

Nonlinear Optimisation Using Production Functions to Estimate Economic Benefit of Conjunctive Water Use for Multicrop Production

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Abstract Uncertainty and shortages of surface water supplies, as a result of global climate change, necessitate development of groundwater in many canal commands. Groundwater can be expensive to pump, but provides a reliable supply if managed sustainably. Groundwater can be used optimally in conjunction with surface water supplies. The use of such conjunctive systems can significantly decrease the risk associated with a stochastic availability of surface water supply. However, increasing pumping cost due to groundwater drawdown and energy prices are key concerns. We propose an innovative nonlinear programming model for the optimisation of profitability and productivity in an irrigation command area, with conjunctive water use options. The model, rather than using exogenous yields and gross margins, uses crop water production and profit functions to endogenously determine yields and water uses, and associated gross margins, respectively, for various conjunctive water use options. The model allows the estimation of the potential economic benefits of conjunctive water use and derives an optimal use of regional level land and water resources by maximising the net benefits and water productivity under various physical and economic constraints, including escalating energy prices. The proposed model is applied to the Coleambally Irrigation Area (CIA) in southeastern Australia to explore potential of conjunctive water use and evaluate economic implication of increasing energy prices. The

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results show that optimal conjunctive water use can offer significant economic benefit especially at low levels of surface water allocation and pumping cost. The results show that conjunctive water use potentially generates additional AUD 57.3 million if groundwater price is the same as surface water price. The benefit decreases significantly with increasing pumping cost.

Keywords Surface water · Groundwater · Conjunctive water use models · Agricultural production and profit functions · Optimal multicrop production · Sequentially quadratic programming (SQP) technique

1 Introduction

Water is the most important input in irrigated agriculture, with timely and reliable supply being a major determinant in cropping decisions (Khan et al. 2006). Irrigators, however, often have to make key decisions on crop acreage and input investments in the absence of reliable information on water availability. This is especially the case with surface water resources which depend upon rainfall and water stored in reservoirs. Climate change and climate variability make seasonal rainfall less predictable and seasonal irrigation supplies more uncertain, potentially eroding agricultural production and farming profitability. Uncertain surface water allocations also deter irrigators from making long-term investments or entering into seasonal water trading and insurance contracts (Dwyer et al. 2005). In addition to the stressors of climate variability, new environmental water demands have priority for water allocation over agriculture, and are thus putting even further strain on the ever dwindling water resources available to farmers (Ward et al. 2006; Wichelns and Oster 2006).

Development of optimum land uses and water allocation plans and operable water delivery schedules are valuable for irrigation schemes in arid and semi-arid regions. Surface water usually has low delivery and extraction costs, but is subject to high variability in supply. Uncertainty and shortages of surface water supplies necessitate development of groundwater in many canal commands. While groundwater can be expensive to pump, it may provide a reliable supply where managed sustainably. Groundwater can be used optimally in conjunction with surface water supplies. Such conjunctive use systems can significantly decrease the risk associated with a stochastic availability of surface water supply. In a conjunctive irrigation region, however, escalating energy prices and decreasing water tables due to overexploitation, are key limiting factors for both sustainable agricultural production and profitability. Energy costs associated with irrigation rank as one of the highest annual variable costs and an increase in energy prices would significantly reduce farm business incomes especially in regions which rely heavily on groundwater pumping. For example, a 17.5 % increase in electricity prices would reduce farm business income by 26 % in Burdekin, Queensland (CME 2013). In the United States, energy cost increases of 7.7 % per year have resulted in a 4.1 % annual reduction in farm income (Sands and Westcott 2011).

Conjunctive use models developed and reported in the literature include simulation models e.g. Safavi et al. (2009) and Raul and Panda (2013), dynamic programming models e.g. Onta et al. (1991) and Provencher and Burt (1994), linear programming models e.g. Chen et al. (2014), hierarchical optimisation models e.g. Paudyal and Gupta (1990), nonlinear programming models e.g. Matsukawa et al. (1992) and Montazar et al. (2010) and others. Recently, there is an emerging use of models based on

multi-objective programming and intelligent algorithms e.g. Yang et al. (2009), Tabari and Soltani (2013), Safavi et al. (2013) and Chen et al. (2013). The readers can refer to Singh (2014) for a comprehensive review on the application of various programming techniques used for planning and management of conjunctive irrigation. The present study estimates the maximum economic value of conjunctive water use strategies with regard to increasing pumping cost using a nonlinear programming model, reflecting the nonlinear nature of most conjunctive water use management problems.

The novelty of our approach is the development of non-linear Cob-Douglas production functions and profit functions and direct use of these functions into a non-linear optimisation model, which provide endogenously optimal yield and profit estimates for various surface water allocation levels, conjunctive water use options and water prices. The present approach is flexible and offers more realistic estimates of yield and profit and differs from the commonly used methods based on given crop yields and gross margins. The model endogenously determines suitable levels of water uses and associated optimal production for a given water availability and maximises net return. Another key feature of our approach is the development of water trading function, which allows water trading (buy and selling) to achieve efficient water use to maximise the net benefit. We also apply the model to estimate the impact of escalating energy prices.

It is noted that in the field of agricultural economic policy and scenario analysis such as those involved in this study much attention has recently been paid to positive mathematical programming (PMP) e.g. Cortignani and Severini (2009) and Buysse et al. (2007), primarily because of its ability to exactly reproduce an observed set of agricultural production practices in the model as the result of optimisation. PMP, however, does not allow to incorporate nonlinear constraints into the optimisation model. In the present approach production functions can capture realistic crop production practices and the nonlinear mathematical programming model is general in which both linear and nonlinear constraints are involved.

The specific objectives of the present study are (i) to develop a mathematical programming model to explore the economic potential of conjunctive water use options, and to arrive at an optimal use of water resources by maximising net benefits and water productivity under various physical and economic constraints; and (ii) to employ the model to evaluate the economic implications of increasing groundwater pumping costs. The proposed model is applied to the Coleambally Irrigation Area (CIA) in southeastern Australia.

