source of water to compensate. As a result, as water restrictions tighten these HRUs also substitute for dryland, because of the amount of water required to produce the same yield.

It is yet to be examined whether it would be more profitable producing dryland crops and trading the water allocation elsewhere in the basin. There has been no record of trading (temporary or permanent) in the unregulated systems in Namoi, although in regulated systems the value of temporary trade can range from $100/ML to $150/ML (Water Exchange, 2006). As will be seen in section 5.2.1, however, water trading may provide a profitable alternative for irrigation water.

5.1.2 *With Water and Deep Drainage Constraints:*

Deep drainage constraints were parameterised while holding water constraints at 100,000ML (no water constraint), 6,000ML, 4,000ML, 2,000ML, and 0ML.

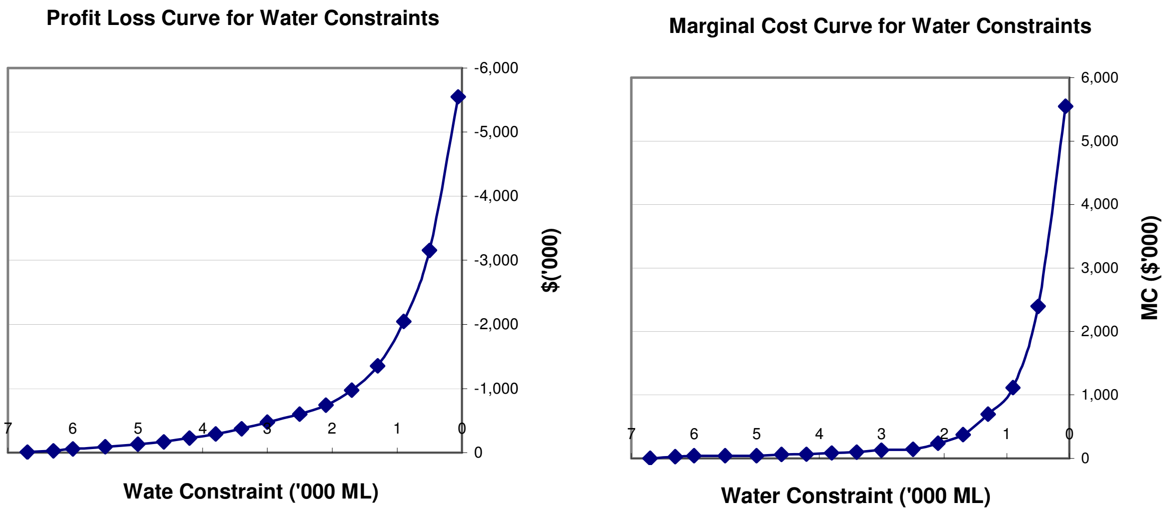
With a lax deep drainage target, and no water constraint, all HRUs are under irrigated production. Assuming the deep drainage coefficient set in SWAT is correct, as deep drainage targets become stringent, only a handful of HRUs begin switching to dryland activity and most remain under irrigated production. A possibility is that the soil profile in the basin is less 'leaky', so less water is lost to deep drainage. As the target becomes stringent, HRUs that have higher shadow prices (opportunity cost) to deep drainage remain in irrigated production while HRUs with lower opportunity cost (shadow prices) substitute for dryland cotton. Grain sorghum is not produced.

With 6,000ML water constraint, both water and deep drainage become binding constraints. Although more HRUs switch to dryland production – predominantly dryland cotton – it is due to binding water constraints rather than the deep drainage target. As the water constraint becomes stringent, the same HRUs that switched to dryland with only water constraints (section 5.1.1) are the same ones to switch to dryland activities. This result is expected since these HRUs have lower productive values for water and therefore low value for deep drainage. However, as deep drainage also becomes binding some higher value irrigated HRUs become restricted, allowing low value producers that have low deep drainage to switch back to irrigated crops. This is evidenced by some HRUs, which began with dryland cotton switching to irrigated cotton for some deep drainage constraints (and switches back to dryland as deep drainage is further reduced). This trend continues with 4,000ML constraint, and with 2,000ML constraint 25% of the HRUs become dryland production, with a majority under dryland cotton rather than sorghum.

