Economic Evaluation of Watershed Management Options in the Irrigated Cotton Areas of the Upper Murray-Darling Basin in New South Wales, Australia

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Abstract

The problems of water use efficiency and water quality in the Upper Murray-Darling Basin, NSW, Australia are of mounting concern. Sustainability of irrigation water use and environmental effects of cotton irrigation, such as groundwater and soil salinity warrant serious scientific investigation. The article combines economic and hydrologic modeling on the watershed level to propose a method for determining optimal spatial location of irrigation enterprises and use of irrigation water by source and intensity of irrigation management. This combination of economic and technical investigation results with solution that explicitly accounts for deep drainage as a source of environmental adversities. Alternative policies to achieve this optimal spatial solution are analyzed and recommended.

Key words: *cotton irrigation, deep drainage, economics*.

Introduction

In recent years Australia has experienced rapidly increasing water demand and dwindling supplies, resulting in over allocation of the water resource and water shortages for both agricultural and municipal use (CoAG). As agriculture accounts for about 80% of all water use in Australia (Smith), significant rationing in this sector will be required in the light of the ever increasing demand from growing urban areas, rising water prices and growing awareness of the environmental aspects associated with the water use. The cotton industry, being one of the most intensive users of irrigation water in Australia will be under continuing pressure to increase its efficiency in using water for irrigation, and to improve its environmental record (Cotton Australia).

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One of the most important cotton growing areas in Australia is the northern and north-western part of New South Wales (NSW), where cotton is grown on approximately 300,000 ha (ABARE). The basins of Namoi, Mooki, and Peel rivers constitute a significant portion of this cotton growing region. The problems of water use efficiency and water quality in this region are growing. Sustainability of irrigation water use and environmental effects of cotton irrigation, such as soil and water salinity, nutrient leaching and runoff have been subject to scientific investigation, but a thorough and integrated economic analysis of these problems is lacking. The present article combines economic and hydrologic modelling to determine an economically optimal spatial location of irrigation enterprises and use of irrigation water on a watershed level. The model explicitly takes into account the quantity of deep drainage (deep percolation) resulting from irrigation activities in cotton and other crops. Deep drainage has serious environmental consequences in terms of increased groundwater and soil salinity, and potential water logging.

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 a very influential paper, Caswell, Lichtenberg and Zilberman, developed a comprehensive theoretical model, incorporating the choice of irrigation technology, efficiency of water use, land quality and deep drainage. They parameterised the model using data from cotton production in the San Joaquin Valley in California. Moore, Gollehon and Carey analysed the role of water price on the optimal decisions of irrigators in the Western portions of the US. They found that the demand for water to irrigate cotton has higher price elasticity then most other analysed crops. More recently, Varega-Ortega et al. 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 model was applied on regional, rather than crop level, in Spain, but it can be readily modified for a watershed analysis, including cotton. The present article also builds on the literature on conjunctive surface/groundwater use (Burt; Buras and Nunn; Bogges, Lacewell and Zilberman).

The literature on the economics or irrigation in Australia has gained momentum recently, in the wake of the drought conditions and a water policy reform (Freebairn). Economics of irrigated cotton in Australia was featured in a recent article by Ritchie et al., in the context of managing risk of climate variability. Treating broader issues of irrigated agriculture, Abawi et al., discussed improving water use efficiency in the Northern Murray-Darling Basin.

The present article builds upon the work of Caswell, Lichtenberg and Zilberman, and Bogges, Lacewell and Zilberman and goes beyond in several important aspects. First, the previous literature typically presented farm level models, while this article develops a method for a watershed level analysis. This expansion of the model allows for an analysis that readily incorporates the social values of water, as well as the environmental problems associated with irrigated agriculture. In addition, the treatment of the problem on the watershed level allows for determination of an optimal spatial location of irrigated enterprises, and implicitly an optimal spatial allocation of irrigation water quantities (Chakravorty and Roumasset). Second, previous literature used average values of the parameters with respect to irrigation effectiveness, deep drainage coefficients, and the costs of irrigation, pertaining to inherently heterogenous land areas. Because the present article employs a bio-physical computerized simulation model, it can treat these parameters on 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. Third, the present article adds an option for choice of crop, and source of irrigation water in addition to the choices of irrigation technology and water use efficiency as presented in previous literature. In contrast to the previous literature on the conjunctive water uses, the present article imposes explicit constraints on the available quantity of irrigation water from surface diversion and groundwater pumping, and empirically derives shadow values for water from both sources.

