Cooperative Research Centre for Sustainable Rice Production

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Program 1: Sustainability of Natural Resources
Project 1201: Optimising Agronomic Options at the Farm Scale

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INTRODUCTION

Large parts of the irrigation areas of the Murray Darling Basin have shallow watertables that threaten crop productivity and financial sustainability of irrigated agriculture due to soil salinisation and waterlogging.

Planning for environmentally sustainable and economically viable management of these problems requires the development, testing and application of mathematical models which can integrate our understanding of water and salt movement with economic assessment of different cropping decisions at a farm scale.

These mathematical models can help in proper selection of agronomic and engineering options to reduce recharge to aquifers and rise of watertables and thereby minimise waterlogging and salinity problems.

This paper gives mathematical details and sample applications of SWAGMAN (Salt Water and Groundwater Management) Farm, a farm scale hydrologic economic model that integrates agronomic, climatic, irrigation, hydrogeological and economic aspects of irrigated agriculture. Optimum land uses for a given farm are determined by optimising an economic objective function using mixed integer non-linear optimisation techniques.

SWAGMAN-Farm has been applied to several farms in irrigated areas of southeast Australia. Model results show that for given hydro-climatic and irrigation conditions some land use types result in overall discharge from soil and groundwater while others induce groundwater recharge: a proper selection of crops can help reduce waterlogging and salinity problems and ensure economic viability of farms.

PROBLEM STATEMENT

Some whole farm linear optimisation bioeconomic models have been developed to deal with whole farm planning issues in dry land agriculture, such as MIDAS (Model of Integrated Dry Land Agriculture Systems) [3].

However these models cannot be used to devise appropriate farm management strategies for irrigated agriculture under shallow watertable conditions due to the complex and different nature of associated hydrological processes (FIGURE 1). Different paddocks on an irrigated farm have different soil types and hydrogeological conditions.

During cropping and fallow periods, water and salt balances under a paddock depend on land use, soil type, changes in soil water content, duration of cropping period, surface runoff, rainfall, evapotranspiration, amount of irrigation, depth to watertable, leakage rates between the shallow and deep aquifers, watertable salinity and leaching fractions.

Environmental factors such as watertable rise and soil salinity changes in a given year, irrigation allocation, farmer preferences, district policies, groundwater pumping options, interaction with deeper aquifers and soil suitability for different crops are some of the constraints on the sustainability of a farm.

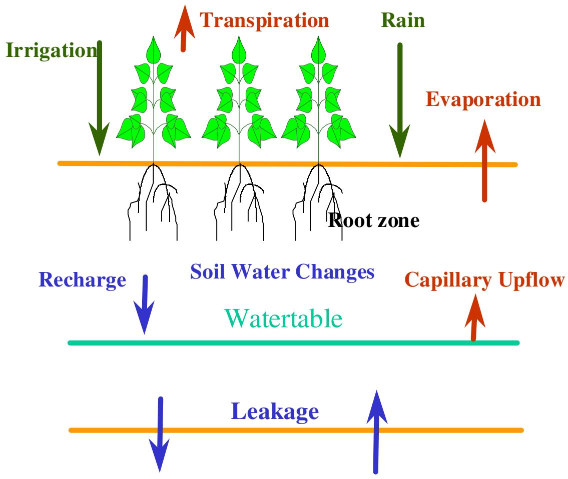

FIGURE 1 - Schematic diagram showing biophysical processes under shallow watertable conditions

The crops selected in a given year can include irrigated rice, soybean, maize, sunflower, fababean, canola, wheat, barley, hay lucerne, grazed lucerne, annual pasture, perennial pasture and dry land wheat and annual pasture.

Each of these crops has different gross margins and therefore offers different incentives to farmers. For example rice may be financially the most beneficial of the crops listed above (gross margin/ha ~$935). The hydrologic economic problem shown in FIGURE 1 can be defined as:

> "Selection of those land uses (crops) for which economic returns are optimum and for which watertable rise and root zone salinity changes are within allowable limits."

1. *Problem Formulation*

The objective function for the hydrologic economic problem solved in SWAGMAN Farm is given by EQUATION 1.

$$TGM = \sum_{C}\sum_{S} X_{C,S}(GMLW_C - IRRN_{C,S} * WPRICE) \quad (1)$$

where TGM = Total gross margin ($), $X_{c,s}$ = Area of a land use C on soil type S, ha $GMLW$ = Gross margin of a land use less cost of irrigation water, $/ha $IRRN_{c,s}$ = Irrigation of land use C on soil type S, ML/ha , $WPRICE$ = Price of water, $/ML , C = Land uses in a farm, S = Soil types in a farm.