5.2 Basin Profit Changes

5.2.1 *With Water Constraints Only*:

Without any water constraints, the optimal volume of water used across the 53 HRUs is 7,245ML, with total basin profit at $64,778,628 and averaging $1,631/ha. Prior to the 2,100th ML of water, the shadow price is fairly low, at less than $300. However, from the 2,100th ML the shadow price increases exponentially to $920 and $1,675 for the 1,250th ML. This suggests that water above 2,100ML could be reallocated for environmental purposes efficiently, due to its relatively low opportunity cost in production and presumably higher value in environmental services. The opportunity cost of water reduction is illustrated by the profit loss and marginal cost curves in Figure 2.



(a) (b)

Figure 2: Profit loss (a) and Marginal cost curves (b) for water constraints.

The total cost of water reduction increases at an exponential rate, with the marginal cost increasing rapidly after the 2,100th ML. The total cost of reducing water use down to 2,100ML is $739,000, which is the cost of providing an extra 5,145ML[4] of water towards the environment. The marginal cost of reducing the 2,100th unit will cost an extra $577 from which point the incremental cost of further reducing water use in the basin increases exponentially. This is illustrated by the cost of reducing water use down to 1,300ML which incurs a total of $1,350,199. Although the profit loss is considerable, relative to the basin profit, it can be considered a fairly cost-effective means of providing water for environmental purposes. The 53 HRUs make up 47.5% of the total area of Mooki[5], and, assuming irrigators are evenly distributed amongst the basin, 47.5% of the 26 entitlement holders in Mooki (13 entitlements) (WMA website, accessed 2006). This means reducing water allocations by 5,545ML, or 71%, for the 13 entitlement holders as a whole would cost $739,000, or just 1.14% of the productive value of the 53 HRUs.

Considering the value of water in trade, it appears that there is scope for water trading in unregulated systems. Although there is no record of water trading in the unregulated systems in Namoi, the temporary trade value in regulated rivers range from $100 to $150. For the 53 HRUs in the unregulated system of Mooki, the average productive value even for less productive water above 1,200ML is $300 – double the market value. The establishment of a water market in the Mooki would allow lower value producers to sell the allocation to higher value producers in the basin, thereby allowing water to be redistributed to its highest value use.

5.2.2 *With Water and Deep Drainage Constraints:*

Scenarios under deep drainage constraints were run holding available water constant at 10,000ML, 6,000ML, 4,000ML, and 2,000ML.

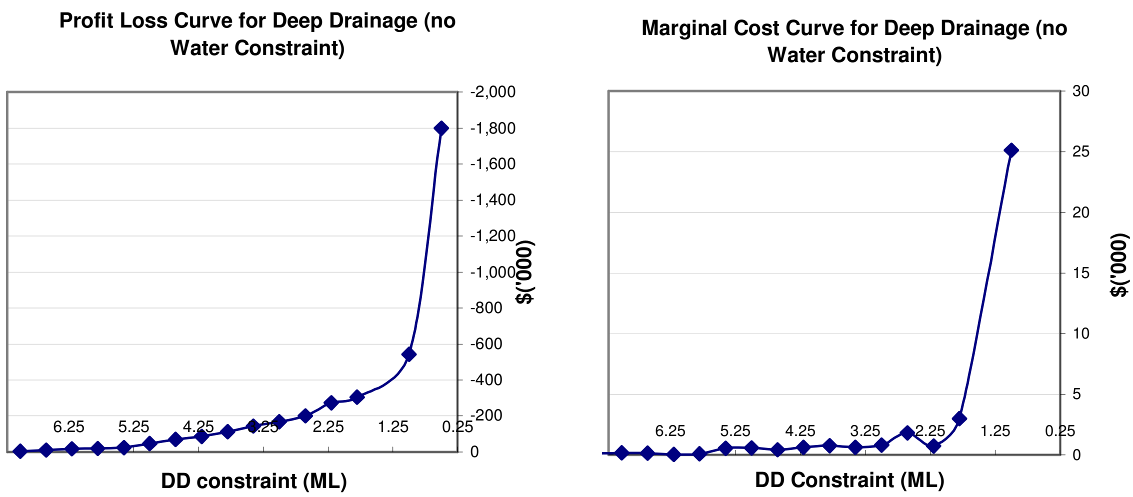
With no basin water or deep drainage constraints, the optimal volume of deep drainage is 7.48ML. The shadow price of deep drainage is relatively low until the 5.40th ML; the 5.80th ML has a shadow price of $114, while the 5.40th ML has a shadow price of $561. The shadow

[4] 7245ML-2100ML

[5] The area of Mooki is 836km^2, and the total area of the 53 HRUs is 397km^2.

price begins to rise for deep drainage reductions below 5.40ML, growing from $561 to $1,824 for the 2.60th ML (Figure 3). Compared to the marginal cost at the 5.40th ML, of $561, the incremental cost of reducing from the 5.80th ML to 5.40th ML incurs just $114 – about one-fifth the marginal cost of reducing the 5.40th unit. This translates into a total cost of $23,594 for reducing deep drainage to 5.40ML, and $46,021 for 5.00ML – almost double the cost for a further 0.40ML reduction.

