A Tool to Aid Development of Land Use Strategies at a Catchment Scale to Reduce Dryland Salinity Risk

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Abstract: The Liverpool Plains catchment in northern New South Wales has a dryland salinity hazard. There is concern that current farming practices, in particular long fallowing, are increasing the risk of salinity due to increased drainage below the root zone compared to native vegetation. Previous work using field experiments and 1-D farming systems modelling has shown that, in this region, drainage can be substantially reduced by adopting opportunity cropping which is more flexible and intensive. That such systems can also increase profitability provides hope that the risk of salinity can be reduced without having to resort to large scale tree planting. However, the question arises of whether such farm level changes can have an effect on the salinity risk of the whole catchment. Farming systems modelling was used to predict long-term drainage, runoff and cropping gross margin for a variety of cropping systems and for pasture and woodland. For each land use, predictions were made for a matrix of climate × soil type combinations. A GIS was used to divide the catchment into 8 climate zones. The catchment was also split into 20 land mapping units (LMUs) on the basis of lithology and slope. The composition of each LMU in terms of soil types was estimated from soil landscape maps. Similarly the composition of each LMU in terms of land use was estimated from land use surveys and expert knowledge. The drainage and runoff (mm/yr) from each climate × LMU combination (CLMU) was estimated from the combined proportions of land use × soil type combinations and the model predictions for each. The relative contributions of drainage and runoff (m^3/yr) by different parts of the catchment can be estimated by multiplying by the CLMU area. In addition, the relative crop income ($/yr) from each CLMU was estimated. This tool can be used by catchment managers to assess the likely impact on unused water and cropping income of potential land use change in a particular CLMU simply by changing the land use proportions. The parameterisation and computation required by this approach is feasible because it separates the temporal and spatial components of the hydrology. A weakness is that it current ignores lateral hydraulic linkages in the landscape.

Keywords: Dryland salinity; Deep drainage; Catchment management; Farming systems modelling; GIS

1. INTRODUCTION

Dryland salinity is a hazard facing many agricultural regions of inland Australia. Clearing of native vegetation and replacement with annual crops with shallower root systems and fallow periods increases deep drainage below the root zone. This can increase the risk of salinity by raising groundwater levels and moving salts stored in the landscape into the root zone.

One dimensional farming systems models can be used to estimate the long term drainage under different land uses and to help design land management systems that reduce drainage. Drainage can be episodic, driven by particular combinations of weather and cropping sequences. Field experiments provide only a limited temporal sample of drainage events and models can be used, in effect, to extrapolate the results from field experiments to the longer term using historical weather data. They are most powerful when locally verified with data from such field experiments. Models also allow spatial extrapolation within a region, by allowing estimation of drainage for a variety of local soil types and climatic conditions. In addition, such models place the various land use options in an economic context, by providing estimates of long term productivity on which to perform economic analyses.

However, the question arises of whether farm level changes can have an effect on the salinity risk of the whole catchment. In this paper we describe a

Table 1. Cropping systems modelled in the long term APSIM simulations. F: fallow; S: sorghum; W: wheat.

Code	Cropping system	Code	Sub-system	Year 1	Year 2	Year 3
LF	Long fallow – 1 wheat and 1 sorghum crop every 3 years with 12 month fallow between each crop.	LF1	Phase 1	F	W	S
		LF2	Phase 2	W	S	F
		LF3	Phase 3	S	F	W
OP	Opportunity cropping – wheat and sorghum			Flexible according to soil water		
S	Continuous sorghum – 1 crop every year			S	S	S
W	Continuous wheat – 1 crop every year			W	W	W

Table 2. Pasture and woodland systems modelled in the long term APSIM simulations.

