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OPTIMISING AGRONOMIC OPTIONS AT THE FARM SCALE

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Project title	Optimising Agronomic Options at the Farm Scale
Rice CRC project no.	1201
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Project collaborators	Mr Geoff McLeod (Murray Irrigation Limited) Mr Arun Tiwari (Coleambally Irrigation) Mr Peter King (Murray Irrigation Limited) Mr Max Goudie (Farmer representative) Mr Ian Gillett (Farmer representative) Mr Geoff Beecher (NSW Agr.)
Project duration	1st October 1998 and 30th September 2001

Summary

Strategic planning and policy development for environmentally sustainable and economically viable management options for the rice based farming systems require the assessment of management options using mathematical models which integrate our understanding of water and salt movement with economic considerations at both the farm and regional scales. This project also had strong links with LWRRDC/MIL/CSIRO project on optimising irrigation intensities in the Murray Valley. During this project a standalone farm scale hydrological economic model SWAGMAN Farm (Salt Water and Groundwater MANagement) was developed and customised for situations in the Coleambally and Murray Irrigation Areas. The model processes were developed and refined by using feed back from irrigation managers, regulators and community groups. The following major achievements have been made:

- Collection of crop, soil, irrigation, climatic and economic data sets for fourteen farms in the Murray Irrigation Districts
- Rigorous validation of model processes by applying the model to fourteen farms with a range of enterprise, soil and groundwater conditions.
- Development of simulation and optimisation modes in SWAGMAN Farm to assess environmental and economic impacts of existing and optimal cropping patterns
- Various improvements of water and salt balance processes to suit conditions in the Murray Districts and the Coleambally Irrigation Area
- Incorporation of soil water content accounting which provides flexibility in the representation of various starting soil profile water content conditions, water availability to crops and rational computation of recharge and watertable rise during the cropping and fallow periods
- Development of a Windows based GAMS independent version of SWAGMAN Farm. GAMS (General Algebraic Modelling System) was an expensive software platform for the previous version with inflexible licence requirements. The new version written in C++ language uses Microsoft Access databases and will be linked with a GIS interface in near future.

These sensitivity runs and model developments gained the confidence of members of the steering committee who provided vital inputs throughout this project. While considerable progress was made, they see the need for the work to continue to the stage where it can be applied to assist strategic planning and policy development, taking into account local regional conditions. Parallel to the modelling project an intensive paddock water monitoring project titled “Rigorously determined water balance benchmarks for irrigated crops and pasture’ was also initiated by the steering committee with the assistance of CSIRO, MIL, NSW Agriculture and LWRRDC. The purpose of the monitoring project was to further customise SWAGMAN Farm to local conditions and to validate the model results with the field data. Since monitoring projects take significant time in setting up and calibrating equipment, data analysis has only recently started, however initial comparisons of model results with the field results suggest that the improved SWAGMAN Farm can reasonably simulate field situations. However this work needs to continue to maximise the benefits of the paddock water balance monitoring.

However, due to the wide range of groundwater, enterprise and soil conditions in the irrigation areas, SWAGMAN Farm needs to be applied to every farm to develop soundly based policy options. The need for application to individual farms is further driven by the complex regional groundwater interactions causing reversal (downward to upward and local discharge zones) of leakage rates in parts of the irrigation areas e.g. Murray Valley.

This project has demonstrated that it is possible to develop methodology which helps assess optimal irrigation intensity within a multitude of biophysical and socio-economic constraints. The methods

developed have scientific validity in capturing and representing key processes, and have community acceptance as a way of examining options that are important to them.

Project objectives

- A computer model that can be used to assess the environmental impacts of on farm options to increase water use efficiency.
- Evaluation of agronomic options of net recharge management (different crop mix with rice areas)
- An enhanced understanding of recharge and discharge components under different climatic and management scenarios
- A model capable of providing bench marks for water auditing at a crop, farm and district level.
- An increased awareness and knowledge of the link between resource sustainability and water use efficiency.

Summary of methods and modifications

The SWAGMAN Farm model has been developed by considering a range of crops, soils, irrigation patterns, climate, watertable, and economic conditions in the Southern Murray Darling Basin. The methods used to develop a reliable policy tool included collection of baseline data for a number of farms, incorporating proper approximations to seasonal soil water content changes and refining definitions of fluxes to and from the watertable and associated salt movements. The new model can account for any initial soil water conditions and changes in the soil water content during the cropping and fallow periods and associated recharge to the watertables. A very active steering committee ensured scrutiny and debate of a number of sensitivity runs to guarantee sensibility of these model results. A user-friendly interface was developed for the model to ensure easy data input and visualisation of results. This has helped ensure adoption of the model to ensure adoption of model by the irrigation companies. An intensive paddock water monitoring project titled “Rigorously determined water balance benchmarks for irrigated crops and pasture” was initiated by the steering committee and resourced by MIL, to further validate and develop confidence in the model. Further details of methods and modifications are given in the following paragraphs.

(a) Collection of baseline data for fourteen farms.

Data sets on crops, soils, irrigation patterns, climate watertable, and economics were collected for fourteen farms in the Murray Irrigation Districts. These data sets have been used to rigorously test the validity of the SWAGMAN Farm model results for a large range of enterprise, soil, climate and groundwater conditions.

(b) Improvement of biophysical processes in SWAGMAN Farm

Soil water content and watertable rise

Soil water accounting processes were incorporated in the model to allow flexibility in the starting soil profile water content, and to improve the estimates of water availability to crops, recharge and watertable rise during both the cropping and fallow periods. Uptake of water by crops from the soil storage was specified in the model using the FAO guidelines (FAO, 1998).

Capillary upflow and salt transport processes

Capillary upflow and the associated salt transport in the root zone were improved based on simulations using a detailed process model, Hydrus 1-D, (time steps less than a day) of the US Soil Salinity Laboratory (Simunek et al, 1998). Model runs were carried out for seven land uses (fallow, maize, wheat, oats, lucerne, winter pastures and summer pastures) for five soil types (sandy soils, red brown earths, transitional red brown earths, non self mulching clays and self mulching clays) for six depths to watertable (0.5m, 0.75m, 1.5 m, 2.5 m and 3.0 m). This gave an array of 7x5x6=210 sets of detailed upward and downward water fluxes at the watertable. The results show significantly different volumes of capillary upflow and leakage varying with landuse (crop type, cropping or fallow period), soil type and groundwater level and salinity. For most landuses, when the watertable is 1m or less, capillary upflow volume is 0.5 to 1.5 ML/ha with 2 to 4 t/ha upward movement of salt for a groundwater salinity of 5 dS/m (e.g. Figs-1 and 2 for irrigated wheat). When the watertable is deeper than 1.5 m to 2 m, most land uses show negligible capillary upflows.

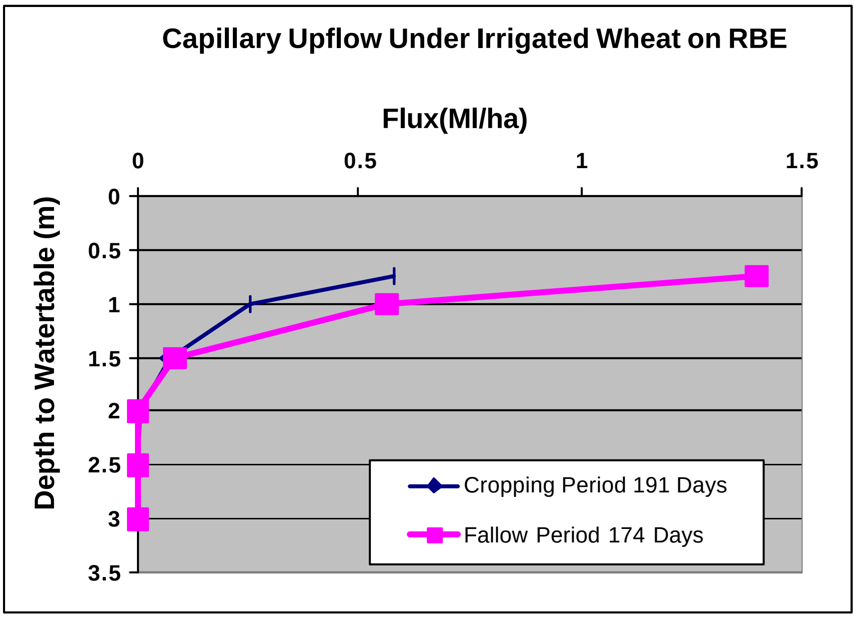


Figure-1 Cumulative capillary upflow as affected by depth to the watertable for irrigated wheat

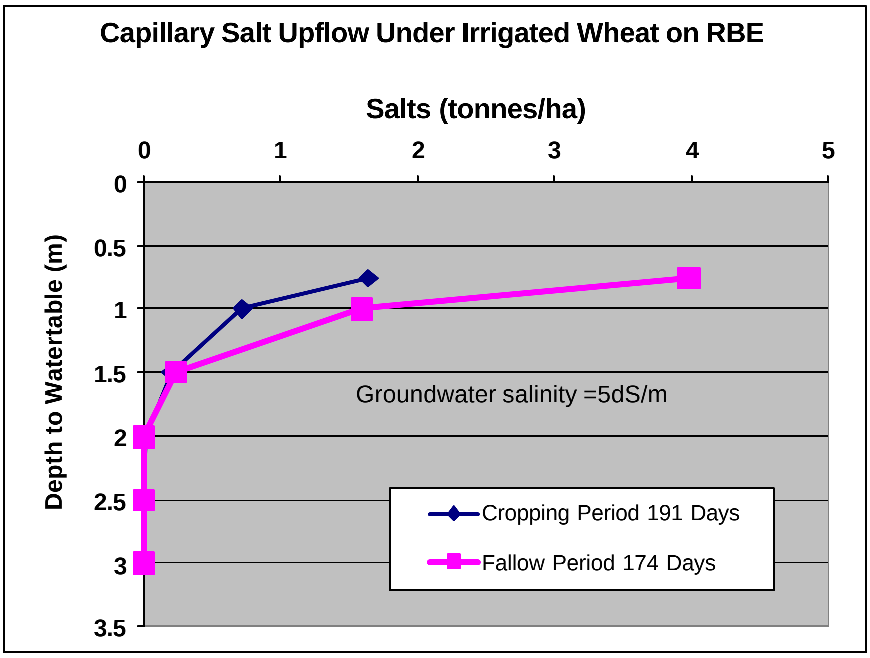


Figure-2 Cumulative Salt flux due to capillary upflow for irrigated wheat

The results of the Hydrus flux computations were used to develop capillary upflow curves for use in the lumped water and salt balance computations in SWAGMAN Farm. The curves were developed using the MODFLOW EVT (Evapotranspiration) approach (MacDonald and Harbaugh 1988).