Based on this, the central objective of the article is to develop a method to devise optimal spatial location of irrigation enterprises, optimal choice of crops and intensity of irrigation management on the watershed level. The method will be empirically tested using a model of the irrigated cotton areas of the Mooki River watershed, located in the Upper Murray-Darling Basin, NSW, Australia. The method explicitly accounts for environmental effects of cotton irrigation and irrigation of other crops with respect to soil and water quality, water availability and deep aquifer recharge. The article also aims to examine the effectiveness of a range of site-specific policy instruments that can be implemented to achieve the desired outcome. Specifically, the economic efficiency of tradable water permits, subsidies, taxes, standards and other policy instruments applied on a site-specific basis is investigated.

Conceptual Framework

Suppose that a given watershed can be partitioned into a number of land areas, so that each land area represents a unique combination of land use and soil type in the watershed, resulting in a unique hydrological response. Let us call these land areas – hydrologic response units or HRUs. Assume further that a watershed is managed by a benevolent watershed manager, whose objective is to maximize total social benefits for the watershed. In the case of water usage, the watershed manager would have to make optimal choices with respect to crop choice, source of irrigation water and the intensity of irrigation management (including the possibility of non-irrigation) on each of the HRUs in the watershed that currently are, or could potentially be irrigated. These optimal choices should be such that maximize total benefits for the watershed, but in the same time take into account any environmental effects that are resulting from the irrigation. The environmental effects are predominantly caused by deep drainage and may be represented by increased groundwater and soil salinity and potential for water logging.

The objective of the watershed manager can be expressed as:

(1) $$\max_{j} \sum_{i=1}^{n} \pi_{ij} = NR_{ij} A_i \ ,$$

where j is the crop chosen in the i^{th} HRU, A_i is the acreage in hectares of the i^{th} HRU, and NR_{ij} is the net return per hectare (or gross margin) associated with the crop choice in the i^{th} HRU. More specifically, the net return can be represented in the form of another objective function to be optimized:

(2) $$\max_{w_{ijz}, I_{iz}} NR_{ij} = p_j f_{ij}\left(\sum_z w_{ijz}(I_{iz})\right) - \sum_z FCI_{iz}(I_{iz}) - \sum_z w_{ijz}(a_{ijz}(I_{iz}) - \sum_z (p_{wz} w_{ijz}) \ ,$$

where p_j is the exogenous price received for the crop grown in the i^{th} HRU, and f_{ij} is the yield response function relating water applied to the yield of the crop chosen in the i^{th} HRU. This function reflects the possibility of non-irrigation, so that $f_{ij}\ (\sum_z w_{ijz} = 0) = y^*$, where y^* is an average yield of the crop chosen in the i^{th} HRU being grown as dryland.

The irrigation water can either be diverted from surface water bodies, or pumped from groundwater. The subscript z refers to this distinction. Both fixed and application costs are higher when using the groundwater source for each individual irrigation technology (because of pumping equipment and costs), but the groundwater is more reliable source than the surface water, and is therefore the marginal source used whenever there is shortage of surface water. The quantity of water applied in the i^{th} HRU, specific to the crop choice (j) and the source of irrigation water (z) as well as the intensity of irrigation management (I_{iz}) in that HRU is denoted by w_{ijz}. The fixed cost of irrigation, which is dependent on the choice of intensity of irrigation management (I_z) in the i^{th} HRU is denoted by FCI_{iz}. In particular, a more intense, water conserving management (centre pivot, drip) using groundwater is expected to have higher fixed cost than the less intensive, traditional technologies using surface water (furrow). Application cost of irrigation in the i^{th} HRU is represented by a_i, which is again dependent on the choice of intensity of irrigation management and the water source. When the water is priced, p_w represents an exogenous price of water. In many instances the institutional arrangements would not take into account the water scarcity rent (an *in situ* price of water) and the effective price charged would be zero. The price of water in these instances is only determined by the cost of diversion or pumping

This defines the set of choice variables to the watershed manager. The manager has to choose the crop in the i^{th} HRU, choose the intensity of irrigation management (including the dryland), and if the crop is irrigated the manager has to choose the quantity of irrigated water from each source. These optimal choices have to be made under a set of constraints that a watershed manager faces. One obvious constraint is the land constraint,

(3) $$\sum_{i=1}^{n} A_i \leq A,$$

where A is the total acreage of land that the manager desires to manage. In the case of irrigation water, the focus would be only on currently irrigated or potentially irrigable land area.

