MODELING SALT, WATER AND FINANCIAL BALANCES OF TYPICAL IRRIGATED FARMS IN THE MURRAY VALLEY, AUSTRALIA

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Abstract

The viability of irrigated agriculture in the Murray Valley is threatened by waterlogging and salinisation induced by rising watertables. By limiting net recharge to the watertable to zero or below, watertable rise can be prevented and the risk of watertable-induced environmental damage can be minimized.

Primary factors affecting the rate of net recharge to the watertable on a farm include: the as determined by soil type and farmer preferences, intensity of irrigation, depth to the watertable, leakage to deeper aquifers. Among these variables, the depth to the watertable and leakage rates are difficult to alter, whereas the landuse and intensity of irrigation can be managed such that net recharge is maintained at or below zero. Such changes to land use and irrigation management must give maximum profits if the farm is to remain a viable enterprise.

To determine the optional land use which give maximum financial returns to the farmer while maintaining net recharge and soil salinisation at zero, we have developed a non-linear programming model - SWAGMAN Farm. SWAGMAN Farm was used to study the effect of leakage, initial depth to the watertable, and landuse restrictions on total gross margin received and optimal intensity of irrigation.

Introduction

In irrigation areas and districts of the Murray Valley of Australia, agricultural enterprises vary from farm to farm. However, nearly all farms face two environmental problems: waterlogging and salinisation. The primary factor controlling these two environmental concerns is the depth to watertable below the soil surface. Depth to watertable is governed by the net recharge to the watertable and lateral groundwater movements. Therefore by managing net recharge to the watertable, the hazards of waterlogging and salinisation can be minimized. Such a strategy should also result in maximum economic return to the farmer.

In order to determine on-farm land use practices and intensities of irrigation which produce an optimum result (maximum economic returns, zero net recharge, and zero gain of salt in the rootzone), an optimization model, SWAGMAN Farm, was developed. The model takes into account distribution of soils within the farm, potential land uses, crop evaporative requirements, current irrigation practices, leaching requirement, annual rainfall, rainfall runoff, leakage to deeper aquifers, depth to watertable, capillary upflow from shallow watertable, salt concentration of irrigation water, groundwater, and rainwater, and the economic returns from potential land uses.

Model description

The objective of SWAGMAN Farm, subject to recharge and salinity constraints is to maximize total gross margin per farm, i.e.,

$$TGM = \sum_3 \sum_s GMLW_c - IRN_{c,s} *WATPRICE \qquad (1)$$

where,

TGM	Total gross margin ($)
GMLW	Gross margin of a land use less cost of irrigation water ($ ha^{-1})
IRRN	Irrigation in use (ML ha^{-1})
C	Land uses considered in a farm
S	Soil types in a farm

Soil types considered in the model were: clay (CLAY), loam (LOAM), and sandy loam (SLOAM). Land uses (C) considered in the model were: rice (RICE), soybeans (SOYB), maize (MAIZE), lucerne (LUCERNE), hay lucerne (HLUCERNE), fababeans (FABA), canola with 4 ML irrigation (CANOLA1), canola with 1.5 ML irrigation (CANOLA2), wheat with 4 ML irrigation (WHEAT1), wheat with 1.5 ML irrigation (WHEAT2), barley with 3 ML irrigation (BARLEY1), barley with 1.5 ML irrigation (BARLEY2), annual pasture (APASTURE), perennial pasture (PPASTURE), dry land wheat (DWHEAT), dry land canola (DCANOLA), and dry land annual pasture (DAPASTURE).

The objective function was solved using a non-linear programming solver, GAMS-MINOS (Brooke et al., 1988), subject to the following constraints.

Area constraints within the model

- SOYB, MAIZE, LUCERNE, CANOLA1, WHEAT1, BARLEY1, and PPASTURE were not to be grown on clay soils.
- Land uses on a particular soil type cannot exceed total area of the soil type.
- Area of a land use cannot exceed maximum allowable area (PMXA). The maximum limit was set to reflect real world considerations such as enterprise diversification, crop rotations, market demand, and restrictions set by natural resource managers.
- Area of a land use must be greater than minimum required area (PMNA).
- Minimum area of any land use (other than FALLOW) selected by the model must be greater than 10 ha to avoid inclusion of an inefficient area of a land use.