The above objective function is optimised subject to the following constraints:

Constraint 1: Change in salt concentration in the root zone is less than or equal to allowable change.

$$\Delta Salt \leq ASRISE \quad (2)$$

where $\Delta Salt$ = change in salt concentration and $ASRISE$ = allowable change.

Constraint 2: Change in water table level is less than or equal to the allowable change.

$$\Delta WT \leq ADWT \tag{3}$$

where ΔWT = change in water table level and $ADWT$ = allowable change.

Constraint 3: Area of a land use is constrained between maximum and minimum areas.

$$\begin{aligned} XC_c &\geq MinArea_c \\ XC_c &\leq MaxArea_c \end{aligned} \tag{4}$$

where XC_c = area of land use C, $MinArea_c$ = minimum area allowed for land use C and $MaxArea_c$ = maximum area allowed for land use C.

Constraint 4: Water allocation to the farm should be greater than or equal to water used for irrigation.

$$\sum_{c,s} X_{c,s} \times IRRN_{c,s} \leq WALL \tag{5}$$

where $IRRN_{c,s}$ = Irrigation water applied to land use C on soil S (ML/ha) and $WALL$ = Water allocated to the farm (ML).

Constraint 5: Sum of areas of all land use types is equal to the total area of the farm.

$$\sum_{c,s} X_{c,s} = Area \tag{6}$$

where $Area$ = total farm area (ha).
Constraint 6: Binary constraints to ensure a minimum land use area if crop area enters the solution vector.

$$\begin{aligned} -XC_c + MinArea &\leq Area \times Y_c \\ XC_c &\leq Area \times (1 - Y_c) \end{aligned} \tag{7}$$

where $MinArea$ = minimum area allowed for any crop in the solution vector and Y_c = binary variable for land use C.

The water and salt balances are defined in the mathematical model on a lumped basis using the results of detailed monitoring [4,5,8], and hydrological modelling [9,10].

The component matrices of water and salt balances are computed for the cropping and fallow periods for all soil and crop combinations. EQUATION 1 with biophysical constraints is solved to find the optimum mix of land uses.

2. Mathematical Solution

The mathematical solution to the Mixed Integer Non Linear Problem [MINLP] (EQUATION 1) is found using the DICOPT (DIscrete and Continuous OPTimser) solver [2] under a GAMS [1] environment. DICOPT starts solving the MINLP using the MINOS5 NLP solver by relaxing 0-1 on the binary variables. If the solution to this problem results in an integer solution the search stops. Otherwise the search is continued with an alternating sequence of non linear (NLP) and mixed integer (MIP) programs. The MIP used by DICOPT is the IBM Optimisation Subroutine Library (OSL).

3. *Description of a Typical Case*

A typical irrigated farm in the Southern Murray Darling Basin has been studied using the optimisation model described above. The total area of the farm is 306 ha and soil types consist of 50 ha of Self Mulching Clays (SMC), 114 ha of Non Self Mulching Clays (NSMC), 80 ha of Red Brown Earths (RBE) and 62 ha of Transitional Red Brown Earths (TRBE). The depth to the watertable under the farm is 2.0 m and salinity of the groundwater is 10 dS/m. The total water allocation of the farm is 1500 ML. The leakage rate under the farm is 0.3 ML/ha per year. The salinity of irrigation water is 0.07 dS/m and salinity of rainfall is 0.01 dS/m. The allowable average watertable rise under the farm is specified as 0.25 m and the allowable increase of root zone salinity is 0.25 dS/m. The maximum area of any one crop is restricted to 110 ha.

Average initial soil water content under the farm is assumed to be 0.3. Average climatic conditions with annual rainfall of 407 mm and 1779 mm of reference evapotranspiration are assumed.

The optimisation model is formulated in GAMS and solved using DICOPT. The statistics of the optimisation model are given in TABLE 1. The progress of optimisation of the objective function using NLP (MINOS5) and MIP (OSL) is given in FIGURE 2.