Other constraints on the objective function are the water availability constraints,

(4a) $$\sum_{i=1}^{n} w_{ijs} \leq w_s, \text{ and}$$

(4b) $$\sum_{i=1}^{n} w_{ijg} \leq w_g$$

where w_s is the total surface water available for irrigation for the whole watershed and w_g is the groundwater available for irrigation for the watershed. The present article at this stage only conducts a static analysis, while a dynamic analysis of both surface and groundwater use over time is planned for a future study.

The watershed manager has to account for the quantity of water that deep drains from irrigation activities. Deep drainage is primary cause of secondary dryland salinity Drainage usually occurs when rain or irrigation water infiltrates moist soil with insufficient capacity to store the additional water. The extra drainage increases the volume of groundwater causing water logging and saline discharge.

The water may deep drain during the storage and conveyance to the field, as well as after it has been applied to the crop. The difference of surface water withdrawn (ww_{is}) and water applied (w_{is}) represent the deep drainage losses during surface water storage and conveyance. A fraction of water that is applied on the field also deep drains. The constraint on deep drainage can be represented as:

(5) $$\sum_{i=1}^{n} w_i g_{ij}(I_{iz}, lc_i) + (ww_{is} - w_{is}) \leq Z ,$$

where Z is the total quantity of allowable deep drainage for the whole watershed.

The fraction g_{ij} is used to quantify water loses to deep drainage through actual application of irrigation water on the crop chosen in the i^{th} HRU. It is a function of intensity of irrigation management (I_{iz}), the crop grown, and the quality of land (lc_i). If desired, an additional environmental constraint may be imposed on the quality of the deep drained water in terms of its electro conductivity measure (salinity).

The first order condition for optimality with respect to the quantity of water used for irrigation in the i^{th} HRU is represented by:

(6) $$p_j f_{ij}'(\sum_z w_{ijz}) = \left(a_{iz}(I_{iz}) + p_w\right) + \lambda_{si} + \lambda_{gi} + \lambda_{ddi} ,$$

where λ_{si} is the Lagrange multiplier pertaining to the surface water quantity constraint expressed in equation 4a, λ_{gi} is the Lagrange multiplier pertaining to ground water quantity constraint expressed in equation 4a, while λ_{ddi} is the Lagrange multiplier pertaining the deep drainage constraint expressed in equation 5. The expression f_{ij}' denotes the first derivative of the function with respect to the control variable. The condition states that at the optimum, the value of the marginal product of water used on the crop selected in the i^{th} HRU should equal the marginal cost of water (application costs plus any price charged for water) plus a surface water scarcity rent (λ_{si}) and/or ground water scarcity rent (λ_{gi}), plus an optimal tax (or penalty) per unit of deep drained water (λ_{ddi}).

Assuming a continuum of intensities of irrigation management (effectively representing a proxy for an irrigation technique), the optimality condition with respect to the choice of the intensity of management would be given by:

(7)

$$-FCI_{iz}'(I_{iz}) = f_{ij}'(\sum_z w_{ijz})w_{ijz}'(I_{iz}) + w_{ij}'(I_i)a_i(I_i) + w_{ij}(I_i)a_i'(I_i) + \lambda_{ig}w_{ig}'(I_i) + \lambda_{is}w_{is}'(I_i) + \lambda_{ddi}w_{ijz}(I_{iz})g_{ik}'(I_i)$$

This condition states that the optimal intensity of irrigation management chosen in the i^{th} HRU should be such that the marginal fixed costs associated with the change of the irrigation intensity should be equal to the marginal effect that this change has on the yield [$f_{ij}'(\sum_z w_{ijz})w_{ijz}'(I_{iz})$], plus any savings (or extra expenditure, which is a reason for inverted signs) on irrigation application costs [$w_{ij}'(I_i)a_i(I_i) + w_{ij}(I_i)a_i'(I_i)$], plus a marginal change of valuation in terms of surface and groundwater scarcity rent [$\lambda_{ig}w_{ig}'(I_i) + \lambda_{is}w_{is}'(I_i)$], plus a marginal change in the optimal deep drainage tax [$.\lambda_{ddi}w_{ijz}(I_{iz})g_{ik}'(I_i)$].