2 Model Formulation

We model yields and gross margins under various water allocation levels and conjunctive water use options using production and profit functions, rather than using exogenous crop yields and gross margins. Production functions represent the yield of main crops in response to water use and are estimated using yearly rainfall data and applied irrigation of specified amounts at set dates during the growing period. Given total water inputs, i.e. irrigation plus rainfall, crop yield production functions are derived for various crops using the SWAGMAN-Destiny model (Edraki et al. 2003). Developed production functions are obtained by fitting the following nonlinear curve using ordinary least squares (OLS) regression analysis:

$$Y(W) = \beta_0 + \beta_1 W + \beta_2 W^2 - \beta_3 W^3 + \epsilon \quad (1)$$

where Y is the yield (tonne per ha), W is the water use (ML per ha), β_i ($i = 0, 1, 2, 3$) are coefficients with associated units and ϵ is the error term.

The profit function of a crop represents the net return after subtracting the input cost and water cost from the output income of that crop, i.e.

$$P(W, X) = p \times Y(W) \times X - C \times X - \left[\gamma \times p^{(s)} \times W + (1 - \gamma) \times p^{(g)} \times W \right] X \quad (2)$$

where p is the output price (\$ per tonne) of the crop, X is the area (ha), C is the growing cost excluding water costs (\$ per ha), $p^{(s)}$ is the surface water price (\$ per ML), $p^{(g)}$ is the groundwater pumping cost (\$ per ML), and γ is the conjunctive water use ratio defined as

$$\gamma = \frac{\text{Surface water}}{\text{Surface water} + \text{Groundwater}} \quad (3)$$

The total gross margin (TGM) denoted by Π for crop production and water trading of the whole farming business is calculated as

$$\Pi = \sum_{i=1}^N P_i(W_i, X_i) + p^{(t)} \times W^{(t)} \quad (4)$$

where i is the crop index of a crop grown in the farm, $p^{(t)}$ is the temporary water trading price (\$ per ML), and $W^{(t)}$ is the quantity of water trading, buying when $W^{(t)} < 0$ or selling when $W^{(t)} > 0$ (in ML).

A nonlinear programming (NLP) model is generated here with the aim of maximising the TGM in Eq. 4 subject to several land, water, technical and administrative constraints. The model is represented in the form of vector functions as follows.

$$\begin{aligned} &\text{maximise } \Pi = f(\mathbf{x}) \quad \mathbf{x} \in \mathbb{R}^n \\ &\text{subject to } c_i(\mathbf{x}) = 0, \quad i \in E \\ &\quad \quad \quad c_i(\mathbf{x}) \geq 0, \quad i \in I. \end{aligned} \quad (5)$$

It can be seen that the objective function $f(\mathbf{x})$ represents the right hand side of Eq. 4 with \mathbf{x} being a vector of the input variables including the water use and area of each crop and the quantity of trading water. $c_i(\mathbf{x})$, $i = 1, 2, \dots, n$ are additional constraint functions. E and I are the index sets of equality and inequality constraints, respectively. In the present work, the objective function is a nonlinear function while the constraint functions can be either linear or nonlinear. More details about the constraint functions are given below:

Surface Water Constraint Total surface water use must not exceed the corresponding announced water allocation for the water year, as shown below:

$$\sum_{i=1}^N \gamma W_i \times X_i \leq SW \times A \quad (6)$$

where W_i is the net crop water use (ML per ha) of crop i , SW is the total surface water entitlement for an irrigation system, and A is the surface water allocation (%) in a given month.

Groundwater Constraint Groundwater licenses/withdrawal of water should not exceed the maximum sustainable yield, as represented through

$$\sum_{i=1}^N (1 - \gamma) W_i \times X_i \leq GW^{(sy)} \quad (7)$$

where $GW^{(sy)}$ is the sustainable groundwater, based on the extraction limit.

Land Constraint Land allocated to various crops must not exceed the total cultivable area during the summer and winter seasons, i.e.

$$\sum_{i=1}^N X_i \leq TA \quad (8)$$

where TA is the total cultivated area available.

Allowable Area Constraints Management considerations, market conditions, machinery capacity of the farm, and climatic conditions restrict the minimum or maximum land acreages for certain crops such as rice to meet the regulations on local land use in the area. For instance

(a) Lower bound

$$X_i \geq \mu_i^{min} TA, \quad (9)$$

(b) Upper bound

$$X_i \leq \mu_i^{max} TA, \quad (10)$$

where μ_i^{min} and μ_i^{max} are minimum and maximum fractions, respectively, of the cultivated area under crop i .

Water Market Constraint Water markets are subject to a set of rules and regulations. These involve placing limits on where water can be traded and the mechanisms for establishing the price, as well as limiting maximum tradable volumes (Khan et al. 2009). For instance

$$W^{(t)} \leq \phi^{max} SW \times A \quad (11)$$

where ϕ^{max} is a fraction of the total allocation that can be traded on temporary water markets.

Non-Negativity Constraints The non-negativity constraints which ensure the solution remains feasible, are given as follows.

$$X_i \geq 0. \quad (12)$$

A sequential quadratic programming (SQP) algorithm with state of the art techniques in MATLAB[®] computing software for handling nonlinear constraint is used to solve the mathematical model (5). For a description of the SQP algorithm, a simplified version with linearized nonlinear constraints is presented in the Supplementary.

3 Application Example

The developed model is generally valid and its application has allowed an estimate of the benefits of conjunctive water use for the CIA, a major irrigated agricultural region located in the Murray-Darling Basin (MDB) in the southeastern New South Wales (Fig. 1).