Climatic variability

Decile and quartile methods were used to determine statistical distributions of rainfall and evaporation at several weather stations in the Coleambally, Murrumbidgee and Murray irrigation areas. The distributions were used to define very dry, dry, medium, wet and very wet rainfall and evapotranspiration years for the model, and weather data sets were prepared using these definitions.

(c) Model Runs and Sensitivity Analyses

The SWAGMAN Farm inputs were adjusted to provide regional and farm specific data for the model runs and sensitivity analyses. The sensitivity runs included changing depth to watertable, cropping patterns, initial soil water content, farm water use, deep leakage rates, groundwater salinity and climate. Hundreds of model runs and sensitivity analyses were undertaken using the baseline data for the 14 project farms. The sensitivity runs were carried out to test the model validity, to identify where improvements were needed, and to identify the parameters having the major influence on sustainability.

(d) Software Development.

Simulation and optimisation options in SWAGMAN Farm

Both simulation and optimisation modelling options were developed in SWAGMAN Farm. The simulation mode can be used to assess watertable, salinity and economic impacts of existing or nominated landuse, irrigation water use and seasonal weather conditions. When run in the optimisation mode the model determines the most profitable mix of landuses to avoid watertable rise and rootzone salinisation beyond nominated limits.

User interface

The post-processor graphics were enhanced to include a breakdown of total farm net recharge (Ml) and soil salinity changes into net recharge by crop (Fig-3).

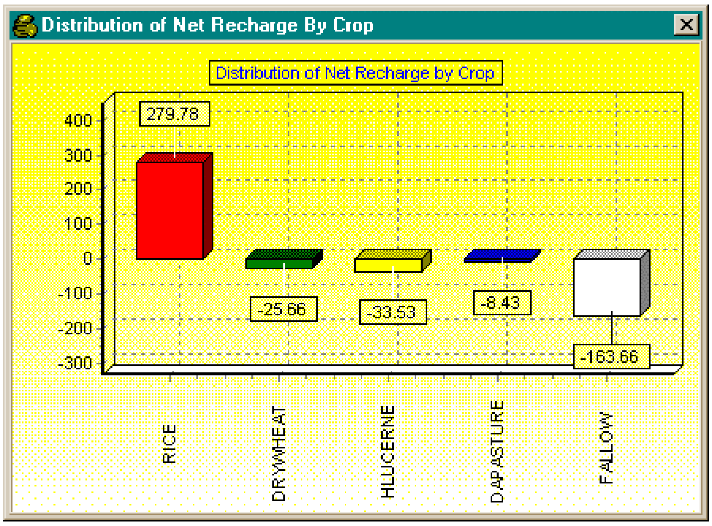


Figure-3 Example of SWAGMAN Farm Post Processing Graphics

SWAGMAN Farm mode suitable for distribution to irrigators

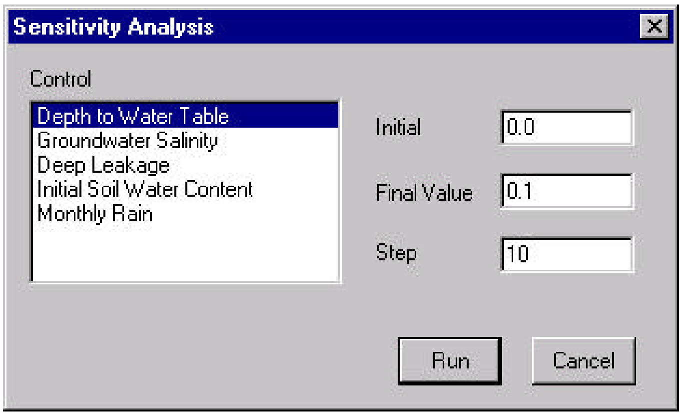
Through additional support from the Rice CRC it was possible to employ a full time programmer (Dr Fei Zhou) and develop a Windows based GAMS-independent version of SWAGMAN Farm. GAMS (General Algebraic Modelling System) is an expensive software platform with inflexible license requirements which was used for the previous version of SWAGMAN Farm. The new version is written in C++ language and could therefore be more freely distributed (eg. to farmers). It is envisaged that new version of SWAGMAN Farm will be distributed at cost to the irrigation companies and farmers in near future, on a CD.

GIS interface

The new C++ model has been interfaced with MS Access database for future linking with the irrigation company GIS databases. This will allow the model to be run for large numbers of farms, as Coleambally Irrigation Cooperative Ltd is starting to do.

Automatic sensitivity analyses

Sensitivity analyses can now be done automatically (sequentially) across a range of values for depth to watertable, groundwater salinity, deep leakage, initial soil water content and rainfall. They can be done in either the simulation or optimisation modes. In the sequential mode the model parameters are changed within the specified limits by the specified increments (Fig-4) and the results are stored in a log file. This is an important feature enabling identification of the critical parameters influencing the model results, and highlighting where effort needs to be expended in determining those parameters that will improve confidence in the model results.



Sensitivity Analysis

Control

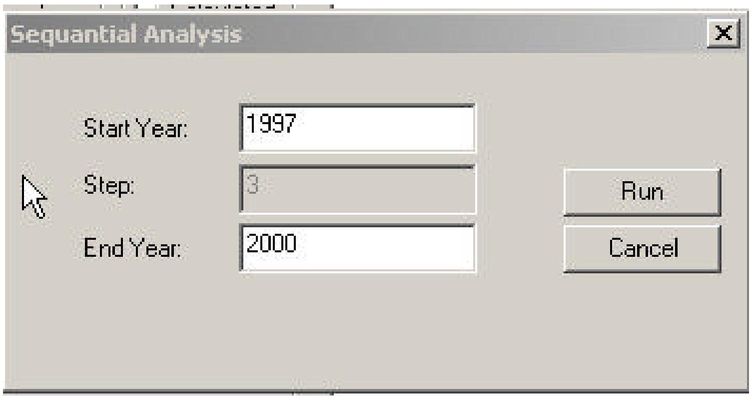
Depth to Water Table
Groundwater Salinity
Deep Leakage
Initial Soil Water Content
Monthly Rain

Initial: 0.0
Final Value: 0.1
Step: 10

Figure-4 Sensitivity analysis option in SWAGMAN Farm

Sequential analyses

Sequential analysis of a number of years of similar irrigation practices and rainfall scenarios can also be done. The model keeps track of soil water content and watertable changes and assigns starting soil water content and watertable conditions internally. This mode helps to understand impacts of a sequence of wet years and continuation of similar irrigation practices in future.



Start Year: 1997
Step: 3
End Year: 2000

Figure-5 Sequential analysis option in SWAGMAN Farm

(e) Comparison with field conditions

An intensive paddock water monitoring project titled “Rigorously determined water balance benchmarks for irrigated crops and pasture” was initiated by the steering committee and resourced by MIL, in recognition of the need for further validation to develop confidence in the model. The monitoring project was greatly enhanced with the assistance of LWRRDC, CSIRO, and NSW Agriculture, commencing in January 2000. The purpose of the monitoring project is to further customise SWAGMAN Farm to local conditions and to validate the model results with the field data. Since monitoring projects take significant time in setting up and calibrating equipment, data analysis has only recently started, however initial comparisons of model results with the field results suggest that the improved SWAGMAN Farm can reasonably simulate field situations.

(f) Stakeholder consultation, sensitivity analyses and adjustment of model parameters

The steering committee met on eight occasions during the life of this project (7 Sept. ‘98, 18 Dec ’98, 18 June ’99, 7 Sept ’99, 11 Nov 99, 4 Feb 2000, 16 June 2000, 10 Nov 2000). Project progress was reported at each meeting, and recorded in the meeting minutes (available on request). The results of the model runs were scrutinised and debated by the steering committee, which helped to identify where improvements were needed, and further questions which needed to be asked of the model (i.e. further sensitivity analyses) to help understand the factors influencing sustainability.

Results and Interpretations

In this section only a brief discussion and interpretation of results are given: for detailed results reference should be made to papers provided in the appendices.

Case study

A case study using the optimisation mode for a hypothetical irrigated farm in the Southern Murray Darling Basin is presented here. The total area of the farm is 306 ha with 50 ha of Self Mulching Clays (SMC), 114 ha of Non Self Mulching Clays (NSMC), 80 ha of Red Brown Earths (RBE), 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 annual 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. Initial soil water content under the farm is assumed to be 0.3 for all soil types. Average climatic conditions with annual rainfall of 407 mm and 1779 mm of reference evapotranspiration are assumed. The model selected land uses resulting in an optimum gross margin of $123,096 as shown in Table-1.

Table-1. Optimum selection of land use (areas in ha)

Land use	Soil Type				
	SMC	NSMC	TRBE	RBE	Total
Rice	50	14	-	-	64
Canola	-	29	-	80	109
Dry Wheat	-	71	-	-	71
Hay Lucerne	-	-	62	-	62
Total	50	114	62	80	306

Due to higher 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 the irrigated canola, dryland wheat, and irrigated hay lucerne are discharging land uses with individual discharges of 37 ML, 24 ML and 30 ML, respectively. The volume of capillary upflow under the farm is 6.7 ML. Table-2 shows a summary of the salt balance for the farm. The net increase in salt in the soil above the watertable is 153 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 into the unsaturated zone by rainfall, irrigation and capillary upflow.

Table-2. 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	+8	+143	-65	+153

Examples of results of sensitivity analyses

Effect of water availability. Figure 5 shows that farm gross margin increases non linearly with increase in available irrigation water and area of rice. The non linearity of Figure 5 can be explained by the fact that the net recharge to the watertable becomes a limiting factor and does not allow further increase in rice area and other irrigated crops due to the watertable rise constraint. The model does not allow the maximum specified area (110 ha) under rice even when sufficient irrigation water is available.

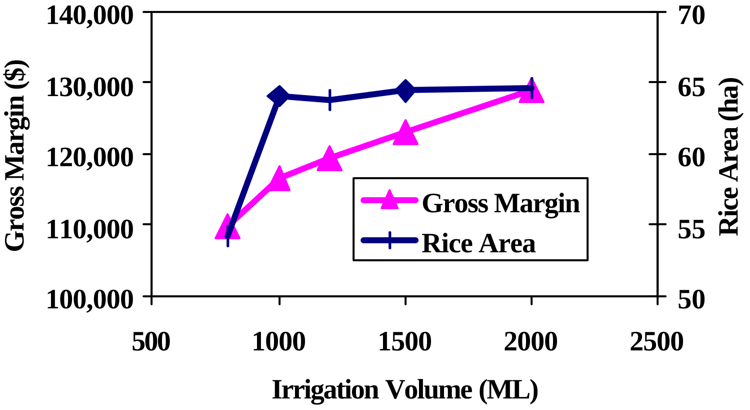


Figure-6. Sensitivity of gross margin and rice area to water availability.