The method developed in this article will be used to first estimate the fraction of water that deep drains (g_{ij}) for each management option in each considered HRU and then to quantify the surface and ground water shadow values (λ_{si} and λ_{gi}), and the shadow value placed on the deep drainage (λ_{ddi}). These will be further used in the discussion of the potential policy design and implementation.

Data

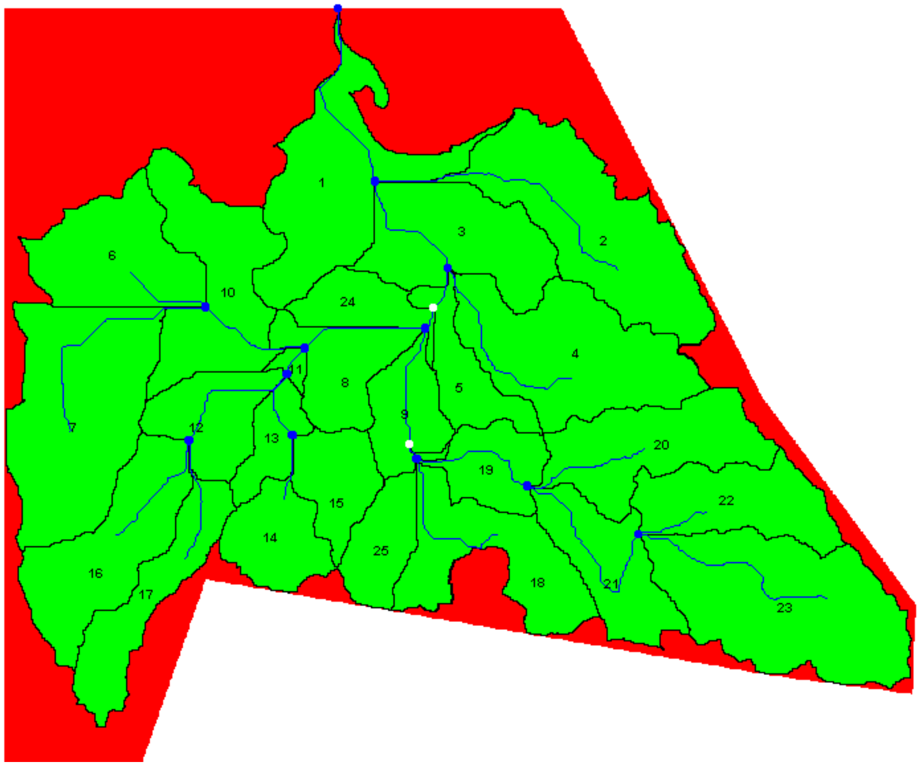
The described theoretical approach toward determination of an optimal allocation of water and optimal choice of crops and intensity of irrigation management will be tested on the case of Mooki watershed in the Northern NSW, Australia. The watershed is characterized with intensive agricultural activities. The production of irrigated agriculture is valued at A$ 2,072 million[1] and is considered as an important contribution to the regional economy (NSW Agriculture, 2001).

The Soil and Water Assessment Tool (SWAT) hydrological model was used to model the Mooki watershed (Shrinivasan et al.; Arnold et al.). Available geographic information systems (GIS) 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 Department of Infrastructure, Planning and Natural Resources – DIPNR), agricultural management data (NSW Agriculture), precipitation data and other climatic data (Commonwealth Bureau of Meteorology – BOM), and stream flow data (DIPNR). Land use data were developed from a land use survey by DIPNR.