TABLE 1

MODEL STATISTICS

Blocks of equations	32	Single equations	116
Blocks of variables	23	Single variables	139
Non zero elements	1236	Non linear N Z	6
Derivative pool	5	Constant pool	13
Code length	90	Discrete variables	17

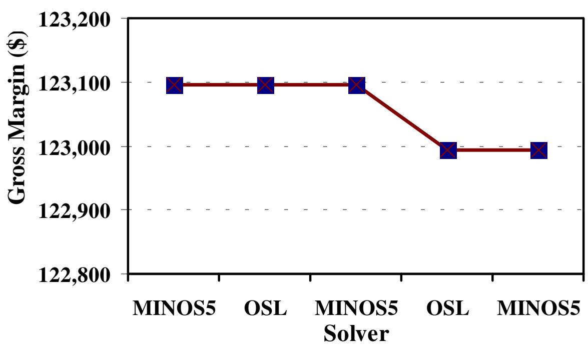

FIGURE 2. Variation of objective function during the DICOPT solution.

The model selected land uses corresponding to an optimum gross margin of $123096 as shown in TABLE 2.

TABLE 2

OPTIMUM SELECTION OF LAND USE (ha)

Land use	Soil Type			
	SMC	NSMC	TRBE	RBE
Rice	50	14	-	-
Canola	-	29	-	80
Dry Wheat	-	71	-	-
Hay Lucerne	-	-	62	-

Due to higher associated gross margins, rice is the most financially attractive land use but its maximum area is restricted due to the constraint on watertable rise. The area of rice selected by the model is 64 ha. The rice area in this case is contributing an overall recharge of 169 ML whereas irrigated canola, dry wheat, and irrigated hay lucerne are discharging land uses with individual discharge of 37 ML, 24 ML and 30 ML respectively. The capillary upflows under the farm is 6.7 ML.

TABLE 3 shows a summary of the salt balance for the farm. The net increase in salts in the soil above the watertable is 152.86 tonnes. The main source of salt is capillary upflow under the farm. Recharge under the rice area during the irrigation and fallow periods partly removes (leaches) the salt brought by irrigation and capillary upflow.

TABLE 3

SALT BALANCE FOR THE EXAMPLE FARM (ALL VALUES IN TONNES OF SALT).

Irrigation Salt	Rainfall Salt	Capillary Upflow Salts	Total Salt Removed	Salt change in the root zone
67.20	7.98	142.5	64.82	152.86

4. Sensitivity of Parameters

Sensitivity analysis can be used to aid in model development, improved understanding of the systems, decision making and communication of results [6]. Another reason for carrying out sensitivity analysis is to test the robustness of non-linear optimisation solvers. The sensitivity analyses presented here include variation of irrigation water availability, salinity constraint, groundwater depth, salinity of groundwater, leakage rates to deeper aquifers and initial soil water conditions. In these model runs all data sets were kept identical to that described for the typical case unless mentioned otherwise. The results presented in the following paragraphs show only the sensitivity of the results to the area of rice selected and the optimum gross margins computed by the model. Other variables such as areas of different crops, water and salt balance are not reported in this paper.

4.1 Effect of water availability

FIGURE 3 shows that farm gross margin increases non linearly with increase in available irrigation water and area of rice.

The non linearity of FIGURE 3 can be explained by the fact that the net recharge to the watertable becomes a limiting factor and does not allow increase in rice area and other irrigated crops above the watertable rise constraint. The model does not allow the maximum area (110 ha) under rice even when sufficient irrigation water is available. This highlights the importance of the environmental constraints.

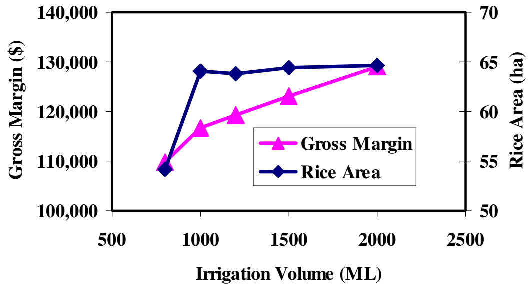

FIGURE 3. Sensitivity of gross margin and rice area to water availability

4.2 Effect of groundwater depth

A constant irrigation rate for rice (12 ML/ha) was used for all watertable depths. FIGURE 4 shows the effect of depth to watertable on the gross margin and optimum area of rice.

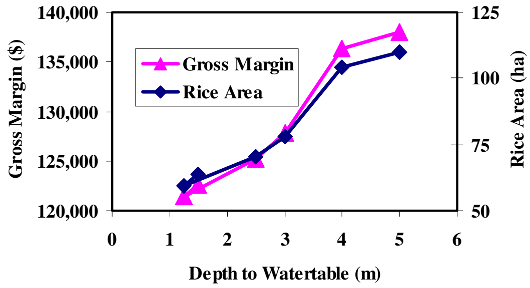

FIGURE 4 - Sensitivity of gross margin and rice area to depth to watertable.