3.1 Irrigation Command Area

3.1.1 Surface Water

Surface water for the CIA is stored in Burrinjuck and Blowering dams and is diverted to the area via the Murrumbidgee River at the Gogeldrie Weir. Rainfall in the CIA is in

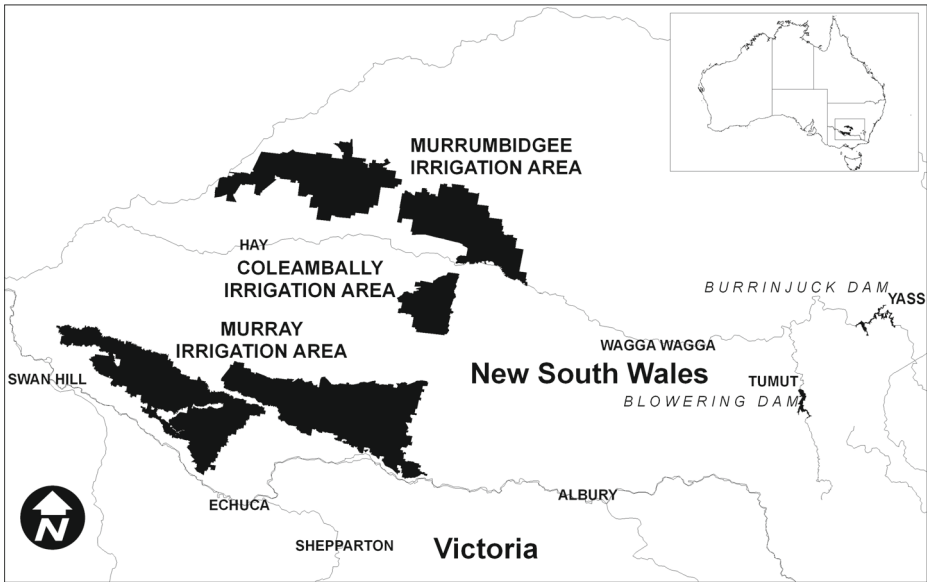


Fig. 1 CIA irrigation command area locates in south east of New South Wales

the range of 400–450 mm per year. There are over 360 landholdings with a total area of 79 000 ha, and a total bulk water license of 629 GL. Prolonged drought severely impacts water availability; for example, surface water deliveries declined significantly from 629 GL in 1996/1997 to 36 GL in 2007/2008, increasing to 427 GL in 2011/2012 following good seasonal rains (Supplementary Fig. 1). Available surface water supplies are allocated on a priority basis; first to high security water and then to general security water. High security consumptive water licenses include town water supplies and permanent crops (in this case, pasture). Irrigators with high security water usually receive close to full entitlement (e.g. at 95 % allocation during 2005/2006). General security water licenses represent most of the CIA's farming business. The first irrigation allocation announcement for general security water users in the CIA is at the beginning of the irrigation season around July–August. This announcement is usually conservative based on a high level of reliability (i.e. that there is a 99 % chance that the announced allocation will be available). General security allocations build gradually over the irrigation season as inflows into storages and rivers occur. Supplementary Fig. 2 shows the trend in the general security allocation for the period, July–December 2011.

3.1.2 Groundwater

Groundwater management policy for the region has been developed since 1955 starting with all water bores constructed requiring a license. Licences were issued in perpetuity with no area or volume based restrictions until 1984 when the volumetric allocation basis was introduced. The annual groundwater entitlement was increased gradually from 147 GL in 1983/1984 to a peak amount of 529 GL in 2000/2001 (Kumar 2002). In 2003, a 10-year water sharing plan (the Plan) for groundwater sources was developed. The Plan uses the average annual groundwater recharge of about 400 GL as the basis for sharing water

between extractive users and the environment. It provides for a portion of the estimated recharge to be reserved for the environment allowing the remainder to be available for extraction. The Plan was implemented in 2006 with total entitlements reduced from 515 GL to the target of 270 GL in 2015/2016. Supplementary Table 1 presents the annual extraction limits of groundwater for the ten years of the Plan from 2006–2016.

3.1.3 Land and Water Use

In the CIA, rice and corn/maize are the main summer crops, with wheat, barley and pasture being the main winter crops. Supplementary Table 2 shows the change in the area and water use over the last five years of seven major crops in the CIA. Prior to the commencement of drought in 2002/03, 2001/02 data indicate that over two-thirds of CICL's water supplies were used by rice. Since 2002/03 the proportion of water supplied to rice crops reduced to less than half of total deliveries in most seasons with only 1.4 % of total water supplied by CICL used for growing rice in 2007/2008. 2010/11 marked the end of drought, with 65 % of water being used on rice, reflecting a return to pre-2002/03 levels. The areas committed to the production of soybeans, corn, wheat, pasture and canola have varied greatly over the last five years in response to the availability of water and changes in commodity prices.

3.2 Model Application

We modeled productivity in CIA for seven crops including wheat, maize, soybean, pasture, lucerne, rice and tomato. More crops can be added to the model straightforwardly. The production functions for the main crops in CIA (Table 1) were obtained from the outputs of SWAGMAN-Destiny model using the yearly rainfall data for Griffith for the years 1962–2001. The total cultivated area available (TA) is the total area of CIA (79 000 ha). The total surface water entitlement (SW) is 629 GL, the total bulk water license. The sustainable groundwater volume $GW^{(sy)}$ is set as the extraction limits before and after the Plan. A typical value of 471.2 GL is used as the extraction limit before the Plan while the extraction limits of the Plan are as given in Supplementary Table 1.