The size of the modelled watershed is about 380,000 ha. The watershed was partitioned into 25 sub-basins and 151 hydrologic response units (HRUs). A sub-basin is defined within the SWAT model as a unique collection of streams that drain to a single outlet. An HRU is a homogeneous land unit with respect to soil type and land use. GIS image of the modelled watershed is given in figure 1.

[1] One Australian dollar was approximately 0.70 U.S. dollars in May, 2004.

Figure 1. A GIS Image of the Mooki Watershed, Northern NSW, Australia



The numerals in the figure represent the sub-basins.

There were on average six HRUs per sub basin. Out of 151 HRU in the watershed, 53 were agricultural, comprising 35% of the whole watershed. The area of currently irrigated crops stretches on 18,800 ha, and comprises about 5% of the whole watershed. Cotton is grown on about 70% of this irrigated area. Other land uses in the watershed are extensively used pastures (on 53% of the watershed area), and forest (7% of the watershed area)

The net-returns to agricultural enterprises were calculated using gross margins for individual crops in the region published by NSW Agriculture. For each agricultural HRU, the net returns were calculated based on the SWAT simulated yield data. SWAT simulated data was also used to approximate the effects of possible alternative irrigation management intensities, as well as to calculate the deep drainage for each irrigation enterprise in the watershed. Indicative data on water prices in the region were obtained from NSW Agriculture. Fixed and application costs of the alternative intensities of irrigation management were derived from publications on various irrigation technologies (Foley and Raine; Raine, Foley and Henkel).

Method and Procedures

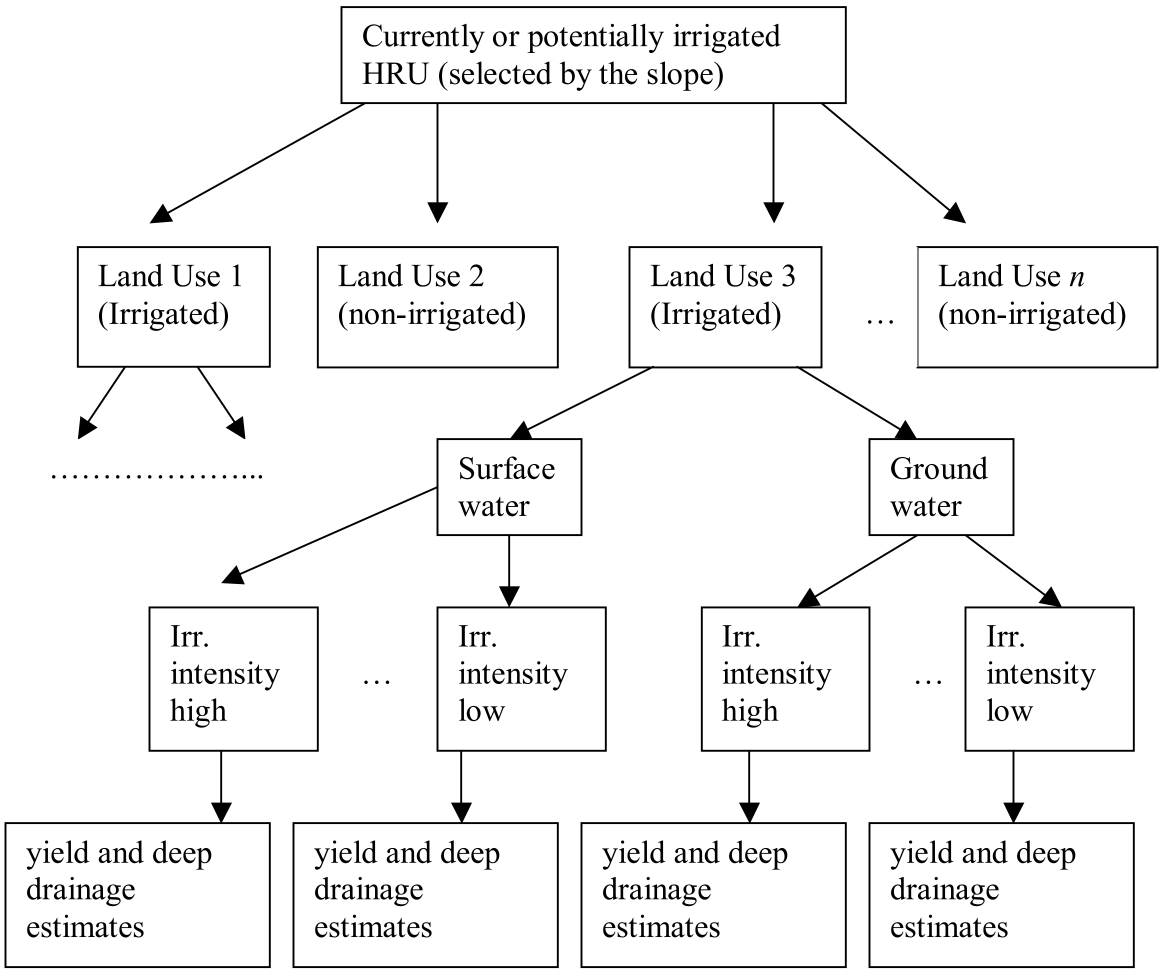
The method developed in this article consists of two steps. SWAT simulations under the use of alternative sources of irrigation water (surface or groundwater), under alternative intensities of irrigation management and associated water quantities used, and alternative crop choice in selected HRUs were first conducted. Each of the designed alternative management options was simulated in each of the selected agricultural HRUs. The resulting estimates (yields, deep drainage) from the SWAT simulations were then integrated in a mathematical program to determine the optimal solution.

