Optimising farm dam irrigation in response to climatic risk

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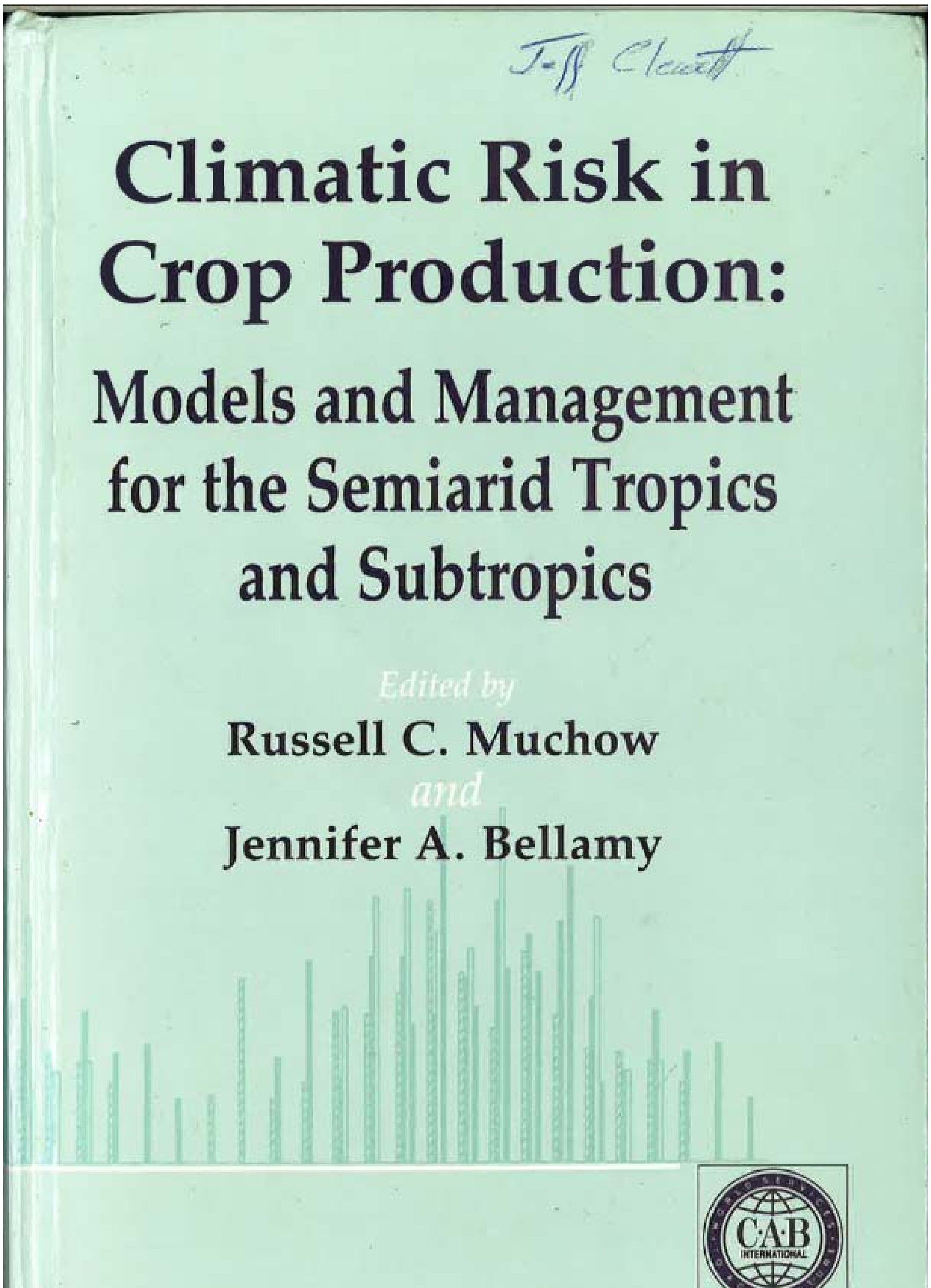

Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics

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CONTENTS

OPTIMISING FARM DAM IRRIGATION IN RESPONSE TO CLIMATIC RISK

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ABSTRACT

Although dryland cropping can be practised in some years in semiarid regions, low and unreliable rainfall creates a high risk of economic failure. Climatic risk can be reduced by the storage of ephemeral runoff in shallow dams for strategic irrigation of grain and forage crops. As these dams do not give a guaranteed supply of irrigation water, the productivity of shallow storage irrigation systems is still closely related to climatic variability. Optimal crop management therefore requires assessment of climatic risk. This paper uses a systems analysis approach to quantify the risk associated with shallow farm dam irrigation, and identifies the Southern Oscillation Index (SOI) as a useful tool for assessing short-term changes in climatic risk and improving crop management.

The SOI is shown to have a large effect on mean summer rainfall throughout Queensland, Australia. An increase in spring value of the SOI from strongly negative (less than -5) to strongly positive (greater than +5) is associated with a subsequent increase in mean summer rainfall of about 200 mm in the semiarid tropics, and about 100 mm in the semiarid subtropics. This change is in excess of 30% of the long-term mean summer rainfall for most locations in Queensland. Furthermore, the predictive relationship between spring SOI and summer rainfall enables probability estimates of crop production.

Principles of crop management are examined using a mathematical model (based on 10 years of experimental data) and computer simulation (based on 60 years of historical climate records), in a study of grain sorghum production from a shallow storage irrigation scheme at Richmond in north-west Queensland. These principles include the optimum design of a shallow storage system, and a strategy that optimises irrigation scheduling by giving priority to irrigation at sorghum panicle emergence. We show how spring values of the SOI are linked to subsequent and large changes in the probability distributions of rainfall, runoff, water storage, crop production and gross margins. The median gross margin in seasons with a strongly negative SOI value before planting was found to be negative (-\$38 ha^{-1}) compared with \$69 ha^{-1} in seasons with a strongly positive SOI before planting. These data are used to show how knowledge of the Southern Oscillation can be used to adjust optimum planting strategy.

Compared to long-term estimates of shallow storage production obtained from 60-years simulation, the results from 10 years of field experiments were found to be biased and, therefore, misleading because of above-average rainfall during the short experimental period. Furthermore, the time-series and probability distributions of runoff, crop production and gross margins produced by computer simulation were found to be very useful in extension to primary producers, because the information was in a form pertinent to management decision making.

INTRODUCTION

The temporal variation in rainfall in Australia's semiarid tropics results in high variability of agricultural and pastoral production (Dick 1958; Skerman 1978; Russell 1981). The perceived high frequency of drought has led to an almost emotional commitment by the Australian community, to achieve reliable crop production in risky environments by using irrigation (Davidson 1969). For social and economic reasons, both large irrigation schemes and on-farm storage of water have been constructed to capture excess rainfall.

This paper focuses on the collection of ephemeral runoff in shallow farm dams for irrigation of crops in the semiarid tropics. The design and evaluation of such schemes requires a systems analysis approach to find optimal solutions to: (i) design factors (topography, soil type, catchment area, dam site, size of dam, area of land irrigated); (ii) management factors (choice of crop, planting time and rate, irrigation time and frequency); and (iii) economic factors (costs, prices, interest rates, equity, utility).

The whole scheme can be described as the movement of water from the catchment through to plant use (Fig. 1). A simulation approach is required since such schemes are expensive to implement experimentally, and in risky environments, evaluation must occur over a long period to sample a range of climatic possibilities. Economic evaluation requires an accurate estimate of the probability distribution of production (Anderson 1991), and hence models are required to extrapolate results using long-term climate data to calculate the probability distributions.

Previous studies in northern Australia have shown changes in rainfall distribution and crop production on a 30 year time scale (Russell 1981; Clewett 1985; Hammer *et al.* 1987). Recent climatological studies (McBride and Nicholls 1983) have shown the importance of the Southern Oscillation as a source of seasonal rainfall variation in northern Australia. These two aspects of rainfall variability provide a basis for evaluating the effects of climatic risk on the performance of cropping systems.