The value of temporary traded water was estimated using a regression model involving the monthly average water trade price and water allocation data from the years 2001/2002 to 2005/2006. The resulting high R^2 value (0.93) indicates that water allocation is the key

Table 1 Estimated water yield production function for the main crops in CIA

Crop	Production function
Wheat	$-0.005 W^3 + 0.008 W^2 + 0.974 W$
Barley	$-0.004 W^3 + 0.007 W^2 + 0.874 W$
Maize	$-0.011 W^3 + 0.128 W^2 + 0.724 W$
Soybean	$-0.005 W^3 + 0.079 W^2 + 0.029 W$
Lucerne	$-0.020 W^3 + 0.315 W^2 + 0.640 W$
Onions	$-0.003 W^3 + 0.790 W^2 + 1.145 W$
Potato	$-0.006 W^3 + 0.365 W^2 + 1.448 W$
Winter pasture	$-0.042 W^3 + 0.377 W^2 + 0.930 W$
Tomato	$-0.003 W^3 + 0.790 W^2 + 1.145 W$
Rice	$-0.007 W^3 + 0.120 W^2 + 0.345 W$

Source: SWAGMAN-Destiny model outputs

factor determining the water market price. The following estimated function was used in the application of the model:

$$p^{(t)} = 407.72 - 10.17A + 0.07A^2 \tag{13}$$

where A is the general security water allocation (%) in a given month.

4 Results and Discussion

The optimisation model, in general, is assumed to have a short term focus and are estimated under the assumption of a relevant output price range and relatively inelastic demand for water. Over the years 2008–2012 the average price of surface water including fixed and variable charges was AUD 35.65 per ML. It is desirable when dealing with optimisation problems that the global optimum be found. To search for the global rather than local optimum, we used the median values of crop water use as starting values. Average crop water use can be found in CICL (2013).

Computer codes for the SQP algorithm are written in MATLAB® language. Supplementary Fig. 3 displays the convergence behaviour of the algorithm applied to the present NLP model at two surface water allocation levels. It can be seen that the algorithm converges well to the maximum value of the objective function after about 210 and 70 iterations at 10 % and 50 % surface water allocation, respectively. At a certain surface water allocation level, the NLP model is firstly run with surface water use only ($\gamma = 1$) to obtain the corresponding TGM of surface water use. We then run the model with conjunctive water use by gradually decreasing the value of water use ratio ($\gamma < 1$). At each value of γ we can obtain the corresponding TGM of conjunctive water use and the optimal value of γ is determined as the value that yields the maximum TGM. The additional economic benefit of groundwater (“groundwater benefit”) owing to conjunctive water use is defined as the difference between the TGM of conjunctive water use and the TGM of surface water use only:

$$\text{Groundwater benefit} = \text{TGM}(\text{conjunctive water}) - \text{TGM}(\text{surface water}). \tag{14}$$

We define “conjunctive benefit” as the difference between the maximum TGM of conjunctive water use and the TGM of surface water use only:

$$\text{Conjunctive benefit} = \text{maximum TGM}(\text{conjunctive water}) - \text{TGM}(\text{surface water}). \tag{15}$$

The economic benefit of conjunctive water use can refer to both the groundwater benefit and conjunctive benefit. Groundwater demand can be determined by the optimal value of γ and the surface water use.

Surface water usually has a lower price compared to groundwater owing to lower delivery and extraction costs. Groundwater can be expensive due to the pumping, social and environmental costs (Rogers et al. 2002). Here we estimate the groundwater and conjunctive benefit defined in Eqs. 14 and 15, respectively, in two scenarios of groundwater prices. Firstly we assume a fixed groundwater price which is the same as surface water price ($p^{(g)} = p^{(s)}$). We then increase the groundwater price via an increment coefficient β defined as follow.

$$\beta = \frac{p^{(g)} - p^{(s)}}{p^{(s)}}. \tag{16}$$

4.1 Economic Benefit of Conjunctive Water Use with a Fixed Groundwater

$$\text{Cost } p^{(g)} = p^{(s)}$$

Table 2 shows the economic benefit of conjunctive water use at different surface water allocation levels before the Plan. As expected, the conjunctive benefit is high at lower levels of surface water allocation compared to those at higher levels of allocation. The maximum benefit appears at 0 % surface water allocation with a negative value for the TGM of surface water use. The negative TGM is a result of the area constraint requiring the farmer to buy water at a high price for growing certain compulsory crops. The use of groundwater at 0 % surface water allocation can potentially result in a maximum economic benefit of AUD 57.29 million while the minimum benefit of AUD 9.35 million appears at 100 % surface water allocation. Groundwater demand reduces from the groundwater extraction limit at 0 % surface water allocation to 155 GL at 100 % allocation. In contrast to the conjunctive benefit, the total gross margin of conjunctive water use firstly increases as the surface water allocation increases to 50 % allocation then becomes flat. Supplementary Fig. 4 shows the proposed optimal cropping areas, associated water use and net profit of the seven crops at 10 %, 30 % and 50 % allocations, yielding TGMs of AUD 56.18, 63.60 and 70.53 million, respectively. At 10 % allocation, due to the shortage of surface water resources farmers make a tactical decision to grow crops with high net profits and the total cropping area is reduced to 53,536 ha which is smaller than the available cropping area in the CIA. The average profit for cropping land is high in this case and is estimated to be AUD 990.2 per ha. In contrast, at 50 % allocation, farmers have enough water resources to grow all crops on the 79,000 ha of available cropping area. The average profit for cropping land for this scenario is estimated to be AUD 883.4 per ha. It is noted that even though the net profit of maize might be high compared to wheat as shown in the case of 50 % allocation (Supplementary Fig. 4c) the cropping area of maize at 30 % allocation is zero due to the area constraint between maize and soybean (Supplementary Fig. 4a). The area constraint also results in the area of soybean exceeding that of maize in the case of 50 % allocation (Supplementary Fig. 4a) even though soybean has a higher water use requirement (Supplementary Fig. 4b) and yields lower net profit (Supplementary Fig. 4c).