Admittedly, these deep drainage shadow prices are, as opposed to the shadow value of water, low. The reduction down to 5ML deep drainage of $23,594 represents less than 0.04%[6] of the profit under optimal conditions. Even if deep drainage were reduced down to 2.60ML, which costs $273,918, this is still only 0.42% of basin profit for a 4.85ML[7] reduction. This suggests that imposing deep drainage targets can be a cost-effective means to achieve salinity reduction, even if stringent targets were imposed. A further implication is that, although it is difficult determining what the most effective deep drainage target is at a basin scale, the marginal cost of over-estimating the reduction required would not be very costly.



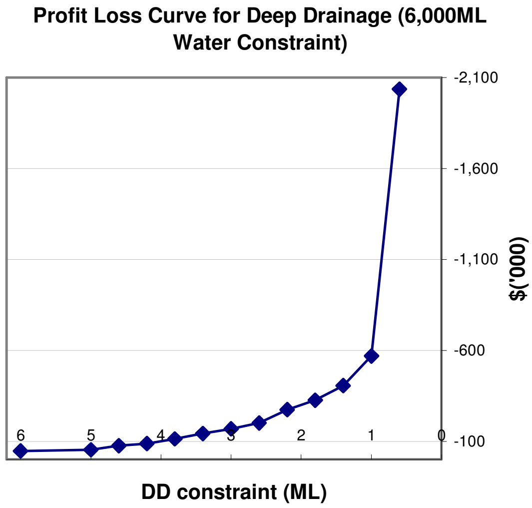
(a) (b)

Figure 3: Profit loss (a) and Marginal cost curves (b) for Deep Drainage constraints (no water constraint).

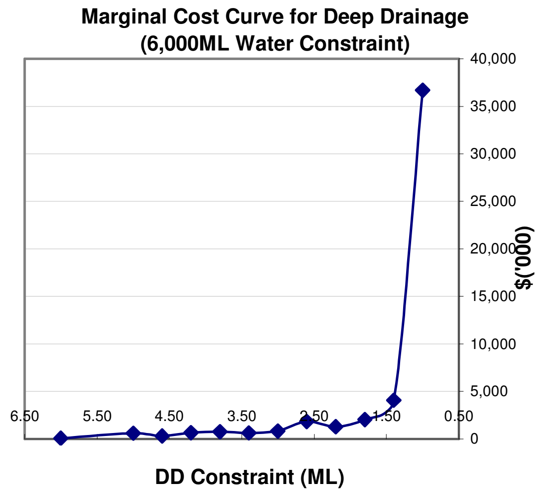
Once water constraints are imposed on top of deep drainage constraints, however, the cost of reducing deep drainage can increase at a faster rate depending on the level of water constraint.

6 Total profit for the 53 HRUs under optimal conditions of no constraints is $64,778,628
7 7.45ML-2.60ML

At 6,000ML water constraint, the shadow prices are very similar to the no water constraint scenario prior to the 2.60th ML of deep drainage; the shadow price of reducing the 5.0th ML of water is $577, and the 4.20th ML is $645. This suggests that with 6,000ML water constraint, and above 2.60ML of deep drainage, producers are yet to become bound by the set constraints. However, at the 2.20th unit of deep drainage the shadow price under 6,000ML water constraint begins to increase significantly, incurring a total cost of $325,201 to reduce deep drainage by 5.28ML[8] under 6,000ML, around 0.5% of basin profit (Figure 4). This is compared to a total cost of $303,649 with no water constraint (0.47%) of basin profit. While this indicates that, imposing a more stringent deep drainage target with more stringent water constraints would adversely impact on basin profit, the difference is very small: this works out to be an extra cost of $0.53/ha[9].