Code	Land use system (nominal)	Tree layer			Grass layer		
		LAI	Height, m	Relative fertility	LAI	Height, m	Relative fertility
Pu	Unimproved pasture	-	-	-	0.6	0.2	0.8
Pi	Improved pasture	-	-	-	1.0	0.2	1.0
T1	Open woodland	0.5	5	1.0	0.6	0.2	0.8
T2	Woodland	1.5	5	1.0	0.6	0.2	0.8
T3	Forest	3.0	5	1.0	0.6	0.2	0.8

modelling tool which places 1-D modelling results in a whole catchment context to assist catchment managers develop strategies of land use change to reduce the risk of salinity.

We build on previously reported modelling results [Paydar et al., 1999; Ringrose-Voase et al., 1999] for the Liverpool Plains catchment which covers 12,000 km^2 of the north west slopes of New South Wales. It is a highly productive cropping area but has a significant dryland salinity hazard. The question of whether changes to farming system significantly affect salinity risk are particularly pertinent because recharge to the groundwater system comes both from drainage under agricultural areas and from drainage and runoff from the ranges and hills, which enter the groundwater at the footslopes [Stauffacher et al., 1997]. Because the hills and ranges have higher rainfall and are largely under native vegetation, there is little opportunity to influence this component of recharge.

2. ESTIMATION OF 1-D DEEP DRAINAGE

2.1. Model Verification

A field experiment on the footslopes of the Liverpool Ranges was used to investigate the growth, productivity and water balance of various crop and pasture systems. The experimental data was used to verify a one dimensional farming systems model, APSIM (Agricultural Production Systems Simulator), [McCown et al., 1996] for local conditions as described by Paydar et al. [1999].

APSIM is a modular model which operates with a daily time step using historical weather data. This allows it to capture episodic deep drainage events. Some important features include:

- The MANAGER module allows complex or conditional management rules to be simulated, including rotations and sowing rules based on soil moisture.
- The water balance module (SoilWat2) simulates runoff, evaporation and deep drainage and provides water to the crop modules for transpiration. SoilWat2 is a 'cascading bucket' water balance model. The water characteristics of the soil are specified by the lower limit, drained upper limit and saturated volumetric water contents. Runoff from rainfall is calculated using the curve number procedure [Knisel, 1980].

2.2. Long Term Extrapolation

The verified model and 41 years of historical weather data were used to estimate drainage and productivity for a range of cropping systems (Table 1). The results for long fallowing (LF) are expressed as the mean of the three phases. Paydar et al. [1999] found long term drainage at the experimental site was significant under LF and continuous winter wheat (W) (30 and 37 mm/yr respectively) but negligible under opportunity cropping (OP) or continuous sorghum (S). Economic analysis [reported by Ringrose-Voase and Cresswell, 2000] showed that OP and S had similar or greater gross margins ($/ha/yr) to LF and W over the long term.

A very simple perennial vegetation module for APSIM was used to simulate pasture and woodland (Table 2) [Ringrose-Voase and Cresswell, 2000]. This showed that, at this location, pasture and woodland have no drainage.

2.3. Spatial Extrapolation

In order to simulate the various land uses for other locations in the Liverpool Plains, other climates and soils were selected that covered the ranges found in the Liverpool Plains.

31 major soil profiles types were selected from the Curlewis and Blackville 1:100,000 soil-landscape maps [Banks, 1995 and 1998] representing 94% of the mapped area. Representative profiles in the

Table 3. Summary of climate data for eight locations in the Liverpool Plains for 41 years (1957-1997).

Location	Elevation	Proportion of catchment represented	Mean annual: Rain	Potential evaporation	Frost*	Last frost*
	m		mm/year	mm/year	days/year	95th %ile
Gunnedah	306	34%	626	1884	32.4	3 Oct
Weblands	385	13%	627	1725	48.9	18 Oct
Quirindi	416	21%	652	1699	50.5	18 Oct
Parraweena	387	13%	680	1718	49.6	20 Oct
Berwicks	457	5%	718	1669	54.3	20 Oct
Roscrae	483	10%	744	1630	55.2	22 Oct
Willow Tree Highlands	892	3%	855	1419	78.3	17 Nov
Warung Forest	1211	1%	950	1366	110.1	12 Dec

*Frosts days were estimated as days with minimum ≤2°C.

survey reports were re-sampled for hydraulic characterization as described by Ringrose-Voase et al. [1999]. The data were used to construct soil parameter files for APSIM. Of the 31 soil profile types, 20 were suitable for cropping, with the remainder generally being too shallow or too steep.