Table 2 Economic benefit of conjunctive water use for different levels of surface water allocation

Surface water allocation	TGM of surface water use (AUDm)	Optimal γ	Groundwater demand (GL)	TGM of conjunctive water use (AUDm)	Conjunctive benefit (AUDm)
0 %	-3.51	0	471.20	53.78	57.29
10 %	12.63	0.12	454.67	56.18	43.54
20 %	20.43	0.21	466.48	60.70	40.27
30 %	28.14	0.29	455.38	63.60	35.46
40 %	34.40	0.36	440.89	66.39	31.99
50 %	38.58	0.41	465.00	70.53	31.96
60 %	43.42	0.48	403.00	70.29	26.86
70 %	47.70	0.56	341.00	70.18	22.48
80 %	52.64	0.64	267.08	70.21	17.58
90 %	56.83	0.73	206.38	70.22	13.39
100 %	61.35	0.80	155.00	70.70	9.35

Figure 2 presents the marginal value of groundwater and its linear fitting lines for three levels of surface water allocation. The lines are in agreement with expectation as the derived willingness to pay for the groundwater increases as the surface water allocation decreases. In each surface water allocation level, the groundwater marginal value decreases as the groundwater demand increases. The groundwater benefits as functions of groundwater demand are presented in Fig. 3. It can be seen that the groundwater benefit for a certain volume of groundwater depends on surface water allocation level. The groundwater benefit is higher at lower surface water allocation level (10 %) compared to those at higher allocation levels (50 % and 80 %). Fig. 3 also allows us to predict the groundwater benefit in the reduction of the extraction limit following the implementation of the Plan.

4.2 Economic Benefit of Conjunctive Water Use with Increasing Groundwater Costs

Groundwater is accessed by pumping for which various forms of energy are used e.g. diesel, electricity generated from fossil fuels or solar panels, or wind energy. The cost of using energy, particularly that derived from fossil fuels, is predicted to increase significantly in the future. In such a scenario the conjunctive water use benefit including groundwater and conjunctive benefit might reduce significantly due to the increasing cost of accessing