SWAT Simulations

The SWAT model was calibrated for stream flow using observed data. The model was run for 10 years, 1993-2003, with effectively five year warm up period. SWAT simulations were conducted for various irrigation management options in the HRUs selected as potentially suitable for irrigated agricultural enterprises. The criteria for selection of the HRUs was their slope. All HRUs currently under irrigated or non-irrigated agriculture and all HRUs currently under grazing, whose average slope was less than 2% were considered as potentially suitable for irrigation.[2] SWAT was used to simulate each possible crop (land use) for each of these HRUs. The considered crops were: irrigated cotton, irrigated sorghum, dryland wheat, irrigated and dryland pasture. For all considered irrigated crops, separate SWAT simulations were run for the source of irrigation water: surface (reach, river) or groundwater. The intensities of alternative irrigation technologies were simulated within SWAT by varying the volume of water applied and timing of the irrigation operations. This was used to obtain a continuum of intensities for irrigation management. The intensities ranged from high volume – low frequency irrigation, with applications at managed time intervals, to low volume – high frequency automatically triggered irrigation. The less intensive irrigation management was envisaged as simulating more traditional irrigation technologies, for example furrow irrigation, while the more intensive management was envisaged to simulate relatively more novel technologies, for example drip irrigation. Other possible irrigation technologies would be in between these two extremes. For each of the considered HRUs, and for each of the SWAT runs, simulated crop yields and the amount of deep drainage were recorded. The methodology of using the SWAT model to arrive at these estimates is summarized in the following figure.

[2] A visual check-up of the GIS image was conducted to further eliminate some HRUs based on various criteria (distance of irrigation infrastructure, unsuitable soils for irrigation ,etc.)

Figure 2. Diagrammatic representation of procedures using the calibrated SWAT model



Income and Cost calculations

Net income for each considered HRU was calculated based on the simulated yield, and irrigation cost data. Since the SWAT is not designed as field scale bio-physical model and its simulation of crop yield may not always be entirely reliable, the simulated yields were normalized. The normalization was conducted by dividing through by the minimum yield for an HRU obtained in a given simulation. This transformed the yields into relative values. The relative values were than multiplied by the average yields for the corresponding crop in the region (NSW Agriculture, 2004), which resulted in an estimate of revenues for each specific HRU in the watershed, under each of the simulated management options.

Costs of using irrigation techniques with alternative management intensities were obtained using data published in Foley and Raine and Raine, Foley and Henkel. The gross margin analysis by crop (NSW Agriculture, 2004) was used to compute net returns for each HRU, for each of the possible crops, source of irrigation water, and irrigation management intensity. Published gross margin analyses for the crops in the region (NSW Agriculture, 2004) were modified to reflect the assumed crop management activities as defined in SWAT, as well as site-specific yields and costs of alternative irrigation intensities. This resulted in a number of activities associated with all possible alternatives in each of the considered agricultural HRUs (for example if there were 5 crops, two water sources and 10 levels of irrigation intensities, for each HRU there will be 5 x 2 x 10 = 100 possible activities). Each of these activates in each of the HRUs had a specific value of net-return and deep drainage. These activities were incorporated together in a mathematical programming model.