Climate data for eight locations across the catchment over a 41 year period from 1957 were generated using 'Data Drill' [Queensland Centre for Climate Applications, 1998] which interpolates from historical data (Table 3). The sites reflect the considerable range in mean annual rainfall which varies from 570 mm/yr in parts of the plains (250 m elevation) to over 1200 mm on the top of the Liverpool Ranges (>1400 m elevation). Rainfall is summer dominant across the catchment. Cropping is possible at the 6 climate locations with the lowest elevations. Frost incidence in the plains increases towards the south (*cf.* Gunnedah in the north and Weblands in the south). This allows both wheat and sorghum to be sown earlier in the north.

The 6 cropping systems and sub-systems were simulated for 20 soils and 6 climate locations, giving 720 combinations. The sowing rules used to determine when crops are sown are described by Ringrose-Voase et al. [1999]. The rules include earlier spring and autumn sowing windows for Gunnedah than for the other locations.

The 5 non-cropping land use systems were simulated for all 31 soils and 8 climate zones, giving 1,240 combinations. All 1,960 simulations were carried out over 41 years. Results for the first year were discarded to remove effects of initial conditions and the long term results expressed as annual means of the remaining 40 years.

Runoff from rock outcrop was simulated for each climate location by assuming daily runoff equals daily rainfall less surface detention of 5 mm.

The drainage, runoff and gross margin results of the simulations were organised in 2-D matrices of annual means for each climate with one dimension being soil profile type and the other land use.

Ringrose-Voase et al. [1999] found that the reduction in drainage on changing from LF or W to OP or S was greatest in the highest rainfall areas. In addition, non-Vertosols, which occur on the sedimentary parts of the catchment, were identified as being particularly 'leaky' under cropping, especially since they are only suitable for winter cropping (*i.e.* W). Ringrose-Voase and Cresswell [2000] found that changing from the least 'leaky' cropping systems to pasture or woodland had little effect on drainage on the heavy clay Black Vertosols [Isbell, 1996] that make up much of the cropping area except in the higher rainfall areas. Conversion of cropping to pasture or woodland is more beneficial on non-Vertosols, because they are more leaky under cropping. Pasture and woodland produce negligible drainage in areas with less than 750 and 850 mm/yr rainfall respectively. Drainage does not differ significantly between woodland types (T1, T2, T3).

3. CATCHMENT WIDE INTEGRATION

3.1. Climate Zones

The catchment was divided into seven *rainfall* zones each represented by the location with the most similar annual rainfall. The driest zone, corresponding to Gunnedah and Weblands, was subdivided according to frost incidence along a line running roughly SW to NE through Tambar Springs and Breeza. The northern zone was represented by Gunnedah and the southern by Weblands. This gave eight *climate* zones in total.

3.2. Land Mapping Units (LMUs)

The catchment was divided into 20 hierarchical LMUs on the basis of lithology, slope and hydrogeology, using datasets available at scales of 1:250,000. First, the plains were defined as areas of Quaternary alluvium with slope <1%. They were subdivided into two units (LMUs 100 and 200) according to the flow rate of the underlying aquifer. Next, the remaining area was divided into six units according to lithology, each unit including any adjacent areas of Quaternary alluvium with slope >1% (LMUs 300-800). LMUs 300, 400 and 700 were of volcanic origin whereas