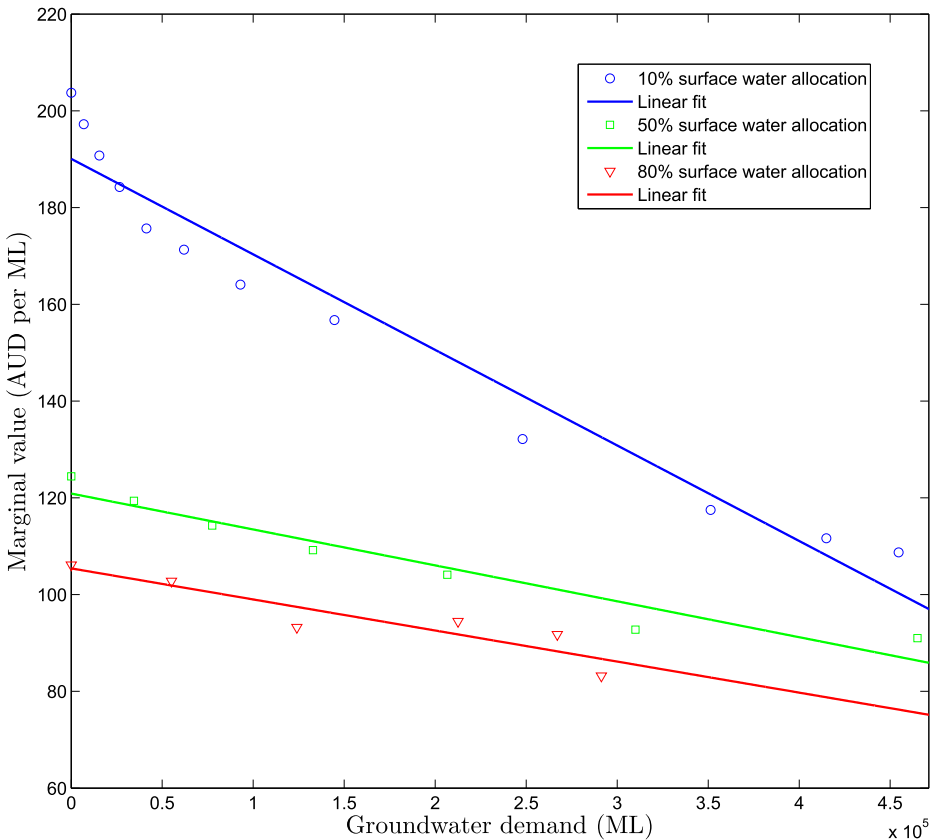


Fig. 2 Groundwater demand lines for three levels of surface water allocation

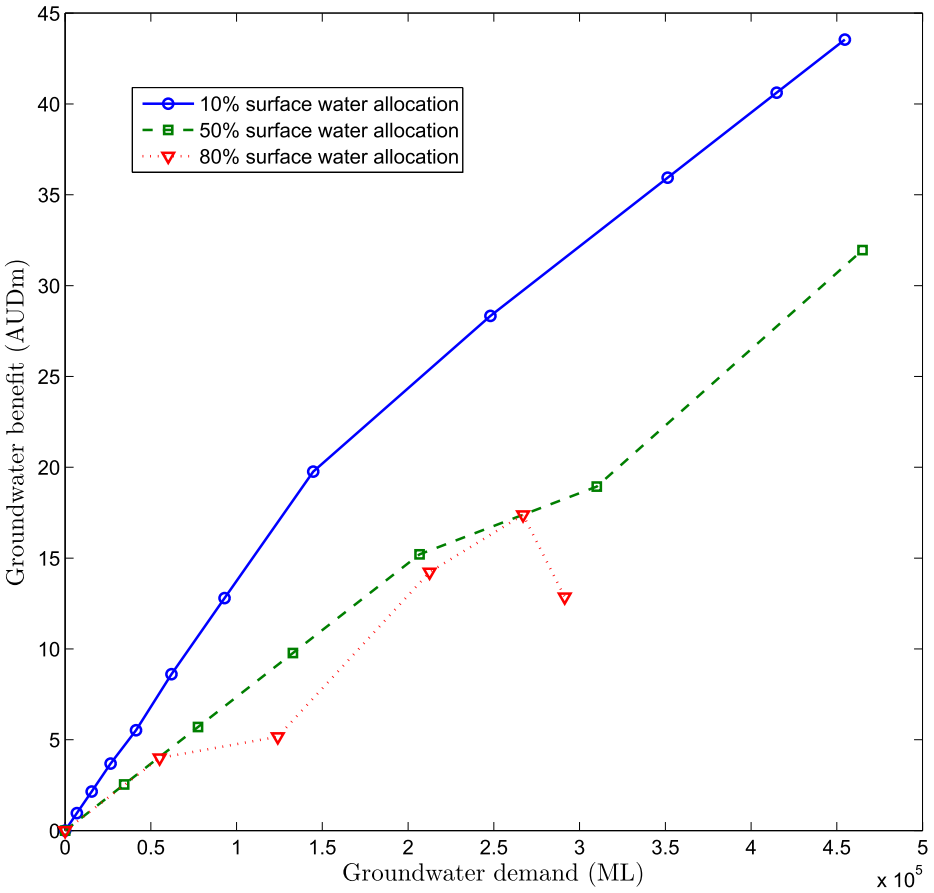


Fig. 3 Groundwater benefits for three levels of surface water allocation

groundwater and the cost of groundwater drawdown if not managed sustainably. Figs. 4 and 5 show the effect of increasing groundwater cost on the groundwater benefit and economic water productivity of groundwater at different water ratios for 10 % and 50 % surface water allocations, respectively. It can be seen that the groundwater benefit and economic water productivity reduce significantly with increasing groundwater cost. For the groundwater benefit in Fig. 4, the effect of increasing groundwater cost is more significant at smaller values of water ratio, i.e. more groundwater use. For example, at 10 % surface water allocation (Fig. 4a) and $\gamma = 0.2$ (i.e. conjunctive water use of 20 % surface water and 80 % groundwater), the groundwater benefit at $\beta = 0$ ($p^{(g)} = p^{(s)}$) is about AUD 28 million. However, when we increase groundwater price by 60 % ($\beta = 0.6$) and 200 % ($\beta = 2$) the groundwater benefit reduces to AUD 23 million and AUD 11 million, respectively. In the same manner, at 50 % surface water allocation (Fig. 4b) and $\gamma = 0.5$ (i.e. conjunctive water use of 50 % surface water and 50 % groundwater), the groundwater benefit reduces from AUD 23 million at $\beta = 0$ to AUD 16 million and AUD 9 million if the groundwater price increases by 60 % and 120 %, respectively. For the economic water productivity of groundwater in Fig. 5, the effect of increasing groundwater cost is almost similar at different conjunctive

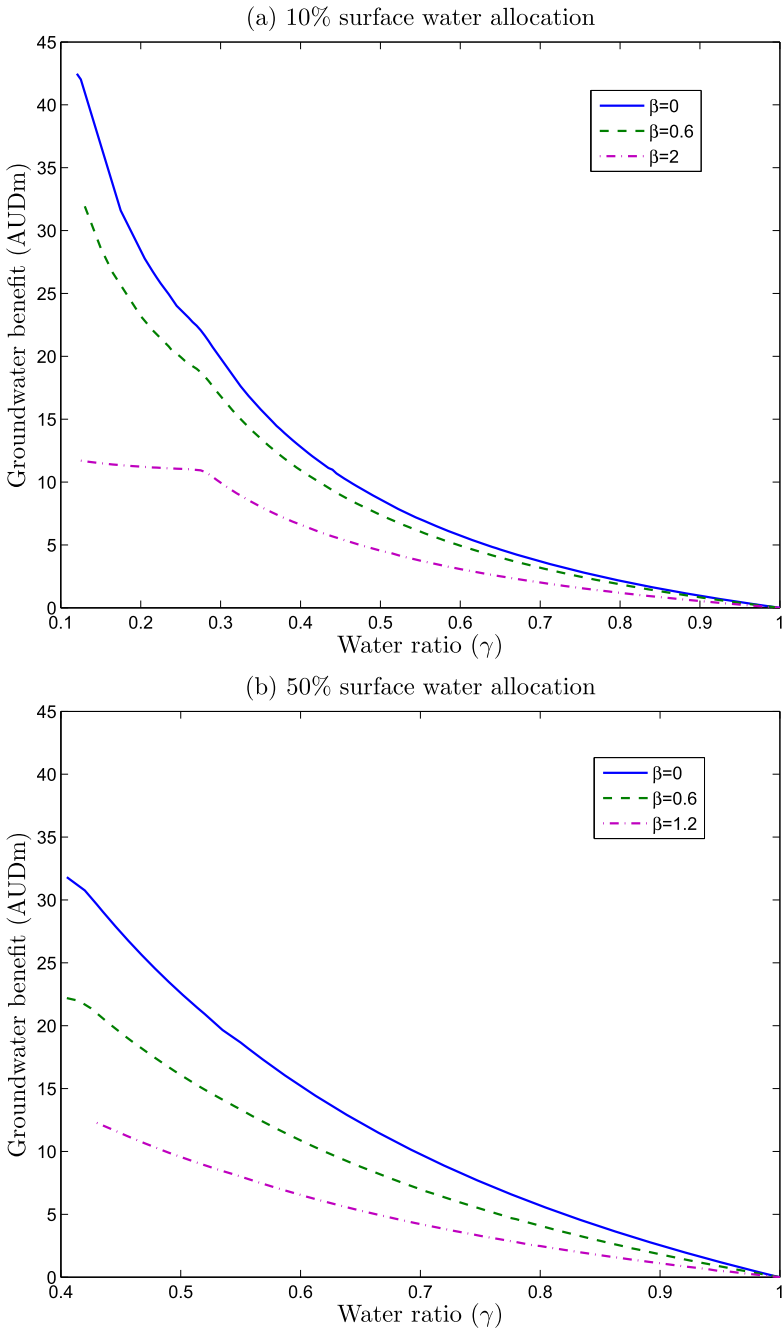


Fig. 4 Effect of increasing groundwater costs on the groundwater benefit. **a** 10 % surface water allocation. **b** 50 % surface water allocation