Mathematical programming model

A programming model was constructed in order to obtain an optimal solution on the watershed level. The objective function of the program corresponded to the objective function of a hypothetical watershed manager, as outlined in equations 1 and 2. The objective was to choose an optimal crop, and if the crop was irrigated, an optimal allocation by source of irrigation water (surface or groundwater), as well as an optimal intensity of irrigation management. This objective had to be met subject to the constraints outlined in equations 3 through 5. The constraint on total water availability required estimates of both surface and groundwater availability on the watershed level. Stream flow in the year corresponding to the year of the used SWAT estimates was employed as a proxy for the surface water availability. Information from DIPNR on the total annual allocation of groundwater for that particular year was used to approximate availability of groundwater.

The constraint on the deep drainage was parameterized for the total allowable deep drainage in the watershed. The starting point for the parameterization was an estimate of a sustainable deep drainage in the watershed published in Ringrose-Voase et al. This estimate was varied from -50% to +50% to arrive at each parameter value. The parameterization was done in order to obtain shadow prizes for deep drainage. The shadow price in the context of a mathematical programming model would represent the value of a change in the objective function as the constraining variable is changed by one unit. The shadow price on deep drainage represents the value by which the total net benefits on the watershed level increase (decrease) as the allowed amount of deep drainage from the whole watershed is increased (reduced). This allows interpreting the shadow prices as marginal cost of reducing deep drainage on the watershed level. The mathematical program was run for each value of the parameterized deep drainage constraint. Each resulting shadow price represents a point on the marginal cost curve. The marginal cost curve was traced out by connecting the shadow prices obtained by resolving the program for each constraint value.

A socially optimal amount of deep drainage, representing an efficient environmental target could be found at the point of intersection of the marginal cost curve with a marginal environmental damage curve (Ancev, Stoecker and Storm). At this stage, the current study was not able to determine the environmental damage cost function caused by the deep drainage in the Mooki watershed, but this is of an imminent research interest. Environmental damages in this particular watershed are predominantly due to salinization of the water in the aquifer. Other environmental damages are potential soil salinity and waterlogging. In the absence of endogenously determined, efficient environmental target with respect to deep drainage, the recommended target for deep drainage (Ringrose-Voase et al.), based on pure technical arguments, was used to illustrate the optimal solution. Assuming that this target was efficient, the solution to the program for that value of the constraint represents an optimal solution on the watershed level.

Policy Options

Once the optimal solution with respect to crop grown, source of irrigation water and the intensity of irrigation management for each of the HRUs in the watershed has been determined, various policy options have to be evaluated to induce the private landholders to achieve this optimal solution. These options are taxes on use of water, taxes on deep drainage, subsidies for implementing more intensive irrigation management, as well as quotas (standards) on water use.

Optimal taxes on water use can be derived from the computed shadow prices for surface and ground water. The shadow prices reflect the water scarcity rent, and their implementation in the watershed would lead to the optimal solution. It is important to note that the optimal tax derived using the proposed method would be specific to the modelled watershed and specific to the particular year for which the analysis was done. The optimal tax, will of course be different for surface and ground water. The mechanism of tax is quite conventional. As the tax is imposed, the users whose marginal valuation (value of the marginal product) of the water in irrigation is lower than the marginal tax will reduce their usage until the point where the marginal valuation and tax are equal. Water quantities freed in this manner will be used by the users with higher marginal valuation of water (high value of the marginal product).

The optimal tax on deep drainage can be also determined using the derived shadow price, which corresponds to the marginal cost of reducing deep drainage on the watershed level. Theoretically, if this tax rate were imposed, the users would take it into account when making their irrigation decisions. In particular, irrigation will proceed up to the point where the marginal benefits from irrigation will be equal to the product of the resulting amount of deep drainage and the marginal deep drainage tax rate. Since this product would be specific to the individual HRUs in the watershed, the marginal tax rate would also have to be specific to achieve the desired outcome. However, this may be practically impossible, politically infeasible and at the minimum will result in enormous transaction costs.