The solution became infeasible for depth to watertable less than 1 m because any combinations of crops can not meet watertable constraints. For deeper depths to the watertable any excess irrigation water (irrigation+rainfall-evapotranspiration by the crop) applied to rice is used first to fill the soil profile. Once the soil profile is full the excess water becomes recharge and the rise of watertable. With increasing watertable depth the gross margins and rice area increase. However, the increases in rice areas and gross margin are relatively small watertable deeper than 4 m.

4.3 Effect of the groundwater salinity constraint

FIGURE 5 shows the effect of changing the limits on the allowable annual rise of root zodetermined by the model.
For the smaller values of the root zone salinity constraint the gross margin and total rice area are small. The solution becomes infeasible when the soil salinity constraint is set smaller than 0.05 dS/m. By increasing the allowable annual rise of root zone salinity a greater rice area is selected by the model because more salts are imported with increased irrigation for greater rice areas.

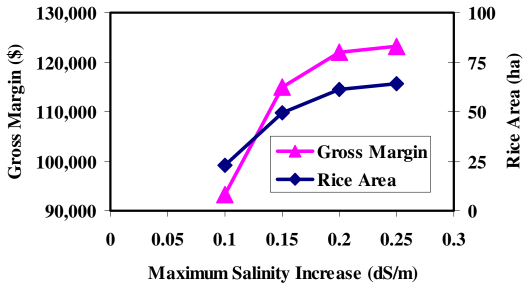

FIGURE 5 - Sensitivity of gross margin and rice area to salinity constraint.

4.4 Effect of leakage rates

FIGURE 6 shows the sensitivity of gross margins and rice area to leakage rates under the farm. Higher leakage rates to deeper aquifers allow more areas of rice and therefore higher gross margins. Under the higher leakage rates the net recharge and hence the net watertable rise is small. This sensitivity analysis clearly demonstrates the importance of aquifer interactions in investigating the sustainability of irrigated agriculture.

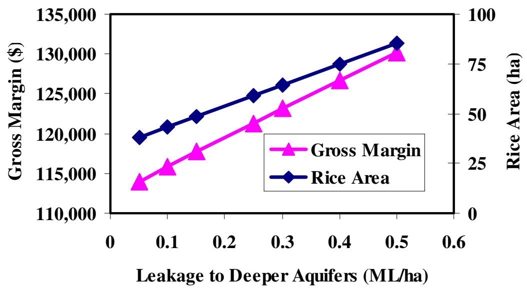

FIGURE 6 - Sensitivity of gross margin and rice area to leakage rate

4.5 Effect of initial soil water content

FIGURE 7 shows the effect of average soil water content on the gross margins and rice areas computed by the model.

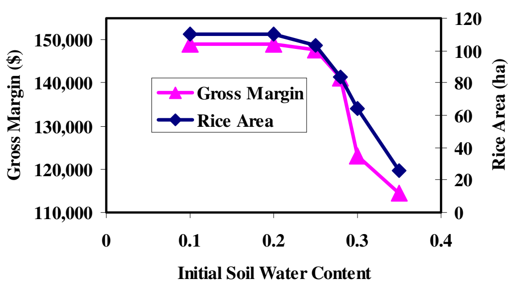

FIGURE 7 - Sensitivity of gross margin and rice area to initial soil water content.

Gross margin decreases with increasing average soil water content of the soil profile. This is explained by the fact that with higher soil water contents there will be higher recharge and net rise of watertable and therefore crop choice is limited to irrigated crops with lower water excess or dry land crops. In the case of lower initial soil water content a considerable amount of excess water will contribute to the soil water storage before adding to net recharge to the watertable.

4.5 Other sensitivity runs

A range of other sensitivity runs (not reported here) e.g. effect of different limits on watertable rise, pumping of groundwater, recycling of irrigation water, crop factors and climatic variability have also been carried out. These sensitivity checks also confirm the robustness of the optimisation routine and appropriateness of biophysical processes represented in the model.

CONCLUSIONS

The following conclusions are drawn from this study:

- The viability and sustainability of irrigated agriculture cannot be solely examined by economic techniques because of the environmental factors limiting future crop production.
- SWAGMAN Farm offers an excellent platform for investigating future implications of limiting available irrigation supplies.
- Wider application of SWAGMAN Farm will allow development of policy option matrices for different farm enterprises to ensure economic viability and environmental sustainability.
- Sensitivity analysis and sensibility checks of model parameters and results provide insight into the robustness of the non linear optimisation solvers.
- MINLP solvers offer tremendous potential for simulating complex hydrologic economic optimisation problems.

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