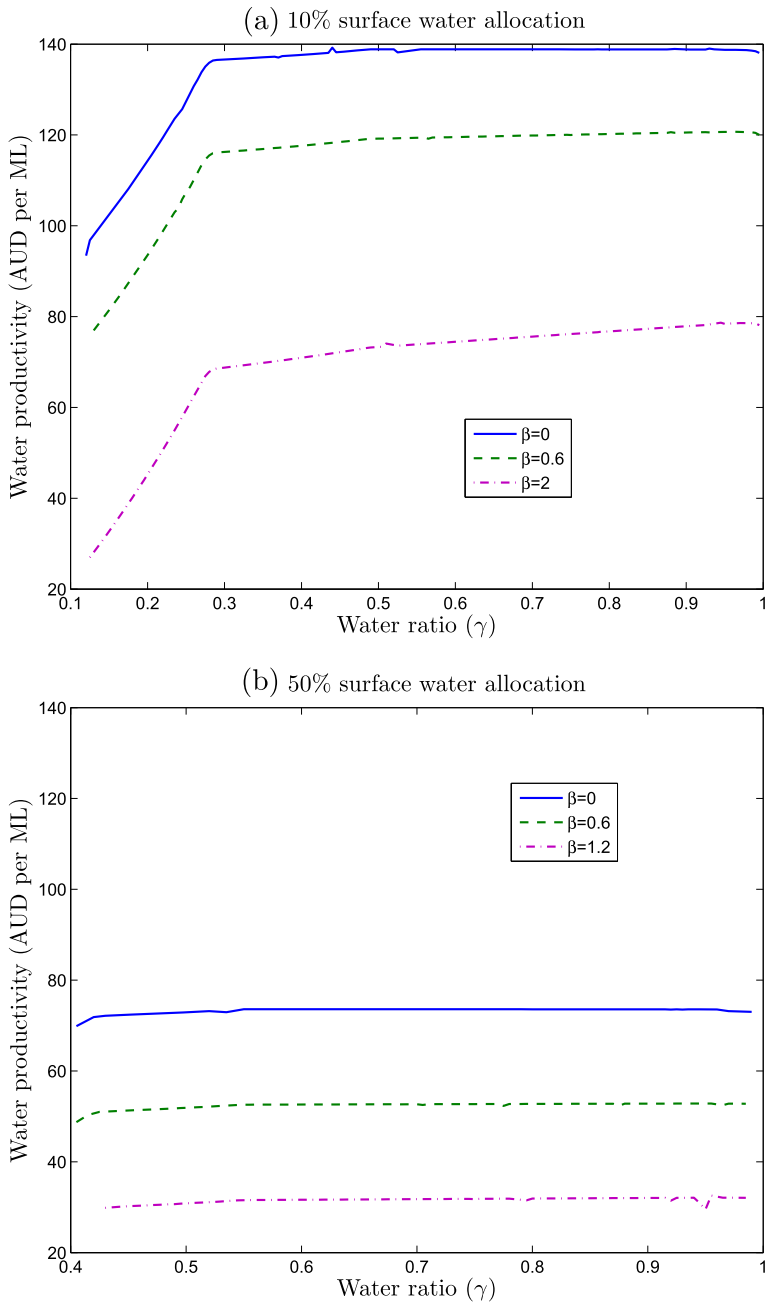


Fig. 5 Effect of increasing groundwater costs on the economic water productivity of groundwater. **a** 10 % surface water allocation. **b** 50 % surface water allocation

water use options (water ratios). At 10 % surface water allocation (Fig. 5a), the economic water productivity of groundwater reduces about AUD 20 per ML if the groundwater price increases by 60 % and about AUD 60 per ML if the groundwater price increases by 200 %. At 50 % surface water allocation (Fig. 5b), the reduction amount is about AUD 20 per ML if the groundwater price increases by 60 % and about AUD 40 per ML if the groundwater price increases by 120 %.

The present NLP model can provide a detailed projection of conjunctive benefit according to the groundwater cost increment as shown in Fig. 6. Conjunctive benefit decreases significantly according to the increment of groundwater prices (β). Zero conjunctive benefit appears at $\beta = 2, 2.1$ and 4.2 (at 200 %, 210 % and 420 % increment of groundwater price) for 10 %, 50 % and 90 % surface water allocation, respectively.

The effect of increasing groundwater costs on the net profit of each crop are presented in Table 3 for the case of 50 % surface water allocation. The net profits of all crops reduce significantly when the groundwater cost increases. It can be seen that soybean and wheat are most sensitive to increasing groundwater costs with 87.4 % and 30.8 % reduction in net profit respectively when the groundwater cost doubles while tomato is least sensitive with 8.1 % reduction. The high sensitivity of soybean and wheat is explained by the low yield values obtained (3.2 and 5.0 tonne per ha, respectively) compared to other crops, while tomato showed the highest yield at 58.0 tonne per ha. The effects of increasing groundwater cost on farm business income at various surface water allocation levels are presented in Table 4. It can be seen that increases in groundwater costs would significantly impact return especially in seasons which rely heavily on groundwater pumping i.e. with low surface water allocations. Indeed, 100 % increase in groundwater cost would reduce the farm business income by 34.7 %, 23.2 % and 10.3 % at 10 %, 50 % and 90 % surface water allocation, respectively. In general, lower levels of surface water allocation result in increased sensitivity of