(a)



(b)

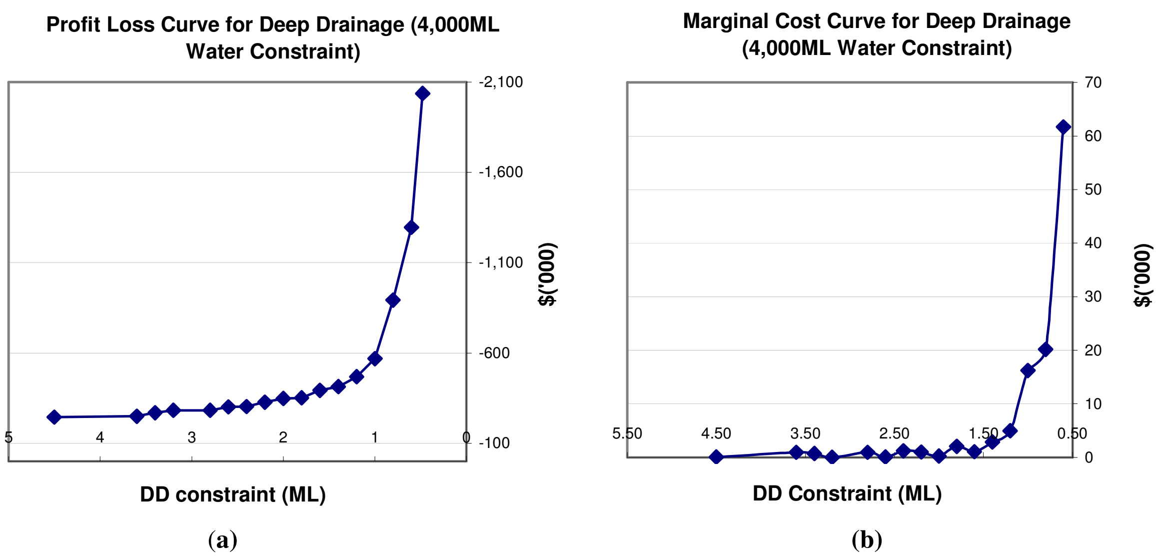
Figure 4: Profit loss (a) and Marginal cost curves (b) for Deep Drainage constraints (6,000ML water constraint).

There is an equally dramatic difference in the shadow price at the 1.00st ML of deep drainage between the 6,000ML and no water constraint scenarios: with a shadow price of $25,115 when there is no water constraint, to $36,392 with 6,000ML water constraint. This translates into a total cost of $568,534 as opposed to $542,878 to reduce deep drainage by 6.48ML[10] when there is no water constraint. This represents 0.87% and 0.84% of basin profit, respectively, which

[8] 7.48ML-2.20ML
[9] ($325,201-303,649) / 39700ha
[10] 7.48ML-1ML

means that for the same deep drainage target, there is only a slight difference in impact between different water constraints. This indicates that the impact of deep drainage targets is manifested only for deep drainage targets of at least 2.20th ML as water is reduced. Nevertheless, it is still of relatively low cost; the average cost of deep drainage reduction down to 1.00ML is around $14/ha. While it may add up at the farm-level, it has a less significant impact on profit relative to the impact of reduced water availability.