Effect of groundwater depth. A constant irrigation rate for rice (12 ML/ha) was used for all watertable depths. Fig-6 shows the effect of initial depth to watertable on the gross margin and optimum area of rice. The solution became infeasible for depth to watertable less than 1 m because no combinations of crops can meet the watertable constraint. 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 causing the watertable to rise. With increasing watertable depth the gross margins and rice area increase. However, the increases in rice area and gross margin are relatively small for watertables deeper than 4 m due to the limited water availability.

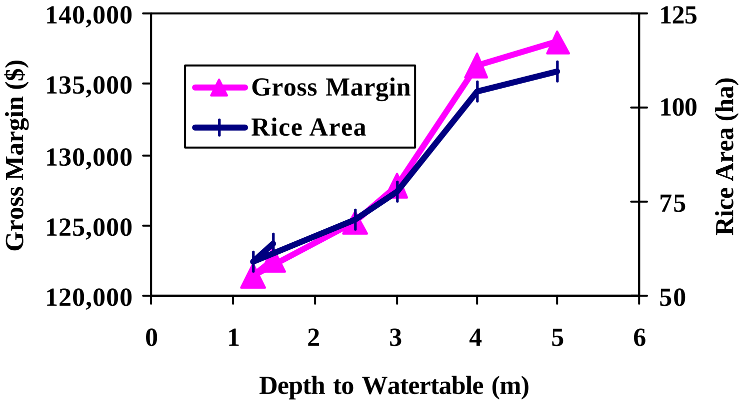


Figure-7. Sensitivity of gross margin and rice area to depth to watertable.

Effect of leakage rates. Fig-7 shows the sensitivity of gross margin and rice area to leakage rate under the farm. Higher leakage rates to deeper aquifers allow larger rice area and therefore higher gross margin. 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.

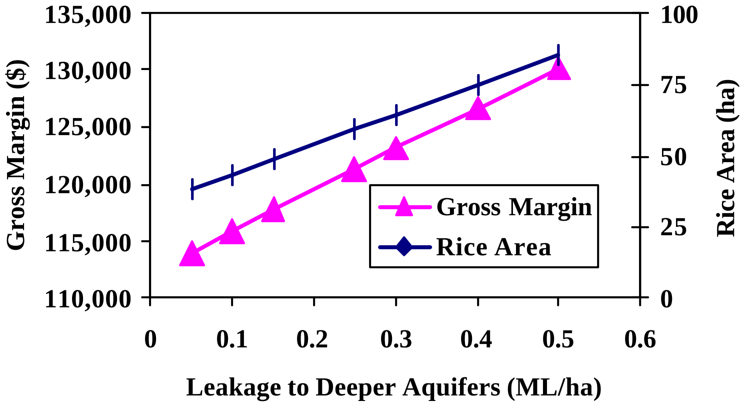


Figure-8. Sensitivity of gross margin and rice area to leakage rate

Effect of initial soil water content. Figure 8 shows the effect of initial soil water content on gross margin and rice area. Gross margin decreases with increasing initial soil water content. This is explained by the fact that with higher soil water contents there will be higher recharge and greater watertable rise and therefore crop choice is limited to irrigated crops with lower water excess or dryland crops. In the case of lower initial soil water content a considerable amount of excess water will contribute to the soil water storage before recharging the watertable.

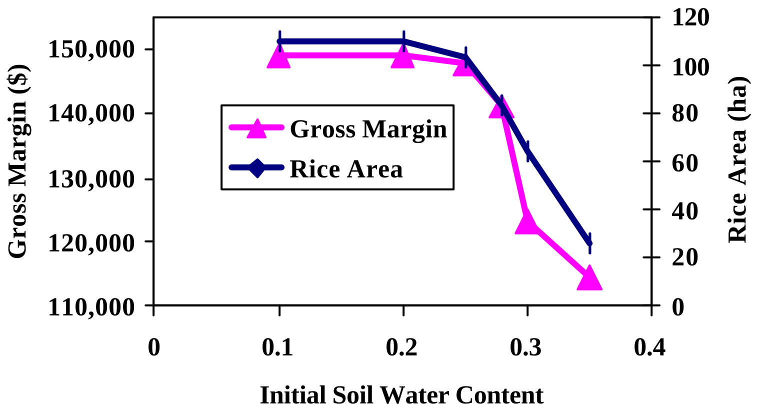


Figure 9. Sensitivity of gross margin and rice area to initial soil water content.

Value of Achievements Made During This Project

Recognising the excellent progress made in customising and refining SWAGMAN Farm to address waterlogging and salinity problems in irrigation areas, Rice CRC has already approved a follow on project to develop a GIS interface of the SWAGMAN Farm Model. The new project will provide continuity of present efforts to integrate results of the paddock monitoring, GIS based developments of SWAGMAN Farm and link on farm management with regional groundwater research.

Practical Significance of Results

- This project has provided insights into the role of initial soil water content in determining the net recharge to the watertables and consequent watertable rise and soil salinisation, and the importance of considering initial soil water content in using paddock water use to identify rice paddocks with excessive recharge.

- The sensitivity analyses have indicated that factors such as rice water application rates, climate and leakage rates to deep aquifers are critical in determining the sustainable landuse for a given farm

- The SWAGMAN Farm model and results produced during this research study are a major step towards helping to create awareness amongst the farming communities on how to select economically viable and environmentally sustainable cropping patterns by considering climatic, hydrogeological and social aspects.

- It is extremely unlikely that farming communities will be able to develop sensible strategies to manage for profit and resources management without tools like SWAGMAN Farm.

- SWAGMAN Farm is a generic in its design. There is no reason why this methodology developed here cannot be transferred and used in other irrigated areas with appropriate local information.

Summary of Communication, Technology Transfer and Adoption Efforts

- During 2001 Shahbaz Khan and Natalie O' Connell gave following presentations:
  - SWAGMAN Farm and regional groundwater hydrology work presented at August 2001 workshop of the Murray R&D Committee Workshop
  - August 2001 SWAGMAN Farm and groundwater management presentation to Berriquin Land and Water Management representatives
  - September 2001 Presentation to SIRDC in Deni
- Rice CRC SWAGMAN Farm Workshop was organised at Yanco during October 2001 in which participants included irrigation company managers, educators, extension officers and co-researchers at the workshop
- October 2001 Shahbaz Khan, Natalie O'Connell, Don Murray and Leigh Vial presented SWAGMAN Farm, GIS, farmer participation and groundwater hydrology work at the Rice CRC SWAGMAN Farm workshop at Yanco.
- SWAGMAN Farm CD's has been provided to CSU, CSIRO Plant Industries, Coleambally Irrigation, University of Sydney and Mr Ary van der Lely independent consultant
- Coleambally Irrigation Cooperative Limited staff has used SWAGMAN Farm model to explore on farm management practices for around 40 farmers
- More than 150 farmers and 10 environmental staff in the Coleambally Irrigation Area and a number of farmers in Murray Irrigation Area has been given hands on sessions on the use of SWAGMAN Farm
- Activity- Stakeholder Participation- Fourteen farmers from MIL participated in the project by making all the necessary data available. Four of these farmers are participating in the detailed data collection for the related NPIRD project.
- Activity- Posters and presentation- Poster sessions were held at the Murrumbidgee Farm Fair in May 2000 in collaboration with the Rice CRC.
- Activity- papers- One journal, two conference and one farmer journal papers and two fact sheets were written (see details in publications).
- Activity- interviews and articles in newspapers - One TV, 2 radio, one Rice Grower magazien and one newspaper interviews. Two articles in the Rice CRC newsletter which is distributed to all rice farmers (copies attached).
- Activity- Review Workshop- SWAGMAN workshop at CSIRO Griffith in September 1999, which was attended by stakeholders.
- Activity- presentation of results at Engineering Mathematics Applications Conference 2000 at RMIT, Melbourne
- Activity- presentations at Rice CRC program meetings in Dec 1999 and Dec 2000 – to wide range of stakeholders including environmental officers from Murray IL, Murrumbidgee IL, CICL, GMW (1999), ricegrowers, district agronomists
- Activity- presentation at Rice Water Use Efficiency Workshop which included above participants
- Activity- presentations to visitors from other research institutes
- Activity- promotion in other countries- potential application in South Africa and in conjuctive water use project in Pakistan
- Activity- presentation at the Upscaling workshop in Melbourne organised by CRC for Catchment Hydrology, November 2000.
- Activity- written articles- presentation O'Connell N & Khan S (2001) Murray Land and Water Management Plan newsletters.

- Activity- presentation - Khan S, Xevi E, Zhou F, O'Connell N & Robinson D (2000) On-farm net recharge management. Presentation to the CRC for Sustainable Rice Production, Program 1 Sustainability of Natural Resources in Rice-based Cropping Systems, December 2000, Griffith.
- Activity- Written article. Khan S, Short L, O'Connell N & Best L (2000) Origin of Salts in Rice Growing Areas. Rice Circle Issue 4, Volume 2, December 2000.
- Activity – presentation & written article- O'Connell N & Khan S (2000) Optimal Irrigation Intensity - Research Project Update. Prepared for the Wakool Land and Water Management Plan Working Group, November 2000.
- Activity – written report- Khan S, O'Connell N & Humphreys E (2000) Achievements of MIL/CSIRO/LWRRDC Project Determination of Optimal Irrigation Intensities for Irrigation Areas. Report to the Project Steering Committee and Murray Irrigation Limited, October 2000.
- Activity – written report- O'Connell N (2000) Determining Optimal Irrigation Intensity for Murray Valley Farms. Project update prepared for the Murray LWMP Research and Development Committee, May 2000.
- Activity – presentation - O'Connell N & Khan S (2000) "SWAGMAN Farm model development – Capillary upflow functions". Presentation to the CRC for Sustainable Rice Production, Program 1 Sustainability of Natural Resources in Rice-based Cropping Systems, December 2000, Griffith.
- Activity – presentation - O'Connell N (2000) Application of SWAGMAN Farm in the Murray Valley. Presentation to the meeting of Component 4 (Irrigation) of the Sustainable Agriculture Program, CSIRO Land and Water, Melbourne, May 2000.
- Activity – presentation - O'Connell N (2000) Application of SWAGMAN Farm in the Murray Valley. Presentation to the Annual Review Workshop, Irrigation Research Group, CSIRO Land and Water, Griffith, February 2000.
- Activity – presentation & written report -O'Connell N (1999) Optimal Irrigation Intensity/Total Farm Water Use. Project update to the Environment Committee, Murray Irrigation Limited Board of Directors, Deniliquin, December 1999.
- Activity – presentation & workshop paper -O'Connell N & Khan S (1999) Water use efficiency at a farm scale – SWAGMAN Farm approach. <u>In</u>: E Humphreys (ed.) Proceedings of the Rice Water Use Efficiency Workshop, CRC for Sustainable Rice Production, CSIRO Land and Water, Griffith, 12th March, 2000. pp: 37-40.
- Activity – presentation -O'Connell N (1999) Determining optimal irrigation intensity for irrigated areas. Presentation to the Annual Review Workshop, Irrigation Research Group, CSIRO Land and Water, Griffith, February 1999.
- Activity – presentation- Madden J (1998) Net recharge management (NRM) SWAGMAN Farm. Presentation to the Annual Review Workshop, Irrigation Research Group, CSIRO Land and Water, Griffith, February 1999.
- Activity – presentation - O'Connell N (1998) On farm management of salinity in irrigation areas. Presentation to students in Post Graduate Diploma in Environmental Management, La Trobe University, Wodonga, July 1998.
- Activity – presentation O'Connell N (1998) Determining optimal irrigation intensity for irrigation areas. Presentation to the Environment Committee, Murray Irrigation Limited Board of Directors, Deniliquin, March 1998.
- Activity – presentation Madden J (1998) On farm net recharge management. Presentation to the CRC for Sustainable Rice Production, Yanco, February 1998.
- Activity – presentation O'Connell N (1998) Determining optimal irrigation intensity for irrigation areas. Presentation to the Irrigation Research Group, CSIRO Land and Water, Griffith, February 1998.
    - Activity – Education of Stakeholders- In the related activities a number of educational sessions were organised for the farmers and environmental managers in the Coleambally Irrigation Area to teach SWAGMAN Farm philosophy.