Salinity constraints within the model

- Salt was assumed to be brought into the rootzone by irrigation (0.12 dS m^{-1}), rain (0.0001 dS m^{-1}), and minimum rates of capillary upflow from the static watertable (concentration of groundwater).
- The total mass of salt brought into the rootzone by irrigation and rainfall, and salt brought to the soil surface by capillary upflow, was required to be removed by leaching and runoff, resulting in zero salt gain on the farm.
- The model required that salt brought into the root zone by irrigation water be removed by leaching. Therefore, part of the irrigation water was required to leach the irrigation borne salts. This leaching requirement was determined from the equation below. The leaching water will recharge the watertable, which ought to dissipate by leakage or capillary upflow. We assumed that the concentration of salt in leaching water was 2 dSm^{-1}.

$$LREQ = CIRRN * IRRN/CDWATER \qquad (2)$$

where,

LREQ	Leaching requirement, ML
CIRRN	Salt concentration in irrigation water, dS m^{-1}
IRRN	Irrigation amount, ML
CDWATER	Salt concentration of leached water, dS m^{-1}.

- Salt brought to the soil surface due to capillary upflow was required to be removed by rainfall runoff. Salt at the surface was assumed to be the product of capillary upflow and groundwater salinity. The upper concentration limit of salt in runoff water was set at 15 dS m^{-1}. This is consistent with data collected in northern Victoria.

Net recharge constraints within the model

- Net recharge to the watertable depends on recharge mechanisms (irrigation and rainfall in excess of actual evapotranspiration) and discharge mechanisms (capillary upflow and leakage to deeper aquifers). The net recharge was required to be equal to zero. It was determined using the equations below.

$$RECHARGE = \sum_{c,s} AREA_{c,s} * IRRN_{c,s} + AREA_c * GRAIN_c - AREA_{c,s} * AET_{c,s} \qquad (3)$$

$$DISCHARGE = \sum_{c,s} AREA_{c,s} * BRAIN_c + AREA_{c,s} . CUFLOW_s - TAREA * LEAKAGE \qquad (4)$$

$$NET\ RECHARGE = RECHARGE - DISCHARGE$$

where,

GRAIN	Rainfall during growing season of land use C(ML ha^{-1})
AET	Actual evaporation use by land use C (ML ha^{-1})
BRAIN	Rainfall during bare season of land use C (ML ha^{-1})
TAREA	Total area of farm (ha)
$AREA_{c,s}$	Area of land use C on soil S (ha)

LEAKAGE	Leakage from watertable to deeper aquifers (ML ha^{-1})
CUFLOW	Capillary upflow (ML ha^{-1})

Model parameters

Estimating minimum capillary upflow from a static watertable

Minimum rates of capillary upflow from a static watertable at 1 and 1.5 m depths under a bare soil (CUFLOW) were determined using a numerical model, HYDRUS (Kool and van Genuchten, 1991). Capillary upflow rates for depths in excess of 1.5m were estimates only. Minimum capillary upflow rates determined for Riverina clay, Mundiwa clay loam, and Hanwood loam were considered as the capillary upflow rates for clay, loam and sandy loam (Prathapar and Madden, 1995).

Estimating actual evaporation (AET)

Initially, monthly reference evaporation (RET) values were used to estimate RET during the growing season of individual crops (Meyer, 1995). The RET value of each crop was multiplied by a seasonally weighted crop factor to obtain seasonal crop evaporative demand (CET). The assumed 'crop factor' for a bare period during average rainfall years was 0.11. This 'crop factor' is considered adequate for summer months but may be too low for the winter period. A better estimate is required to reflect the winter bare-period crop factor.

Actual evapotranspiration (AET) was determined by multiplying the CET by a correction factor (PDFACT). This was to account for irrigation management as well as soil water deficit, and was determined with the equation:

$$PDFACT = 0.8-0.7*(CET-WAVAIL)/CET \quad (6)$$

where WAVAIL is the sum of irrigation and infiltrating rainfall during the growing season.