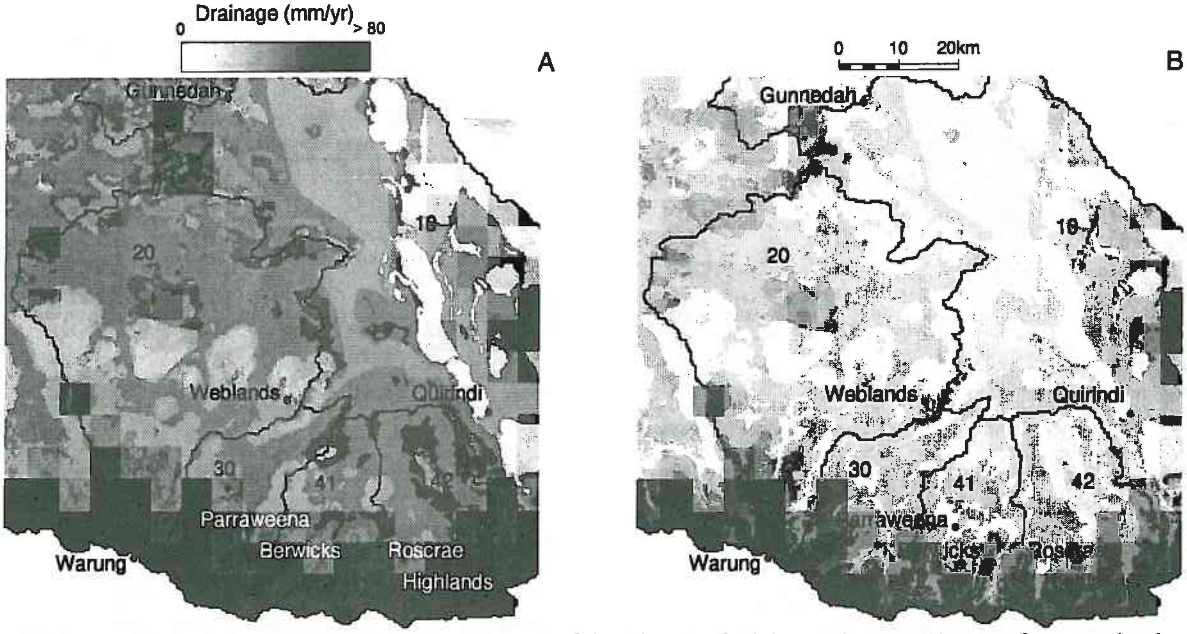

Figure 1. Predicted mean annual drainage in part of the Liverpool Plains under an estimate of current land use (A) and under land use strategies 1, 3 and 4 combined (see section 4) (B). Place names refer to climate locations in Table 3. Numbers refer to various sub-catchments.

500, 600 and 800 were sedimentary. These units were subdivided into three. The first subdivision (LMUs 310, 410 etc.) consisted of the areas of adjacent alluvium with slope >1%, which were considered to be colluvial. The second (LMUs, 320, 420 etc) consisted of remaining land with slope <8% and the third (LMUs 330, 430 etc.) that with slope >8%.

The LMUs served two purposes: to extrapolate the available soil survey information and to act as units for land use change.

3.2.1. Soil Profile Type Composition of LMUs

Soil-landscape mapping had been completed for about one third of the area [Banks, 1995, 1998]. A geographic information system (GIS) was used to estimate the composition of each LMU in the mapped area in terms of its constituent soil-landscape units (SLU). It was assumed that these proportions were the same in the unmapped areas on the basis that lithology and slope are reasonable predictors of soil type.

Each SLU comprises more than one soil profile type. The surveyor's report or expert judgement were used to determine the proportions of soil profile types making up each SLU. The proportion of rock outcrop in the survey report was also included as a 'soil type' in each SLU. Rock outcrop occupies only 5% of the whole catchment but up to 30% of some LMUs. It also produces much more runoff than any other soil type.

The soil type composition of each LMU is represented as a 1-D matrix of area proportions estimated by combining the soil type composition of each SLU with the SLU composition of each LMU.