Adoption of Results

In the related activities SWAGMAN Farm has been adopted as a principal natural resource management tool in the Coleambally Irrigation Area (CIA). The environmental staff and farming community are helping test the model processes and outputs for a range of conditions by applying the model to individual farms in the CIA.

Assessment of commercial potential

There is no commercial potential of this project.

List of Publication Titles

1. Khan S., Robinson D., E. Xevi, O'Connell N and (2001) Integrated hydrologic economic modelling techniques to develop local and regional policies for sustainable rice farming systems. 1st Asian Regional Conference on Agriculture, Water and Environment, ICID, September 2001, Seoul, Korea. (CD)
2. Khan S., Xevi E., and Meyer W. S. (2000) Salt, Water and Groundwater Management Models to Determine Sustainable Cropping Patterns in Shallow Saline Groundwater Regions – paper submitted to the special volume of the Journal of Crop Production entitled Crop Production in Saline Environments
3. Khan S, Xevi E, O'Connell N, Madden JC and Zhou F (2000) A farm scale hydrologic economic optimisation model to manage waterlogging and salinity in irrigation areas. In RL May, GF Fitz-Gerald & IH Grundy (eds.) EMAC 2000, Proceedings of the Fourth Biennial Engineering Mathematics and Applications Conference, RMIT University, Melbourne 10-13th September, 2000. pp: 179-182.
4. Meyer W. S. and Khan S., (2000) Software package lifts the water efficiency – Farming Ahead 104: 36-37.
5. O'Connell N. and Khan S., (2000) Investigation of water use efficiency at a farm scale - SWAGMAN Farm approach, Rice Water Use Efficiency Conference, CRC for Sustainable Rice Production.
6. Khan S. (2000). Irrigation: getting the balance right. Research project information sheet no. 11. CSIRO Land and Water.
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8. Khan S, Short L, O'Connell N & Best L (2000) Origin of salts a factor in management. Rice Circle Issue 4, Volume 2, December 2000.
9. Khan S, O'Connell N & Robinson D. (2001) Integrated hydrologic economic modelling techniques to develop local and regional policies for sustainable rice farming systems 1st Asian Regional Conference On Agriculture, Water And Environment, ICID. (Abstract accepted, paper in preparation)
10. O'Connell N & Khan S (2001) [Article for Murray Land and Water Management Plan newsletters (in preparation)

Listing of attachments

Publications as listed above and the communication articles.

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Details for Further Information

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Appendices

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Salt, Water and Groundwater Management Models to Determine Sustainable Cropping Patterns in Shallow Saline Groundwater Regions

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ABSTRACT

This book chapter describes models which can consider the interactions between plants, soils, water, irrigation practices, crop yields and economics under shallow, saline groundwater conditions. Personal computing capability has now made it possible to develop a range of interactive modelling tools based on existing and new biophysical concepts. The number of available models is rapidly expanding. Therefore it is not possible to cover all modelling efforts in a single chapter and the discussion in this chapter is limited to farm and irrigation area scale salt, water and groundwater management models. This chapter provides an introduction to the SWAGMAN suite of models that have been used in Australia to determine sustainable cropping patterns under shallow, saline watertable conditions. Salient features and applications of a detailed process based (SWAGMAN Destiny), a lumped hydrologic economic (SWAGMAN Farm) and a distributed biophysical model (SWAGSIM) are provided.

Keywords: Shallow, Saline, Watertable, Crops, Management, Modelling

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1. OVERVIEW OF HYDROLOGICAL MODELS FOR SHALLOW SALINE GROUNDWATER CONDITIONS

The models described in this chapter span the range from very detailed point scale models to lumped and distributed hydrological economic frameworks at the irrigation area scale. These are necessary to understand the complex interactions between crop, soil, water, salts and shallow watertable dynamics at point, paddock, farm, sub-irrigation and irrigation area scales. The data requirements of these models vary as the level of aggregation varies. In the case of point scale models data requirements may include hydraulic characteristics of soil, climatic parameters, salinity of soil and groundwater conditions. For lumped hydrologic economic modelling frameworks data on cropping, gross margins, soils, groundwater conditions and economics are required. For physically based hydrologic economic modelling, large amounts of data on regional cropping patterns and other landuses, markets, hydrogeology and surface-groundwater interactions are required for model development and calibration. Sometimes these data sets are either not available or are very expensive to collect. The real difficulty and uncertainty associated with developing spatially distributed models is the lack of confidence that the values given to aggregated parameters such as soil properties, irrigation efficiencies, climatic parameters and crop yields are truly representative. This uncertainty compounds that associated with the uncertainty of the gross process representation.

The ability of a model to represent field situations largely depends on conceptualisation of processes and accuracy of data sets. The modelling framework to be selected for exploring crop, soil, salt and groundwater interactions is dictated by the purpose of study and availability of data. Realising these constraints, CSIRO Land and Water developed a suite of tools called the SWAGMAN (Salt WAter and Groundwater MANagement) series of models. This suite of models is designed to investigate shallow saline groundwater conditions at a range of scales with varying degrees of complexity depending on the purpose and data availability. Models in this series include SWAGMAN Destiny (Meyer et al., 1996), SWAGMAN Whatif (Robbins et al., 1995), SWAGMAN Farm (Khan et al., 2000), SWAGMAN Options (Prathapar et al., 1995) and SWAGSIM (Prathapar et al., 1994). This chapter describes applications of a detailed biophysical model SWAGMAN Destiny, a farm scale hydrologic economic framework SWAGMAN Farm and a distributed biophysical model SWAGSIM.

2. CLASSIFICATION OF MODELS

2.1 Detailed Point Scale Biophysical Models

Models that fall under this category include United States Soil Salinity Laboratory Hydrus1-D (Simunek et al, 1998) and Hydrus 2-D (Simunek et al, 1999) and the CSIRO Land and Water SWAGMAN Destiny model (Meyer et al, 1996). These models simulate detailed crop response, soil water changes and fluxes to and from the shallow watertables. These models are based on water balance approaches that either use a modified “tipping” bucket approach with the soil profile divided into a number of vertical compartments or various numerical solutions of Richard’s Equation (Richards, 1931).

2.2 Lumped Biophysical Economic Models

These types of models use salt and water balance estimates determined by the detailed local biophysical models such as SWAGMAN Destiny and Hydrus 1-D to define lumped water and salt balance parameters. The models in this class include SWAGMAN Farm (Khan et al 2000). These models can be used either to assess the impact of given cropping systems on shallow water tables and soil salinity or to determine an optimum profitable mix of crops for which the watertable and salinity changes are within specified limits.

2.3 Distributed Biophysical Models

Distributed biophysical models solve the groundwater flow equations in two or three dimensions for the variably saturated porous media using analytical and/or numerical methods. Models in this class include SWAGSIM (Prathapar et al 1995).

2.4 Distributed Biophysical Economic Models

Development of regional management policies for shallow saline watertable areas requires integration of spatial hydrogeological dynamics with economics to capture and integrate watertable rise, salinity change and economic options for the entire irrigation area. The inputs and outputs of economic significance are defined over larger scales than those for the detailed biophysical models. An example of this class of models is the hydrological economic model developed by Stubbs (2000) which includes state reduction techniques (Moore, 1981) to define detailed distributed system response (aquifer response) at the economic unit level. The groundwater flow system is initially represented using a finite difference groundwater model and the number of groundwater states is significantly reduced using state balanced truncation techniques commonly used in control engineering. The crop production and unsaturated zone hydrology are simulated for different soil and land use types and is incorporated into the hydrologic economic framework as non-linear functions of net recharge, relative yield and irrigation water use using a one dimensional finite element model. The hydrologic representation of groundwater flow and soil salinisation is incorporated into an economic optimisation model which simulates different policy options such as crop area restrictions and water trading over 15 and 30 year periods using nonlinear optimisation techniques. So far this model has been applied in the Murrumbidgee and Coleambally Irrigation Areas of Australia to investigate the effect of rice area restriction and water trading policies on the overall economics using common pool and social optimum options.

3. FEATURED MODELS

Details of SWAGMAN Destiny (Detailed Process Model), SWAGSIM (Distributed Biophysical Model) and SWAGMAN Farm (Lumped Biophysical Economic Model) are presented in the following sections.

3.1 SWAGMAN Destiny

SWAGMAN-Destiny simulates the effects of soil water and salt on plant productivity in the presence of shallow water tables. It is used to identify crop and land management strategies that minimize water table rise and salinity development which are economically viable. The model uses the water balance routine described in Ritchie (1985). This model is multi-layered and simulates the infiltration, drainage and upward fluxes of water and salts. It estimates potential evapotranspiration and incorporates a root water uptake routine to determine actual transpiration. In addition, this model has the capability to determine the depth to the water table and has procedures to simulate tile drainage. The model is one-dimensional and uses a daily time step.

The main processes simulated in the model include infiltration, drainage and upflow, groundwater interaction, crop growth and crop response to salinity.

3.1.1 Infiltration

Infiltration into the profile is simulated using a time to ponding approach following Broadbridge and White (1987). Daily rainfall is disaggregated using an assumed triangular distribution for rainfall and rectangular distribution for irrigation. A triangular distribution with a base equal to the duration of rainfall and height equal to maximum rainfall intensity is constructed. When rainfall and irrigation exceed ponding depth, runoff occurs. The maximum depth of ponding as well as soil surface hydraulic properties are model inputs. The depth of ponding is based on rainfall intensity and the hydraulic conductivity of the soil surface. Daily amounts of infiltration, runoff and changes to the level of ponded water are calculated.