The actual evapotranspiration values and estimates of recharge for the land uses are presented in Table 1. Negative values of recharge imply water moving from the watertable to met evaporative requirements of the land use.

Representative farms

Six representative farms in the Murray Valley were considered for investigation. Characteristics of the six farms are summarized in Table 2.

Table 1. Estimated AET and recharge for land uses during an average year (mm)

Land use	AET	Recharge
Rice Clay	1203	293
Rice Loam	1203	493
Rice Sloam	1203	893
Soyb	689	385
Maize	581	486
Lucerne	1188	259
Hlucerne	1188	259
Faba	404	80
Canola1	461	115
Canola2	287	40
Wheat1	474	110
Wheat2	287	40
Barley1	392	85
Barley2	277	38
Apasture	416	187
Ppasture	1115	356
Dwheat	172	-7
Dcanola	172	-7
Dapasture	158	7
Fallow	210	-110

Table 2. Characteristics of representative farms

Farm ID[1]	Farm Number	Area (ha)	Clay (ha)	Loam (ha)	Sloam (ha)	GW Salinity[2]	DWT (m)
WKD	1	200	50	100	50	5	1
WKR	2	550	500	50	-	40	4
WKP	3	500	350	100	50	15	3
DNE	4	460	92	368	-	10	4
DNW	5	1000	750	250	-	20	7
BQR	6	284	160	124	-	3	3

[1] WKD: Wakool dairy farm; WKR: Wakool rice farm; WKP: Wakool mixed-pasture farm; DNE: Denemein East mixed farm; DNW: Denemein West mixed farm; BQR: Beriquin rice farm.

[2] Groundwater salinity in dSm^{-1}.

Major determinants of the model

Since the objective of the model is to maximize gross margins while constraining net recharge to zero, the model will initially choose that land use which gives maximum gross margin per unit of recharge. Therefore the primary determinant will be the recharge efficiency ratio (PER). We define recharge efficiency ratio as the ratio between gross margin and recharge for a land use. In general CANOLA, DWHEAT, CANOLA2, and DAPASTURE-D result in higher gross margins per ML of recharge than the other land uses.

Another important controlling factor is the ratio of gross margin to actual evaporation, which will identify land uses that result in maximum gross margin per unit of water used by the crop. Therefore, the secondary determinant will be the evapotranspiration efficiency ratio (ERR). In general, DCANOLA, CANOLA2, MAIZE, and APASTURE-D result in the highest gross margins per ML of recharge.

Table 3. The recharge efficiency ratio (PER) and evapotranspiration efficiency ratio (EER) of land uses during an average year.

LAND USE	PER ($ML⁻¹)	Land Use	EER ($mm⁻¹)
DCANOLA	-2759[1]	DCANOLA	115
DWHEAT	-1218	APASTURE-D	101
DAPASTURE-D	1173	MAIZE	97
CANOLA2	673	CANOLA2	93
DAPASTURE-M	461	SOYB	81
FABA	339	CANOLA1	70
LUCERNE-D	308	LUCERNE-D	67
HLUCERNE	288	FABA	67
CANOLA1	283	HLUCERNE	63
WHEAT2	282	PPASTURE-D	54
APASTURE-D	226	DPASTURE-D	53
BARLEY1	194	DWHEAT	51
RICE-Clay	175	RICE-Clay	43
PPASTURE-D	171	BARLEY1	42
SOYBEAN	146	RICE-Loam	41
WHEAT1	136	WHEAT2	39
BARLEY2	118	RICE-SLoam	37
MAIZE	117	WHEAT1	31
LUCERNE-M	114	APASTURE-M	30
RICE-Loam	100	LUCERNE-M	25
APASTURE-M	68	DAPASTURE-M	21
RICE-SLoam	51	BARLEY2	16
PPASTURE-M	36	PPASTURE-M	12
FALLOW	0	FALLOW	0

[1] A negative value indicates discharge

These two sets of coefficients are the major determinants of the model. However, the final results of individual runs will also depend on specific features and constraints attributed to individual farms. Generally, irrigated crops have higher evapotranspiration efficiency ratios and higher gross margins than dryland crops. This will result in the selection of irrigated crops over dryland crops, provided recharge is not limiting.