The political and practical difficulties with farm specific (site specific) marginal tax rates may be overcome if a system of tradable rights were introduced. The system in this case would have to comprise both water quantity rights and deep drainage rights. The mathematical programming solution presented above in fact mimics the workings of a tradable permit system. The shadow prices derived would represent the equilibrium prices of water quantity permits and deep drainage permits. An obvious problem with a system of tradable rights is the monitoring, since it is difficult to observe the actual deep drainage values. Although the SWAT model presented in this article is just an approximation of the reality, its estimates of deep drainage on site-specific basis may potentially be used as a reliable indication of the relative contribution of individual HRUs to the deep drainage on the watershed level. These estimates could also be potentially used in determining trading ratios of the deep drainage permits among individual landholders.

Subsidisation on the introduction of more efficient irrigation technologies has been suggested as another policy option to address the problems of water use and the associated environmental effects. To evaluate this policy, an additional set of mathematical programming runs has to be conducted, where the fixed costs associated with higher intensities of irrigation management will be reduced by a proposed subsidy, while the fixed costs of lower intensities will remain the same. This in effect decreases the cost difference between the modeled intensities of irrigation management. The expected result is that the subsidy can be used to achieve the desired optimal solution. However, if the cost of the subsidy is endogenous to the watershed (the watershed taxpayers pay at least a portion of the subsidy), the total benefits to the watershed will be reduced as compared to the previous policy scenarios. In addition, under the subsidy, an incentive for more irrigation will be created and in the long run an expansion of the irrigated area in the watershed can be expected (Tietenberg).

A final evaluated policy option is to impose a strict quota on the water use from both surface and ground water source. If this quota is uniform for each HRU in the watershed, the effect will be grossly suboptimal water use and reduced deep drainage, but not at the optimal level. The only way a quota may achieve the desired optimal solution is if it is applied on site-specific basis, for each individual HRU separately. In this case, the solutions derived from the programming model may be used to set the standards. However, this policy would also suffer from excessive transaction costs imposed by the difficulties with monitoring, enforcement and administration.

Conclusion

The article presented a method that can be used to determine optimal crop choice, source of irrigation water and intensity of irrigation management for each of the considered land areas in a given watershed. The method is a combination of hydrological and economic modelling. This method represents an advance of the current state of the art in that it functions on a watershed level, but can still capture the site specific characteristic of individual agricultural enterprises. In contrast to some previous studies the method is designed to use site-specific irrigation and deep drainage parameters, rather than averages over heterogenous land areas. The method also explicitly accounts for deep drainage associated with irrigation activities, which is of particular importance in the Australian context.

The developed method is intended to be tested using a SWAT model of the Mooki watershed in north-western NSW, Australia. This watershed was chosen because it is characterised with significant irrigated agriculture activities dominated by irrigated cotton. Although severe environmental consequences from irrigation are still not experienced, some warning signs are already present. The analysis was conducted from a perspective of a hypothetical watershed manager whose objective was to maximize net benefits on the watershed level, subject to water quantity and deep drainage constraints. The constructed mathematical program was solved to determine optimal shadow values for surface water, ground water and deep drainage. The obtained shadow values are useful in policy design and implementation.

Several alternative policy options to achieve better water management and reduce deep drainage in the watershed were evaluated. Taxes on ground and surface water as well as on deep drainage would be effective policy instruments but may be practically and politically difficult to implement. Tradable permits on water quantity and deep drainage may be the best available solution, but the problem of thin markets may exist. Subsidies on more efficient irrigation techniques, could also be used to achieve the policy objective, but they would be fiscal burden and would create incentives for expansion of irrigation in the long-run. Strict quantity and deep drainage standards would only be effective if applied on the site-specific basis, which is practically very difficult to achieve.

Management of the water resource on a watershed level using integrated bio-physical, environmental, economic and social approach is encouraged by policymakers in Australia and elsewhere. This article contributes toward this integrated approach by defining a method that can be used for further exploring various aspects of irrigated agriculture.

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