3.1.2 Drainage and upflow

Water flow through the soil is modeled as a simple cascading system from the top layer to the layer below. The flow of water is dependent on the lower limit of plant extractable water, the drained upper limit and saturated water content. Only water between the drained upper limit and saturation can drain freely. Upward capillary flux is calculated from the prevailing water contents of the layers above a saturated layer and an internally computed diffusivity value normalised between soil types as a function of the lower limit of available water.

3.1.3 Groundwater interaction

A water table exists in a soil profile when the hydraulic properties of a layer prevent water draining freely and drainable water accumulates. There may be more than one water table present in the soil, as often occurs immediately following an infiltration event. In SWAGMAN Destiny the depth of the water table is determined from the bottom of the profile upward by considering the rate at which drainable water drains from the layer and comparing this with the drainage rate from the lowermost soil layer.

3.1.4 Crop growth

The crop growth routines of Destiny are simple procedures for estimating daily increments in Leaf Area Index (LAI), above ground biomass and root biomass and their response to aeration, nitrogen, water deficit and salt stress. To date, procedures for simulating rice, wheat, maize, sunflower, lucerne, pasture, citrus, vines and deciduous fruit have been developed.

3.1.5 Crop Response to Salinity

Soil salinity has various effects on plant growth. This has a direct effect of reducing leaf expansion growth. In SWAGMAN Destiny, a zero to unity stress index is used each day to modify expansion growth. On a day-to-day basis the amount of salinity stress the plant will experience depends on where roots are located in the soil profile and where water and salt are located. The index used integrates the layer by layer salt concentration, and root water uptake into a single index.

Maas and Hoffman (1977) developed indices that relate seasonal average soil salt concentration to relative yield for a particular species. The approach in Destiny is to develop a scalar for salt response for each layer in the profile according to its prevailing salt concentration. These scalars are derived from three coefficients which are unique for each crop. These define a threshold salt level (as estimated from soil solution electrical conductivity, EC) before there is a response to salinity and the slope and terminal response values.

3.1.6 Input data

Destiny requires three sets of data: 1) meteorological data; ii) soil data; and iii) crop data. The meteorological data required are the maximum and minimum daily temperatures, solar radiation (MJ/m), daily rainfall, dew point temperature and wind speed. These data must be entered into a database. The soil data include soil water content at lower limit, drained upper limit and saturation for each layer defined for the soil profile. Crop data include genetic specific information to calculate plant development rate. In addition, EC of irrigation water and soil is required.

3.1.7 Outputs

Outputs consist of time series information on soil water content for various layers, time series of ground water level, time series of soil salinity for each layer, and time series of crop variables: plant biomass, LAI, rooting depth, top fraction, final crop yield

3.1.8 SWAGMAN Destiny Example

Model simulations of maize were conducted using 10 years of weather data (1962 – 1971) from Griffith, Australia. The soil used was Mundiwa clay loam and the crop was irrigated using water of 5 different salinities (EC(dS/m) = 0.2,0.5,1.0,1.5,2.0). The irrigation water application schedule was based on depletion of soil available water within the top 50 cm of soil with a minimum irrigation interval of 10 days. The probability of yield estimates and end of cropping season salinity of the top 40 cm of soil for each level of irrigation water salinity are shown in Figures 1 and 2.

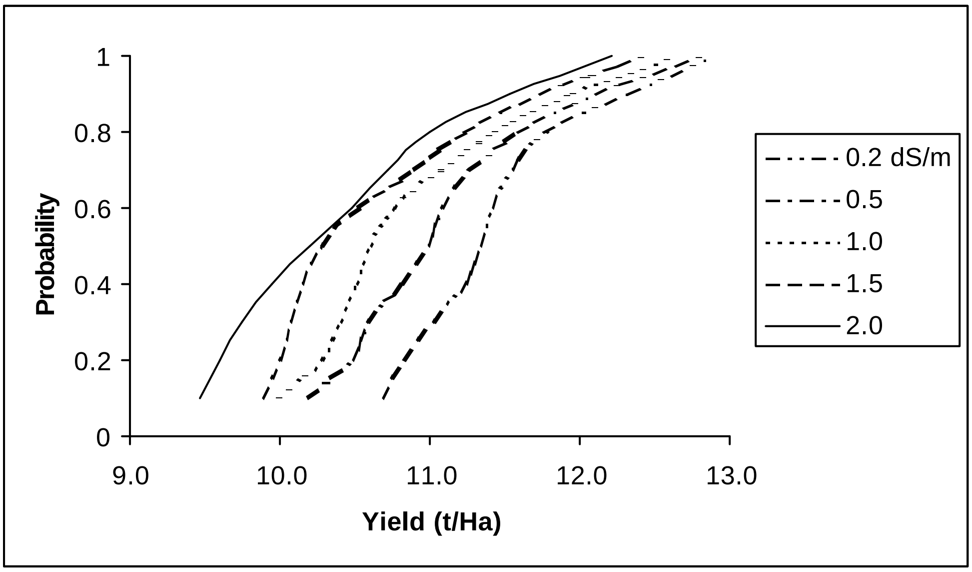

Figure-1 Probability of yield as affected by irrigation water salinity

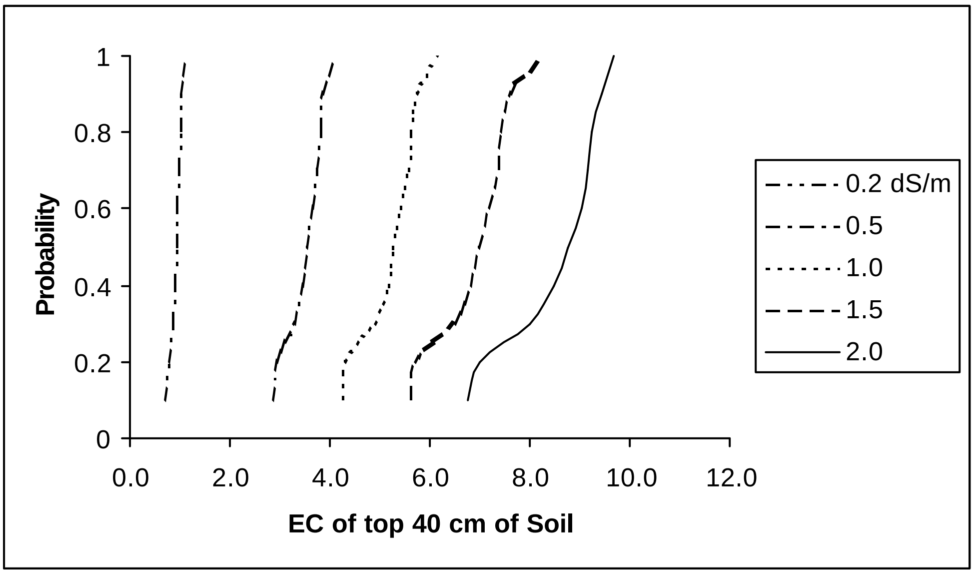

Figure-2 Probability curves for EC changes predicted by SWAGMAN Destiny

3.2 SWAGSIM

SWAGSIM is an acronym for Soil Water And Groundwater SIMulation. Under shallow saline watertable conditions the recharge to and discharge from the watertable strongly depend on the conditions in the unsaturated zone and on the saturated zone groundwater dynamics. Therefore it is crucial to combine unsaturated zone dynamics and water fluxes with the saturated groundwater flow conditions. SWAGSIM uses an infinite time series solution to define the distribution of matric flux potential within a homogeneous soil profile with roots above the watertable (Prathapar et al. 1992) using diffusivity and unsaturated hydraulic conductivity relations discussed by Gardner (1958) and Philip (1987). The analytical solution of the unsaturated zone is integrated with the unconfined flow through a finite difference solution of the saturated transient groundwater flow equation in two dimensions (Prickett and Lonnquist, 1971).

SWAGSIM simulates evapotranspiration through the root zone of crops, micropore recharge and capillary upflow from the watertable through the soil profile, macropore (preferential) flow through cracks, groundwater flow in the unconfined aquifer and vertical leakage to and from the deeper aquifers. It can consider both horizontal and vertical drainage options such as mole drains, tile drains and drainage wells. It can model surface/groundwater interactions such as surface channels and/or rivers and evaporation ponds. It simulates temporal and spatial fluctuations of shallow watertables on a daily time step with a uniform or variable discretisation of space.

Two grids are defined for SWAGSIM to reduce data requirements for uniform land uses. The first grid (Figure-3) divides total model area into sub-areas with similar crops and irrigation to determine recharge or capillary upflow on a daily basis. The second grid (Figure-4) subdivides the shallow groundwater zone for the finite difference computation of saturated groundwater flow equation.

3.2.1 SWAGSIM Example

To illustrate the application of SWAGSIM a 150 ha area divided into 14 sub-areas was modelled. A 2m deep starting watertable depth was assumed across the modelling area. In this example a finite difference grid of 50m x 50m square mesh size consisting of 24 rows 25 columns was used. The input data sets (not described here) used for this example included average air temperature (°C), dew point (°C), wind run (km/d), radiation (MJ/m^2) and rainfall (mm), hydraulic properties of the soils, thickness of aquifers and irrigation events. The model output consists of watertable depth, piezometric level, recharge and capillary upflow both a cell by cell and sub-area average base. A sample output of SWAGSIM consisting of depth to watertable change, recharge and capillary upflows averaged over sub-area number 5 is shown in Figure 5. The negative flux values indicate recharge to the watertable and positive flux values indicate capillary upflow from the watertable. SWAGSIM has a facility to keep the rainfall or irrigation excess on the soil surface where it exceeds the infiltration capacity of the soil as determined by the soil storage and saturated hydraulic conductivity.