Sensitivity analysis

The model was used to determine the sensitivity of leakage to deeper aquifers, depth to the watertable and minimum rice areas on selected farms.

Leakage

The model was used to evaluate the sensitivity of leakage rates on gross margins and optimal intensity of irrigation on Farms 1, 2, and 3. The leakage rates used are -0.1, 0, 1, 0.2.25 and 0.4 ML ha^{-1} yr^{-1}. The following observations were made.

For farm 1, all five runs gave feasible solutions. Optimal irrigation intensity increased from 1.39 ML ha^{-1} (leakage = -0.1 ML ha^{-1} yr^{-1}) to 2.46 ML ha^{-1} (leakage = 0.4 ML ha^{-1} yr^{-1}). The upper bounds set for lucerne and hay lucerne were reached in all runs. This reflects high returns obtainable for lucerne on dairy farms. As the leakage increased, dry land annual pasture substituted irrigated pasture.

For farm 2, when there was upward leakage it was not feasible to meet salinity and recharge constraints. This farm had a deep water table (DWT = 4), and so the opportunity to discharge water in the form of capillary upflow was not available. Four other scenarios (leakage greater than or equal to zero) gave feasible solutions. Optimal irrigation intensity increased from 0.00 ML ha^{-1} (leakage = 0 ML ha^{-1} yr^{-1}). With an increase in leakage, dryland crops decreased and irrigated crops increased; notably FABA was introduced and DCANOLA was replaced by CANOLA2.

Depth to the watertable

The effect of shallow water tables was studied by raising the watertable to 3 m below the soil surface in Farms 2,4, and 5. This enables capillary upflow to occur.

For farm 2, when upward leakage was 10 mm it was not feasible to meet recharge and salinity constraints, i.e., the capillary upflow rates are still inadequate to offset upward leakage. Recall that the soil type in farm 2 is predominantly clay, which precludes a number of high-value irrigated crops. The optimum intensities of irrigation, without resetting the watertable at 3 m, were 0.0, 0.33, 0.98 and 1.7 ML ha^{-1}. In contrast, when the watertable was reset at 3 m, the optimum intensities of irrigation estimated for comparable runs were: 0.09, 0.53, 1.10 and 1.83 ML ha^{-1}.

For farm 4, when upward leakage was 10 mm, it was not feasible to meet recharge and salinity constraints. However, feasible solutions were obtained when leakage was zero. Recall that, for such a condition, and without resetting the watertable at 3 m, feasible solutions were not obtained. The optimum intensities of irrigation, without resetting the watertable at 3 m, for runs with positive leakage were 0.33, 0.98 and 1.55 ML ha^{-1}. In contrast, when the watertable was reset at 3 m, the optimum intensities of irrigation estimated for comparable runs were: 0.55, 1.14 and 1.62 ML ha^{-1}.

Minimum rice area requirement

For this set of runs, minimum area of RICE was set at 40 ha for farms 2,5, and 6. Runs were made with five leakage rates (-0.1, 0, 0.1, 0.25 and 0.4). For farm 2, feasible solutions were obtained when the leakage was 0.4. For farm 5, feasible solutions were obtained when the leakage was greater than 0.25 and the rainfall was average or wet. Farm 6 had no feasible solutions.

Although it is unfeasible to maintain zero net recharge in these farms if rice is grown on 40 Ha, rice remains the preferred crop for most farmers. Watertable rise in these farms may be avoided if groundwater pumping is adopted. For example, in farm 6, where the initial watertable depth is 3 m, growing 40 ha of rice will result in the watertable at a depth of 2.73 m in an average rainfall year. This watertable rise can be avoided if 1.68 ML ha^{-1} yr^{-1} of groundwater pumping is implemented.

Areas for further development

We believe that the model has performed in a logical manner for the runs carried out. However, some of the assumptions made in the model could be refined which would improve the model. This section outlines perceived weaknesses in the assumptions.