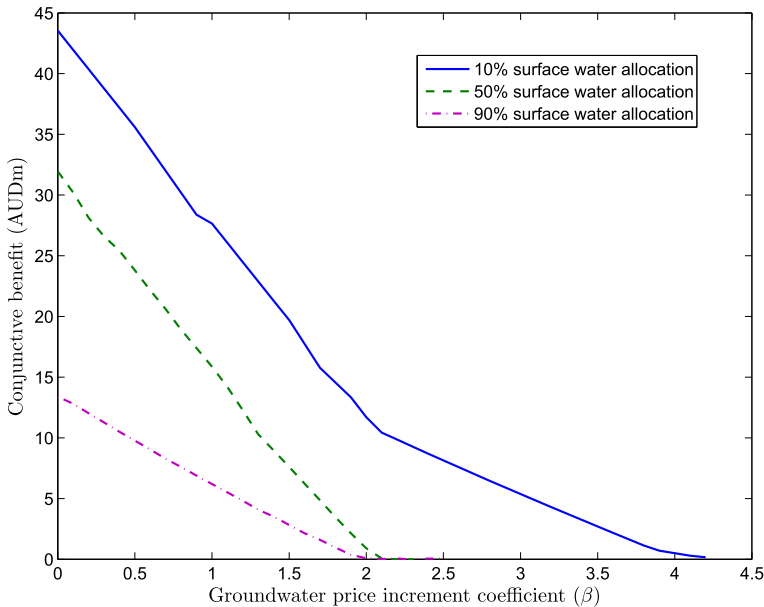


Fig. 6 Effect of increasing groundwater costs on the conjunctive benefit for three levels of surface water allocation

Table 3 Effects of increasing groundwater cost on the net profit of each crop at 50 % surface water allocation

		Net profit (AUD/ha)												
β (%)	Wheat	%	Maize	%	Soybean	%	Pasture	%	Lucerne	%	Rice	%	Tomato	%
0	413	-	1,211	-	245	-	822	-	1,442	-	927	-	2,110	-
20	387	-6.3	1,170	-3.4	202	-17.6	794	-3.4	1,395	-3.3	872	-5.9	2,076	-1.6
40	362	-12.4	1,130	-6.7	160	-34.7	765	-6.9	1,348	-6.5	816	-12.0	2,041	-3.3
60	337	-18.4	1,075	-11.2	117	-52.2	737	-10.3	1,301	-9.8	761	-17.9	2,007	-4.9
80	312	-24.5	1,049	-13.4	74	-69.8	708	-13.9	1,255	-13.0	705	-24.0	1,973	-6.5
100	286	-30.8	1,008	-16.8	31	-87.4	679	-17.4	1,208	-16.2	650	-29.9	1,939	-8.1

Table 4 Effects of increasing groundwater cost on the total gross margin (TGM) of conjunctive water use

β (%)	TGM at various surface water allocation (AUDm)					
	10 %	%	50 %	%	90 %	%
0	56.18	–	70.53	–	70.22	–
20	53.00	–5.7	67.26	–4.6	65.40	–6.9
40	49.82	–11.3	63.99	–9.3	67.32	–4.1
60	42.23	–24.8	60.66	–14.0	61.61	–12.3
80	37.92	–32.5	57.44	–18.6	64.41	–8.3
100	36.68	–34.7	54.17	–23.2	62.96	–10.3

farm business income to the groundwater cost. It is noted that the estimations here are based on the assumption of a specific surface water price. The reduction in farm business income might be more severe if the surface water price increases.

4.3 Discussion

The model developed in this study can be applied to any irrigation command area to help farmers in making management decisions for irrigation and productivity in the face of the climate variability and increasing energy prices. The irrigation management capability of the model enables an optimal and sustainable volume of groundwater use to be determined for a given or projected level of surface water availability; it also takes into account the impact of energy prices on the net economic return. Such capability helps reduce the risk associated with the high variability of surface water supply and increases in groundwater cost. The decisions around optimising productivity (e.g. crop type, cropping area, crop water use) are endogenous outputs of the model which are valuable for farmers. As an example, in Supplementary Fig. 5, we compare the model results of land and water use for several crops with those reported for the CIA in the irrigation year 2011/12 (CICL 2012). The surface water allocation is assumed to be the average surface water allocation from Supplementary Fig. 2 which is about 50 %. It can be seen that there is a potential improvement in productivity using the model to determine optimal levels of land and water use at the regional level. Model results encourage the increase of crop areas to high value crops such as paster and rice. In regards to potential for improved crop water uses, model results suggest potential to reduce water use for rice while allocating more water to other crops such as wheat, maize and pasture to increase economic returns of the CIA irrigation system.

5 Conclusions and Policy Implications

We have developed a nonlinear programming model as an innovative tool for the optimisation of productivity in an irrigation command area with conjunctive water use. The model uses production and profit functions to estimate yield and gross margins for various water allocation levels, which is conceptually different from the commonly used approach based on given crop yields and gross margins. The model has been applied to the CIA and has been proven able to project the conjunctive water use benefit, marginal value of groundwater at different surface water allocation and groundwater demand levels. The conjunctive water use benefit in the scenario of increasing groundwater costs is also considered which shows

remarkable reductions in the benefit with the increasing groundwater prices. The increase in groundwater costs also significantly reduces the net profit of each crop and farm business income. Critically, the current model can be integrated with a surface water forecasting model for the effective management of water resources in an irrigation command area such as the CIA.

With regard to the policy implication of this study, the findings raise some concerns for governments as to whether or not they should provide additional support to farmers to develop conjunctive water use system in the face of projected increase in energy prices. It can be seen that conjunctive water use is necessary for agricultural production in regions with low surface water allocations and uncertainty of surface water supply due to climate change. However, careful economic benefit estimation incorporating increases in energy prices and associated environmental impacts is a critical step before the implementation of such irrigation systems.

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