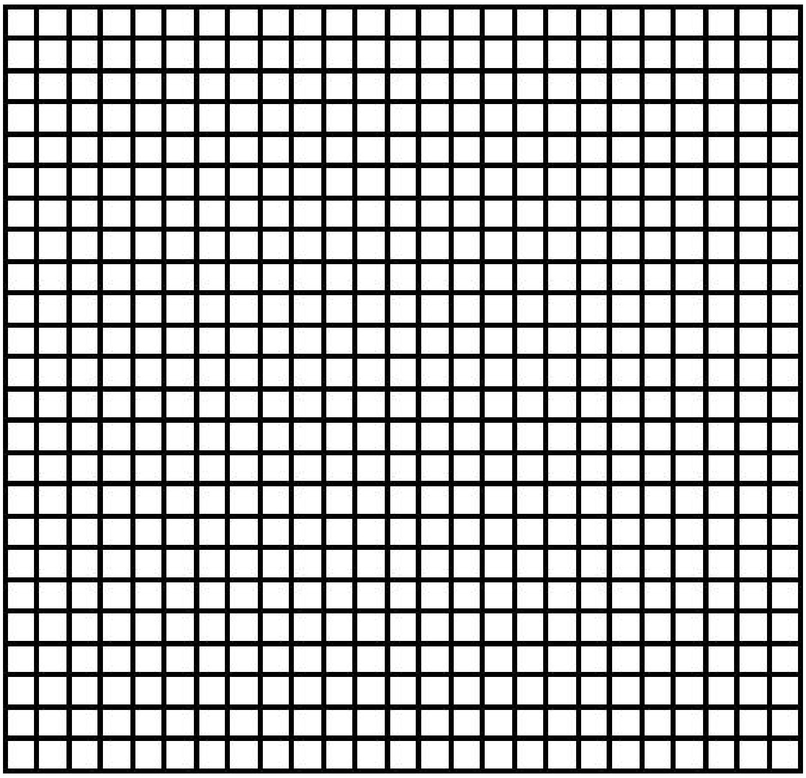

Figure-3 Finite Difference Grid Used by SWAGSIM

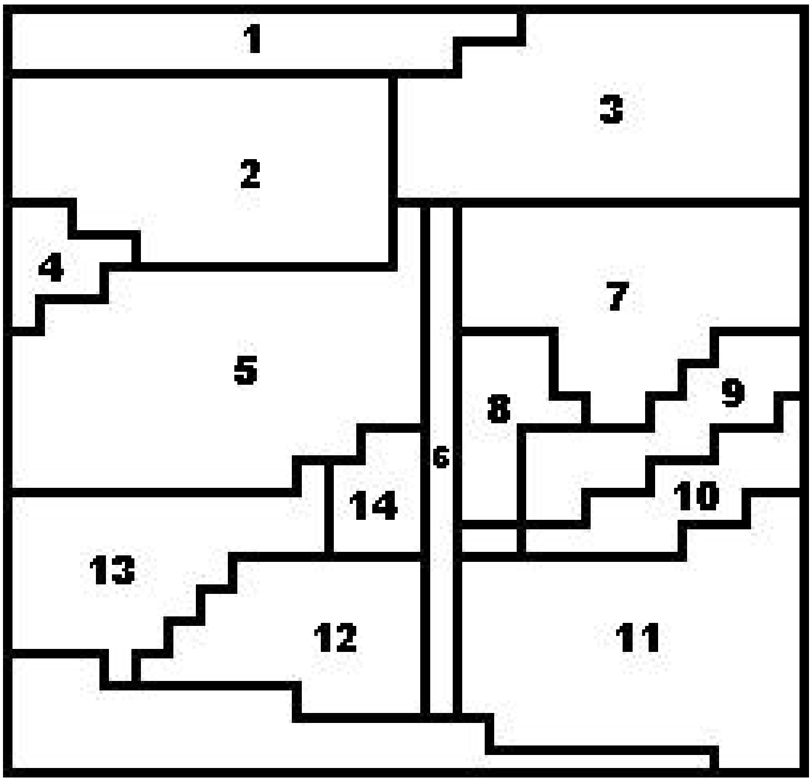

Figure-4 Uniform Land Use Grid Used by SWAGSIM

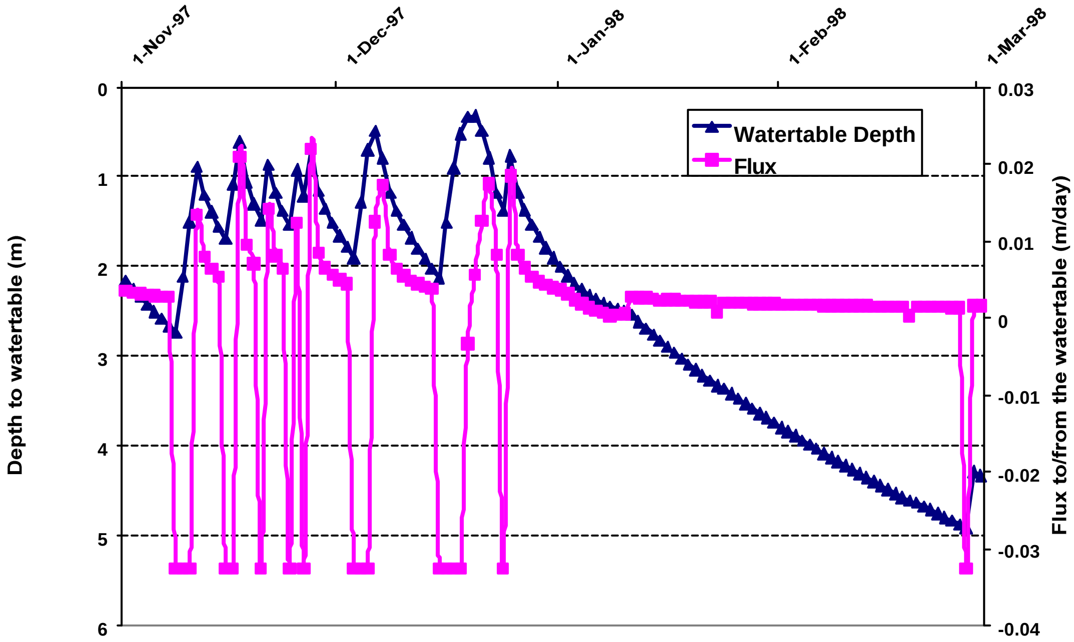

Figure-5 Average changes in watertable depth and fluxes to and from the shallow watertable for sub-area 5

Applications of SWAGSIM include incorporation into an integrated hydrological economic modelling framework to examine futures of irrigation areas in the Murray Darling Basin of Australia (Fordham, 1998), evaluation of rice growing policies (Prathapar et al., 1994a, 1995), evaluation for shallow groundwater pumping options and subsurface drainage options to control shallow watertables (Prathapar et al., 1994b, Prathapar et al., 1995) and simulation of surface-groundwater interactions (Punthakey and Prathapar 1995).

3.3 SWAGMAN Farm

SWAGMAN Farm is a lumped water and salt balance model which integrates agronomic, climatic, irrigation, hydrogeological and economic aspects of irrigated agriculture under shallow watertable conditions at a farm scale (Khan et al., 2000). This model has been used to develop management concepts such as "net recharge management for control of shallow watertables" which focuses on managing the component of recharge greater than the vertical and lateral regional groundwater flow. In SWAGMAN Farm the lumped estimates of the water and salt balance (Figure-6) components for the cropping and fallow periods are computed for a range of irrigated crops such as rice, soybean, maize, sunflower, fababean, canola, wheat, barley, hay lucerne, grazed lucerne and annual pasture, perennial pasture and for dry land wheat and uncropped areas, for different irrigation, climatic soil and hydrogeological conditions. The water and salt balance computations for each of the crops are derived using the results of detailed monitoring (Meyer et al 1990, Prathapar and Meyer, 1992) and hydrological modelling (Prathapar and Madden 1995, Prathapar et al., 1992, 1994, 1995, 1996). This model can simulate the effects of growing a certain crop mix on shallow watertable and soil salinity or it can compute an optimum mix of crops for which the watertable rise and soil salinity remain within the allowable constraints for given hydro-climatic conditions. The optimisation problem can be stated as:

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

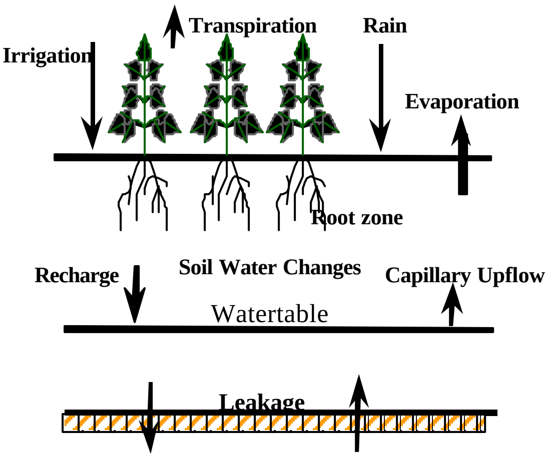

FIGURE 6. Schematic diagram showing biophysical processes under shallow watertable conditions

The total gross margin for a given farm is optimised subject to six contraints:
Constraint 1: Change in salt concentration in the root zone is less than or equal to allowable change.
Constraint 2: Change in water table level is less than or equal to the allowable change.
Constraint 3: Area of a land use is constrained between maximum and minimum areas determined by physical limits and farmer preferences.
Constraint 4: Water allocation to the farm is greater than or equal to water used for irrigation.
Constraint 5: Sum of areas of all land use types is equal to the total area of the farm.

Constraint 6: Binary constraints to ensure a minimum land use area if crop area enters the solution vector.

This model has been written in GAMS (General Algebraic Modelling Systems) (GAMS Corporation, 1999) and utilises Mixed Integer Non Linear Programming solvers such as DICOPT (DIscrete and Continuous OPTimser) to find optimum cropping patterns for given soil, climatic, irrigation and hydrogeological conditions. The convergence and appropriateness of optimisation routines is checked using the sensitivity analysis techniques for a range of shallow watertable situations (Panell, 1997).

3.4 SWAGMAN Farm Example

A hypothetical irrigated farm example is represented here to illustrate the application of SWAGMAN Farm. 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), 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 volumetric 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 model optimised land uses resulting in a gross margin of $123096 are shown in TABLE 1.

TABLE 1. 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 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 discharges of 37 ML, 24 ML and 30 ML respectively. The capillary upflow under the farm is 6.7 ML.

TABLE 2 shows a summary of the salt balance for the farm. The net increase in salts in the soil above the watertable is 153 tonnes. The main source of salt is capillary upflow under the farm. Recharge under the rice area during the irrigation and fallow periods partly remove (leach) the salt brought in by irrigation and capillary upflow.

TABLE 2. Salt balance for the example farm (all values in tonnes of salt).

Irrigation	Rainfall	Capillary Upflow	Total Salt	Salt change in

Salt	Salt	Salts	Removed	the root zone
67	8	143	65	153

The SWAGMAN Farm model has been applied to determine optimal irrigation intensities and develop net recharge management options in the shallow saline watertable areas (Prathapar and Madden, 1995, Madden and Prathapar, 1999, Khan et al, 2000).

4. CONCLUSIONS AND FURTHER RESEARCH NEEDS

Shallow saline watertable conditions demand integration of a number of disciplines such as plant science, soil physics, hydrology and economics. Investigation into sustainable cropping patterns demands selection of proper tools at the appropriate scale considering the study objectives and data limitations. The SWAGMAN series of models can simulate shallow saline watertable conditions at a range of scales with minimum data requirements and therefore offers a tremendous potential to address environmental sustainability and economic viability issues of irrigated agriculture. Further research is needed to upscale farm and irrigation area understanding of cropping systems under shallow watertables to the catchment level to understand the impacts of shallow saline watertables on discharge into streams.