Estimating gross margins

The model uses gross margins as an indicator of profitability. Gross margins are simply income derived from an enterprise minus the variable costs directly associated with this income. The gross margin is not a profit figure and ideally should only be used to compared activities with similar resource use. As the model recommends optimal land uses, any major changes in a farm plan should be evaluated. This could be done externally to the model.

At present, the yield of a crop does not change as the level of water deficit changes. A crop-specific function need to be developed to account for this problem.

Salt and water balance of the farm

We assumed that the farms had reticulation systems, so that, irrigation runoff (drainage) was assumed to be zero. This may not be the case in some farms. Further, the levels of irrigation were not changed with changes in weather conditions. For example, RICE was assumed to use 20 ML ha^{-1} on a sandy loam, irrespective of weather.

Soil hydraulic properties

The optimal intensity of irrigation depends on minimum capillary upflow rates (CUFLOW) of soil types within a farm. Additional work is required to determine these rates under bare surface conditions and varying depths to the watertable.

Role of SWAGMAN Farm in the development and implementation of L&WMPs

Currently in NSW, Victoria and South Australia there is a move towards privately run irrigation systems, managed by irrigation boards. "For the privatization process to take effect, irrigation boards are required to develop Land and Water Management Plans (L&WMP) which are acceptable to Governments. We believe that SWAGMAN Farm has the following roles to play in the development and implementation of such L&WMPs.

SWAGMAN Farm could be used for educational purposes. Since SWAGMAN Farm accounts for aspects of agronomy, irrigation, salinity, soils, hydrogeology, and economics it can be used to evaluate the impact of a change in any one of the above variables. Therefore, agency personnel, members of irrigation boards, and the farming community at large will be in a position to understand the net effect of a potential change in farming practices.

Irrigation boards are required to identify and promote best management practices which will contribute to overall enhancement of the irrigated environment. We believe that SWAGMAN Farm could be used to determine guidelines for best management practices. Although SWAGMAN Farm is not comprehensive enough to be a farm management model, it can also be used by farmers to aid planning and management.

Conclusions

The following general conclusions can be made from this study:

1. The recharge efficiency ratio is the critical controlling factor. As the discharge capacity increased selection of a land use depended on the evapotranspiration efficiency ratio. However, the final solution depended on farm-specific characteristics and constraints.
2. As the leakage increased, total gross margin per farm increased.
3. The optimal intensity of irrigation (ML ha^{-1}) was low when the watertable was at depths below 3 m, the groundwater salinity was high, and the soil type in the farm was predominantly clay.
4. Considering the results of the study we believe that the optimal intensity of irrigation in the Murray Valley is approximately 2.5 ML ha^{-1} yr^{-1}, conditional on farm type, soil types and depth to the watertable. This compares with a current average rate of 4-5 ML ha^{-1} yr^{-1}.
5. When the watertable is deep and highly saline and the soil type is clay, it is advisable to avoid irrigation to prevent watertable rise and salinisation.
6. For a loam soil, when the watertable is deep and moderately saline, irrigation must be combined with groundwater pumping in order to maintain zero net recharge.
7. If area restrictions are not imposed as constraints, total gross margins per hectare received by the farm were high. This was primarily due to the cultivation of crops that had higher recharge and evapotranspiration efficiency ratios.
8. For the farm considered it is not feasible to maintain net recharge at zero and maintain rice area at 40 ha per farm, unless the level of leakage is high.

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Discussion

Dr. Prathapar's responses to questions from the audience were summarized as follows:

- Information on leakage is indeed essential for sustainable agriculture in this region. This information can be obtained, due to a well developed piezometer network in the area.
- Evaporation ponds in this region do not need to be lined, because they leak into an acquifer which is already saline.
- Agriculture in this region is sustainable, in spite of shallow and saline groundwater. This is possible due to high frequency of irrigation applications (every ten days), which remove the salt.
- Farmers accept the restrictions imposed on them to make irrigated agriculture environmentally sustainble, because they are consulted in the decision-making process through workshops. The model shows them the financial implications of various management practices. Acceptance is easier when farmers see that they can still make money.