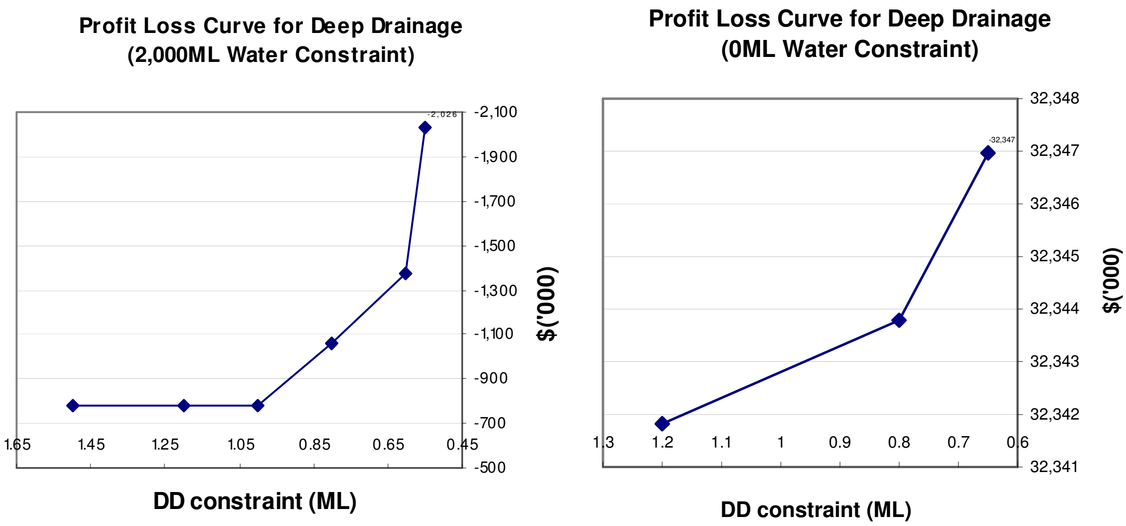
This result also reiterates the finding that, even with stringent targets, it is not significantly more expensive to reduce deep drainage if water availability also becomes stringent; there is no substantial difference in the impact on basin profitability under different levels of water availability. In fact, the cost of reducing deep drainage *decreases* as water constraints become tighter. It appears that when water availability is low, increasing deep drainage will not improve profit since the water constraint is binding. The trend in the shadow price of deep drainage with 4,000ML water constraint is equivalent to 6,000ML constraint, whereby the shadow price of deep drainage increases at a faster rate for levels below 2.2ML (Figure 5).



(a) (b)

Figure 5: Profit loss (a) and Marginal cost curves (b) for Deep Drainage constraints (4,000ML water constraint).

However, below the 1.80th unit of deep drainage, the shadow price with 4,000ML is lower than with 6,000ML water constraint. For the 1.00st unit, the shadow price becomes $16,198, and $20,182 for the 0.80th ML (compared with a shadow price of $36,692 for the 1.00st ML with 6000ML water constraint). The shadow price with 2,000ML at the 0.60th ML is only $13,731, and with 0ML water the shadow price for the 0.80th ML is $211. This again indicates that if there is not enough water to use for irrigating, raising the level of deep drainage will not increase profit by much. The main impact on basin profit comes from the water constraint rather than from deep drainage, which is evident when considering the basin profit under 2,000ML and 0ML. With lax deep drainage constraint, the profit with 2,000ML is $64,002,638, which falls to $32,436,808 under 0ML water constraint (Figure 6). This represents a drop of 1.2% and 49.9% of basin profit, respectively. This indicates that impact on basin profit is due to the binding water constraint rather than the deep drainage target, as indicated by the low shadow value of deep drainage at low water supply levels.



(a) **(b)**

Figure 6: Profit loss curves for Deep Drainage for 2,000ML (a) and 0ML water constraint (b).

6. Discussion and Conclusions

Overall, the results suggest that deep drainage constraints may be imposed at a relatively low-cost regardless the level of water availability, and with no significant increase in cost. However, if the water constraint is too tight then deep drainage targets becomes meaningless; if there is insufficient irrigation water to begin with, imposing deep drainage constraints would have no significant consequence on profit. At the extreme, under lax deep drainage constraints, the profit with 0ML water is half the profit with 2,000ML water – a 50% reduction in profit resulting from tighter water restrictions alone. This result corresponds to the previous finding that water above 2,100ML could be reduced at relatively low cost, but below 2,100ML will have significant impact on the basin's profitability. This means deep drainage constraints can be set at low cost, without impacting on the profitability of producers; the main impact would come from the volume of irrigation water available. When simultaneously setting deep drainage and water extraction rules, so long as basin water is not excessively binding, deep drainage constraints can be a cost-effective means of controlling salinity. However, as mentioned earlier, the assumption for parameter values e.g. percolation and soil conductivity or crop growth have crucial implications for the reliability of the outcome. Thus the results should be considered indicators for policy direction, focusing on magnitude and direction of change rather than the actual values.

While there are more complexities to be built into the model, the aim of this paper is to present a model that could assist in developing a catchment management framework. Some of these complexities include hydrological interrelationships between the HRUs, on-farm storages, alternative irrigation systems, and also to investigate the benefits of a well-functioning water market. The framework presented is applicable to not only the Mooki basin, but adaptable enough to be applied other catchments. This model could be used to examine the influence and effectiveness of policy-driven constraints pertaining to environmental flows or deep drainage, and provide future policy directives that aim to achieve a socially optimal outcome.

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