5. ACKNOWLEDGEMENTS

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INTEGRATED HYDROLOGIC ECONOMIC MODELLING TECHNIQUES TO DEVELOP LOCAL AND REGIONAL POLICIES FOR SUSTAINABLE RICE FARMING SYSTEMS

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Abstract

Globally the long term sustainability of major rice growing areas is threatened in many semi-arid regions by salinisation as a result of shallow watertables. Shallow watertables are caused by combinations of factors including inefficient irrigation practices, high recharge rates from fields, poor surface and groundwater drainage and inappropriate crop rotations. A number of rice farming policies aimed at achieving long term environmental sustainability of irrigated agriculture have been introduced in southern Australia. These policies include concepts such as rice suitable land, maximum rice water use and limits on the area under rice. Simulation of the various hydrologic and economic conditions of different irrigation areas under these management policies requires the development of generalised hydrologic economic frameworks, which are then customised to area specific conditions. The generalised frameworks should be able to upscale and integrate the results of field scale hydrologic and economic processes from the field to the farm, subdistrict and irrigation area levels. This paper describes application of a generalised hydrologic economic framework SWAGMAN® (Salt Water and Groundwater MANagement) Farm. This model is currently being used to develop management policies in irrigation areas in southern Australia. In describing this model factors external to the rice based farming systems (externalities) are discussed. The paper discusses the necessity of including externalities such as groundwater discharge from rice paddies to non rice growing areas in a farm or adjoining farms, groundwater pumping in and outside the irrigation areas, leakage to the deeper aquifers and preferential flow along underground prior stream channels.

With the objective to maximise economic returns, model results show that watertable and salinity below a farm can be managed by proper selection of areas of recharging and discharging crops. Results of regional hydrologic economic models suggest that policies aimed at sustainable development of rice farming systems must also consider waterlogging and salinity effects in non-rice areas. These models have highlighted the importance of considering groundwater discharge and recharge zones in and around an irrigation area.

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1. INTRODUCTION

Presently the total rice area in southern NSW is around 150,000 hectares situated in the Murrumbigdee (MIA), Coleambally (CIA), Murray Valley (MVID) Irrigation areas and districts (Fig. 1) and along the rivers and creeks. These rice growing areas use about 2000 GL of water to produce 1.4 million tonnes of grain with a farm gate value of $300 million (Humphreys et al, 1999). Rice is grown under ponded conditions for approximately five months and it contributes 40-50% (Humphreys et al, 1994) of the total accessions to the groundwater in the rice growing areas of south eastern Australia.

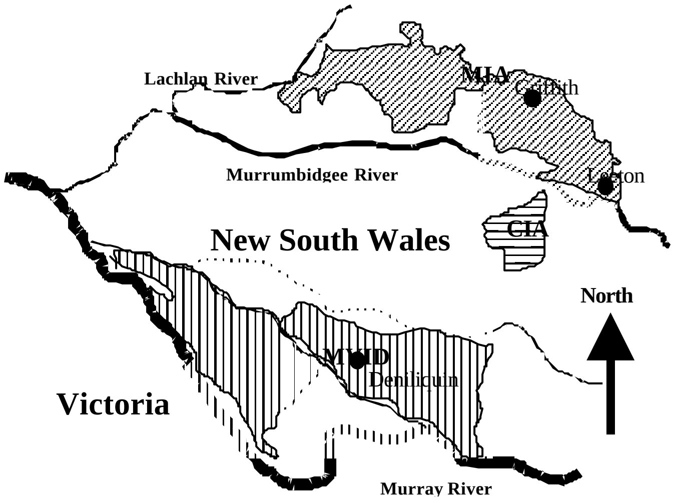

Figure 1 Location of Major Rice Growing Areas in Australia

Pre-irrigation salinity in the underlying soils was caused by rainfall over thousands of years when the magnitude of rainfall was not enough to leach the salts to the deeper watertables. With the introduction of irrigation these salts were leached into the groundwater resulting in high groundwater salinities. The water tables in the rice growing areas have risen by around 12 to 18 m since the start of irrigation. Now, due to the presence of shallow saline watertables within 2 meters from the soil surface, capillary upflows and evapotranspiration have caused soil salinisation in the root zone. Rising watertables and soil salinity raised concerns among the farming communities and regulation bodies and therefore a range of measures were introduced to control excessive recharge under rice paddocks. These measures include introduction of polices to restrict rice growth to suitable lands only, and restrictions on the total area of rice per farm and the amount of water used to grow rice. Most of these policies aimed to reduce groundwater accessions on a farm level and thereby achieve sustainability at the irrigation area level. It is important to consider the potential impacts between individual farms and surrounds, and to restrict rice farming to those parts of the landscape which cause the least lateral flows to the adjoining non rice growing areas. A range of farm and regional scale models can be used to determine economically viable and environmentally sustainable cropping patterns by considering climatic, hydrogeological, economic and social aspects at the farm and regional levels.

2. REVIEW OF POLICIES AIMED AT ENVIRONMENTALLY SUSTAINABLE RICE FARMING SYSTEMS

Until the late 1980s, the total area of rice was strongly influenced by the ability of the industry to handle and market the crop profitably, and by political pressure with some environmental guidelines attached (Humphreys et al, 1994). Statutory restrictions on rice growing were removed in 1989, which led to the rice industry expanding from approximately 40,000 ha in 1970 to 150,000 ha in year 2000. The main restrictions on rice growing are now determined by the availability of water and by environmental factors, particularly recharge to the water table and the quality and quantity of surface drainage. The rice growing policies aimed at reducing impacts on watertables and root zone salinity can be broadly classified as:

- Maximum water consumption policies
- Soil suitability policies
- Rice hydraulic loading

2.1 Maximum water consumption policies

During the 1940's the first signs of waterlogging problems occurred in parts of the MIA. To address this situation rice growing was restricted to locations where previous water use was below 27 ML/ha and the water table below 1.8 m. The maximum rice growing area was 24 ha if it was underlain by shallow aquifers and 40 ha if it was not. These restrictions were dropped in 1960 when it was recognised to be inappropriate, as deep percolation is less where the water tables are already near the surface. In 1985, a target rice water consumption policy was implemented with the objective to restrict rice growing on land with a record of high water use. Rice was gradually restricted to paddocks where water use was less than 16 ML/ha/season, with adjustments for annual variations in potential rice evapotranspiration taken into account in the early 1990's. This was based on the assumption that 12 ML/ha is consumed in evapotranspiration and the remaining 4 ML/ha becomes surface drainage and deep percolation. The target of 16 ML/ha was phased in over a six year period starting from 1986 to minimise economic hardship on the farmers. However, this policy was still considered an unsatisfactory method for detecting large amounts of deep percolation due to inaccuracies in the water measuring methods and estimation of water diversions to non-rice crops within farms. In 1997 the method for calculating the target (Evaportranspiration-Rainfall+4 ML/ha) was introduced which effectively lowered the target to 14 ML/ha (Humphreys et al, 1999).

2.2 Soils suitability based policies

During the late 1960's soil based criteria were adopted to identify areas unsuitable for rice growing. Land excluded from rice growing were sand hill formations, land suitable for horticulture or adjacent to horticultural land (up to 100 m) and land overlying or closely associated with prior streams or shallow aquifers.

During the early 1970s soil suitability criteria based on soil texture (amount of clay), thickness of clay layers and infiltration rate were introduced. These were coupled with compulsory soil profile examination (boring of a 3 meter hole per 4 ha on a 200 m x 200 m grid) for all new rice lands, and for any current rice land suspected of having too much deep percolation. The objective of this policy was to confine rice to within the least permeable part of the landscape. For example, unrestricted rice growing in the CIA required at least 2.1 m of heavy to medium clay in the top 3 m. A greater thickness of clay was specified in the MVID since the profile examination were not as accurate. Only the flood plain soils (transitional red-brown earths, red-brown earths, self-mulching and non-self-mulching clays) were considered suitable for rice growing. In 1994, the soil suitability criteria were modified to 3 m of medium to heavy clay in the top 3.5 m in both the Murrumbidgee, Murray areas and districts and regions along rivers. In some cases in the Murrumbidgee Region 2 m of clay may be approved, for example, where the subsoil is a very low permeability dispersing clay.

Since soil surveys are expensive and laborious alternative methods based on electromagnetic surveys using the Geonics EM-31 instrument are now being used with Global Positioning Systems and computer mapping technology to assess soil variation within rice fields (Humphreys, 1999) enabling targeted and more efficient soil assessment.

2.3 Hydraulic loading policy

The concept of hydraulic loading was introduced in 1988 but only in irrigation areas with high watertables (less than 2 m) with the objective to restrict total percolation from the rice approved areas to a sustainable maximum value. A maximum allowable rice area of 65 ha per farm (69 ha in the CIA) or 30% of the rice approved land (whichever the greater) was to be phased in by 1993/94. Rice growing was not necessarily confined to soils with the least permeability because leaching of saline areas was required due to the capillary upflow of salts. On farms outside the MIA where watertables are deeper, the hydraulic loading policy does not apply but there are total area restrictions. The maximum allowable rice area may not exceed 25% of the rice approved area of the farm, or 100 hectares per 972 ML of irrigation water licence held, whichever is the smallest. Other associated environmental policies included a buffer of 150 m to any natural waterway.

3. MATHEMATICAL MODELS TO ASSESS THE ADEQUACY OF RICE ENVIRONMENTAL POLICIES

There are three main types of models which can aid the development, assessment and implementation of rice environmental policies:

a) Rice water use estimation models
b) Farm scale hydrologic economic models
c) Regional scale hydrologic economic models

3.1 Rice water use estimation models

The amount of water supplied to rice farms in the rice growing areas of Australia is mostly measured using a Dethridge wheel meter, and farmers are required to provide data about the proportion of water that is going to rice versus other uses to irrigation water suppliers. These data, together with crop areas measured from aerial photographs are used to calculate farm average rice water use (ML/ha). Where possible, water use is also calculated for individual rice paddocks to identify which paddocks are leaky (high water use) (Xevi, 1998). Irrigation flows to individual rice paddocks are generally hard to quantify especially when losses due to deep percolation and errors due to inaccuracies in the Dethridge meters are unknown. LeakyPad is an optimisation program designed to estimate recharge under individual rice paddocks based on area of each rice paddock, historical annual farm rice water application (and paddock water use where available) and theoretical evaporative rice water use. To achieve a solution, LeakyPad requires several years of historical data. Using the GAMS (1996) programming environment, the model minimises the sum of positive and negative errors over several years induced by the difference between rice water use in excess of evaporative demand (WEX) subject to the constraint that recharge is always positive. Although this type of modelling framework is useful to identify leaky paddocks to assist in implementing maximum rice water use policy, it does not take into account soil types, physical characteristics of soils, depth to watertable and local and regional groundwater dynamics.

3.2 Farm scale hydrologic economic models for assessing rice policy options

Rice farming policies can be assessed using SWAGMAN® (Salt Water and Groundwater Management) Farm which is a hydrologic economic model. SWAGMAN® Farm integrates agronomic, climatic, irrigation, hydrogeological and economic aspects of irrigated agriculture at the farm scale (Khan et al., 2000). During cropping and fallow periods, water and salt balances under a rice paddock depend on 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. SWAGMAN® Farm can simulate watertable and soil salinity variations in a given year taking into account irrigation allocation, farmer cropping preferences, district policies, groundwater pumping options, interaction with deeper aquifers and soil suitability for different crops.