3.2.2. Current Land Use Composition of LMUs

Broad categories of land use (woodland, pasture, cropping) within each LMU were estimated from 1:100,000 land use maps from 1985. The proportions of the cropping area under different cropping systems were estimated using local expert knowledge. Pasture was allocated to Pu and woodland to T2. The proportions represent current land use and are presented as 1-D matrices.

3.3. Climate × Land Mapping Units (CLMUs)

The climate zones were combined with the LMUs to produce CLMUs. Each CLMU has a single climate represented by one of the eight climate locations and defined proportions of soil types.

Each CLMU also has defined proportions of land uses, which can be either those representing current land use for the LMU or those representing an alternative land use scenario.

The area proportions of each combination of land use × soil profile type within a CLMU were calculated by multiplying the 1-D matrix of land use proportions by the 1-D matrix of soil types to produce in a 2-D matrix. This was not a simple multiplication but took the following steps:

- Because rock outcrop is not mapped as a land use, it was assumed it is included in areas mapped as forest and pasture. Therefore the 67% of the rock area was subtracted from the area of forest and 33% from that of pasture.
- Next the areas under various cropping systems were attributed *pro rata* to soils suitable for cropping.

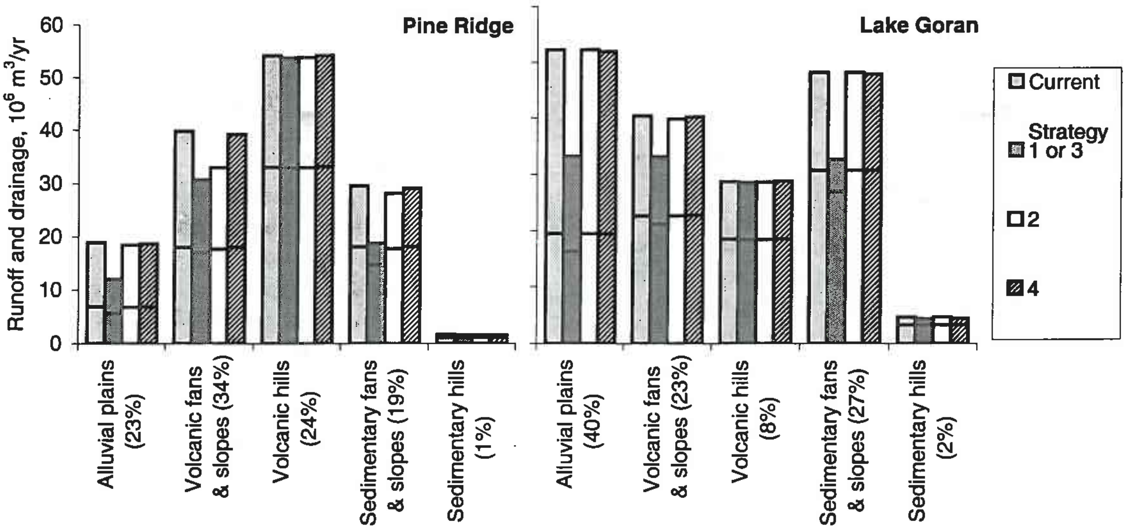

Figure 2. Mean annual volume of runoff (lower column) and drainage (upper column) from various parts of the landscape (with proportion of sub-catchment area in parentheses) under different land use strategies in two sub-catchments: Pine Ridge (labelled 41 and 42 in Figure 1) and Lake Goran (labelled 20)

- Finally the areas under pasture and woodland were attributed *pro rata* to the remaining area.

3.4. Estimating CLMU Drainage and Runoff

The mean drainage and runoff from a CLMU (in mm/yr) were estimated by multiplying the matrix of mean annual drainage or runoff values for the relevant climate zone (from APSIM) by the matrix of area proportions. The results can be expressed as drainage or runoff maps (Figure 1) which show the most 'leaky' parts of the landscape. The mean cropping gross margin ($/ha/yr) of each CLMU was estimated in the same way.