SWAGMAN® Farm models total farm water and salt balance for rice and other crops for a given (simulation mode) or optimum mix of crops (optimisation mode). Optimum land uses for a given farm can be determined by optimising an economic objective function using mixed integer non-linear optimisation techniques available in GAMS (1996). In the optimisation mode constraints such as soil suitability, permissible rise of watertables and soil salinity, farmer preferences can be used to develop rice farming options that meet prescribed environmental constraints. The simulation model can be used to test the environmental and economic impacts of adopting a given rice farming policy.

To assess different rice farming policies a typical farm in the CIA has been considered. The total area of the farm is 214 ha and soil types consist of 80 ha of Self Mulching Clays (SMC), 86 ha of Transitional Red Brown Earths (TRBE) and 48 ha of Sands. The depth to the watertable under the farm is 2.0 m and salinity of the groundwater is 3.0 dS/m. The total water allocation of the farm is 1300 ML. The leakage rate under the farm is 0.3 ML/ha per year. The salinity of irrigation water is 0.15 dS/m and salinity of rainfall is 0.01 dS/m. Rice is restricted to SMC and TRBE. Average initial volumetric soil water content under the farm is assumed to be 0.3. Average climatic conditions with annual rainfall of 346 mm and 1779 mm of reference evapotranspiration are assumed.

If 16 ML/ha is the rice water use limit the maximum area which can be put under rice is limited to 80 ha which is much less than the total area of rice suitable lands (SMC+TRBE=166 ha). Therefore in this case the total area under rice is limited by water availability rather than the maximum rice water use policy. If the rice water use per ha can be reduced more area can be put under rice. Fig. 2 shows the net recharge from rice (overall balance of water reaching the watertable) and percentageof the rice suitable area that can be allowed to rice with different rice water use per ha, under average climate conditions. The net recharge per ha increases with increasing rice water use. Although the areas of rice suitable land on this example farm is not a constraint, the net recharge under the farm becomes a limiting factor in deciding total area under rice when net recharge constraints are imposed.

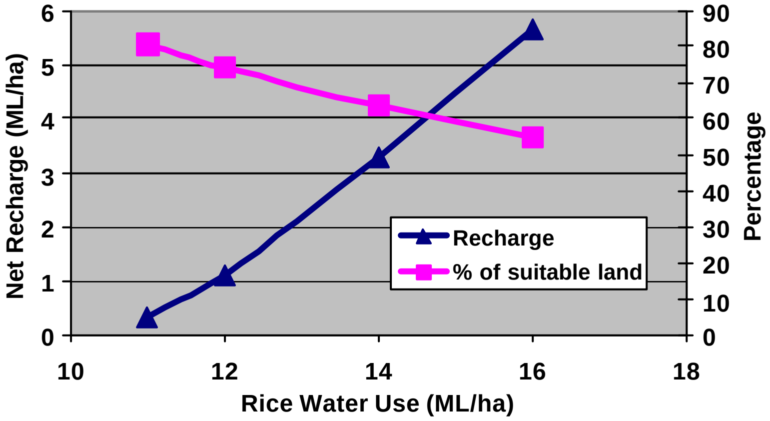

Figure 2 Impact of rice water use on net recharge

To consider the whole farm impact with a mix of crops and the same climate, initial soil water content and leakage rates described previously the cropping pattern shown in Table-1 is used as an example:

Table-1 Crop mix for example farm

Crop	Area (ha)	Water Use (ML ha^{-1})
Rice	60	12
Winter Pasture	30	3
Wheat	41	4
Soybean	36	9
Fallow	22	0

The following conclusions are drawn from the results of a range of model runs:

- Fig. 3 shows that the initial volumetric soil water content is very important in estimating the net recharge to the watertables for a given rice water use. If a wet rainfall year is followed by another wet rainfall year or consecutive rice crops are grown, the average soil water content would be quite high and any small increase in rice water use is associated with a corresponding increase in net recharge and watertable rise.

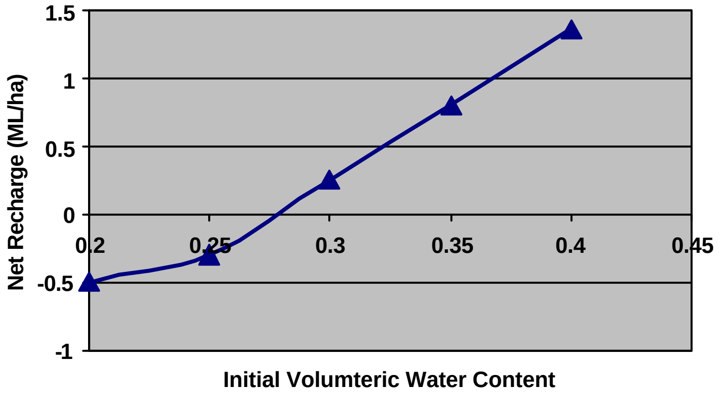

Figure 3 Impact of initial soil water content on net recharge on farm for a given water use

- Fig. 4 shows the impact of downward leakage to deeper aquifers on net recharge for the example farm. The deep leakage is linearly inversely correlated with net recharge and is an important factor determining the sustainability of rice based farming systems. If the leakage is upwards (negative values) due to higher pressures in the deeper aquifers the net recharge can be positive, giving an overall rise in the watertable on farm for a given water use.

- Fig. 5 shows the impact of watertable depth on net recharge. It is noted that at 1 m depth the net recharge is less than that for 1.5 m depth due to higher capillary discharge at the shallower depths. In this example the net recharge to the watertable decreases with the increasing depth of the watertable below 1.5 m. This example clearly illustrates the importance of incorporating depth to watertable in rice farming policies.

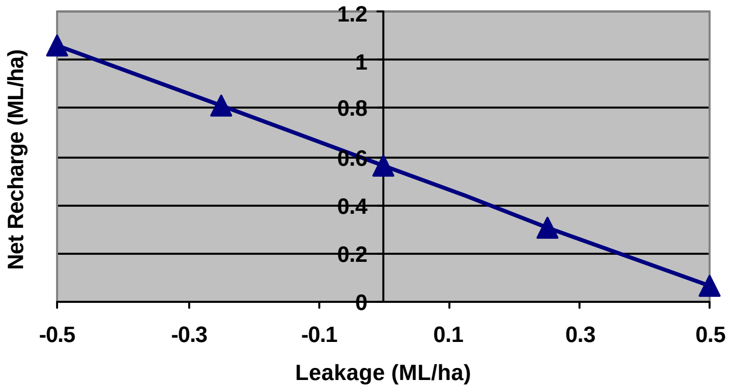

Figure 4 Impact of deep leakage on net recharge

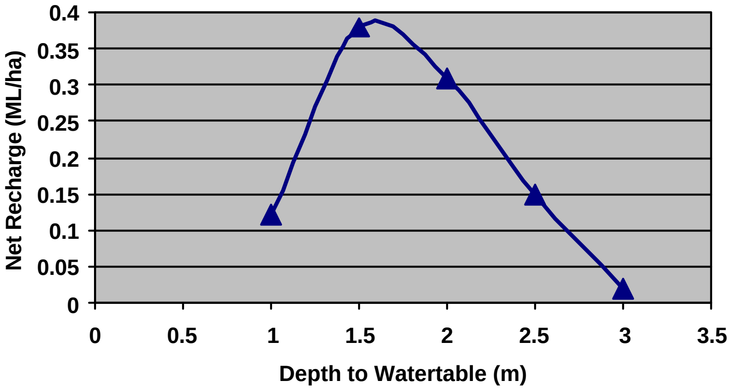

Figure 5 Impact of initial watertable depth on net recharge

3.3 Regional scale hydrologic economic models

The hydrology and economics of rice paddocks and individual farms need to be upscaled at the irrigation area level to integrate with regional groundwater dynamics, prior stream interactions and regional drainage options. This will help ensure the success of farm scale improvement in management to achieve desired lowering of watertables and soil salinity levels for the irrigation areas. On the basis of knowledge of groundwater flow directions it is possible to divide irrigation areas into groundwater management zones which are independent of each other - any changes in rice water use in one zone will have no impact on the other zones.

The regional groundwater dynamics, higher hydraulic conductivity interconnected soil lenses and pumping from different aquifers for reducing shallow watertable and salinity conditions are important externalities in determining the sustainable cropping patterns. An example of a model which can include these spatial externalities with economic options for the entire irrigation area is the regional hydrological economic model developed by Stubbs (2000). This model includes detailed hydrogeological response using a finite difference groundwater model of the irrigation area. The crop production and unsaturated zone fluxes are defined in the hydrologic economic framework as non-linear functions of net recharge, relative yield and irrigation water derived using detailed simulation results of a one dimensional finite element model. This model can simulate the impacts of different rice area policies and water trading over 15 and 30 year horizons using nonlinear optimisation techniques. To date this model has been applied in the MIA and CIA to investigate the impact of rice area restriction and water trading policies on the overall economics. Results of the regional hydrologic economic model indicate that rice should be grown in the shallow watertable areas where the rice water requirements are minimum.

4. DISCUSSION

The maximum rice water use, soil suitability and rice hydraulic loading policies alone may not be successful in achieving sustainability of rice based farming systems. These concepts cannot be applied uniformly to the entire irrigation area due to differences in depth to watertable, soils, groundwater dynamics and initial soil water conditions. With the introduction of water reforms the value of irrigation water has increased tremendously due to restrictions on water availability and water trading. Under the new water availability scenario, farmers are trying to maximise $/ML returns therefore management policies such as limits on rice areas and water use alone may not be enough to control watertables and percent salinisation. The shallow groundwater accessions due to ponding are strongly influenced by the regional groundwater dynamics which need to considered in formulating rice farming policies with objective of maximising economic returns for the region.

5. CONCLUSIONS

The following conclusions are drawn from this study:

- Simple water use tracking methods such as Leakypad model can be very useful in identifying paddocks with higher rice water use history.
- Models such as SWAGMAN Farm can be effectively used to develop and evaluate environmental management policies for rice growing areas.
- The farm scale model results clearly indicate that policies such as maximum rice water use, rice suitable soils and maximum rice areas alone fail to capture a number of important factors such as spatially variability in deep leakage to aquifers, initial volumetric soil water content, climatic variation and initial depth to groundwater.
- In developing any policies for environmental management of rice it is important to consider the total farm water and salt balance. A combination of recharging and discharging land uses can help achieve net recharge balance for the farm and the irrigation region.
- It is important to divide irrigation areas into groundwater management zones to help devise effective rice policies and to effectively implement groundwater management options.

Acknowledgements

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