The annual volumes of drainage and runoff (m^3/yr) from each CLMU were calculated simply by multiplying by the area of each CLMU within the catchment or sub-catchment.

A tool for easy assessment of alternative land use scenarios was created to implement the above methodology for the catchment wide integration of APSIM results. It uses proprietary spreadsheet software to interrogate a database containing APSIM results.

4. APPLICATION

The modelling tool described above was used to assess strategies for land use change, one of whose aims was to reduce the risk of dryland salinity by reducing drainage [Dames and Moore Pty Ltd, 2000]. The strategies involve changing the mix of land uses in different parts of the landscape. The changes can be simulated simply by changing the area proportions of the land uses within the relevant CLMUs. This changes the area proportions in the land use × soil type matrix for the CLMU and recalculates the mean annual drainage from the matrix of APSIM results without further model runs (unless a new land use is introduced).

There are four strategies that can be implemented individually or together:

1. In cropping areas on Vertosols, convert LF and W to OP or S. Vertosols occur predominantly on the plains (LMUs 100, 200) and areas of volcanic origin (300, 400, 700).
2. Where rainfall >700 mm/yr, convert all cropping to improved pasture (Pi).
3. Convert all cropping on non-Vertosols to Pi. Non-Vertosols used for cropping occur predominantly in sedimentary areas (LMUs 500, 600, 800).
4. Increase tree cover in each LMU to a specified level considered appropriate for that LMU.

The predicted volumes of unused water (runoff + drainage) are shown in Figure 2 for two contrasting sub-catchments. Pine Ridge has a large proportion of volcanic hills with high rainfall. The unused water from this area, which cannot be easily reduced, forms a large proportion of the total for the sub-catchment. In Lake Goran the volcanic hills have less influence.

Clearly, Strategy 1 was the most effective, reducing total unused water by 11% in Pine Ridge and 15% in Lake Goran. It also increases total gross margins from cropping by 49% and 39% respectively. Relatively large areas (334 and 677 km^2 respectively) are involved mainly in the plains and volcanic slopes.

Strategy 2 is ineffective in Lake Goran and only slightly effective in Pine Ridge where it reduces unused water by 6% but also reduces crop gross margin by 44%, because 108 km^2 are taken out of crop production.

Strategy 3 involves removing cropping from the most leaky and least productive cropping areas (93 km^2 in Pine Ridge and 173 km^2 in Lake

Goran). It reduces unused water by 8% and 9% respectively. Crop gross margins increase by 7% in Pine Ridge, due to cessation of unprofitable cropping , but decrease by 5% in Lake Goran.

Although Strategy 4 involves converting large areas of pasture to woodland (129 km^2 in Pine Ridge and 165 km^2 in Lake Goran) it has only a negligible effect on the volume of unused water. This is because most of the plantings are in the lower areas where rainfall is moderate to low and drainage under pasture is already very low. It is possible that the extra rooting depth of woodland could intercept lateral flows of water and make strategically placed bands of woodland effective. This effect cannot be investigated with this tool because it ignores such lateral flows.

5. CONCLUSIONS

The modelling tool described allows 1-D modelling results from APSIM to be placed in a catchment context. The framework separates the temporal modelling by APSIM from the spatial modelling by ignoring lateral hydraulic connections. This causes some loss of realism where such connections are important and is the subject of further research. However, it has the advantage that it allows the potential impacts of land use change in particular parts of the landscape (CLMUs) to be assessed simply and rapidly by changing the area proportions of the various land uses within a CLMU without having to conduct more APSIM modelling.

The model avoids requiring specification of a single land use and soil type at each location, which would be inappropriate at the broad scale for which it is intended. Rather, each part of the landscape has a defined suite of land uses and soil types, allowing for spatial variation impossible to resolve at this scale.

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