This paper, firstly, reviews a detailed case study of a farm dam irrigation scheme on the Mitchell grass plains of north-west Queensland. This involves systems analysis to determine a set of decision rules to optimise design, irrigation strategy, and time of planting for grain sorghum production. Secondly, the scheme is re-examined to determine how fluctuations of the Southern Oscillation may be used to adjust optimal management strategies. Finally, a general framework is proposed for future evaluation of such schemes elsewhere in the semiarid tropics.

CASE STUDY OF SHALLOW STORAGE IRRIGATION

The major feature of climate on the Mitchell grass plains is the high year to year variation in summer rainfall (coefficient of variation of 48%). For example, the historical rainfall record at Richmond shows long periods (e.g. 1918-38) of generally below average rainfall (Fig. 2). This is consistent with the general pattern of historical rainfall in eastern Australia (Russell 1981).

The gently undulating topography and fertile, cracking clay soils of the Mitchell grass plains are well suited to cropping. Dryland cropping in the region was successful during above-average rainfall periods in the mid 1950's (Skerman 1958). However, the frequency of financially successful dryland cropping has been shown to occur in only 30% of years (Clewett 1969). Irrigation was seen

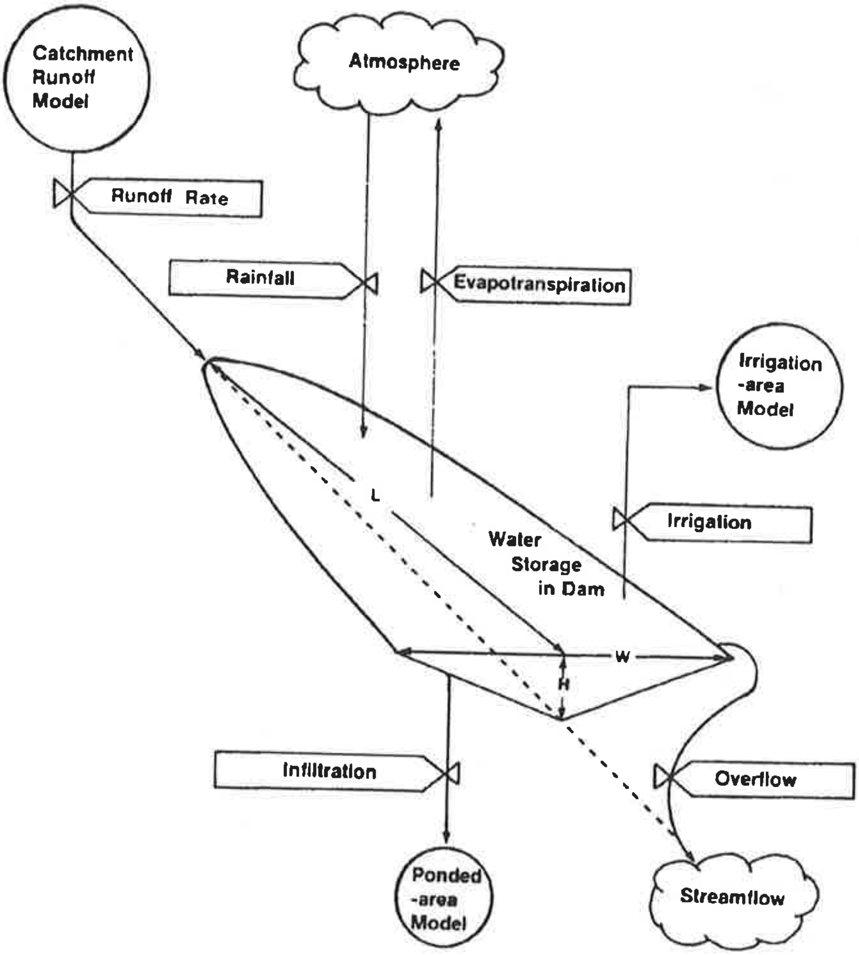

Fig. 1. Flow diagram of water balance sub-model for a shallow storage dam. (Water storage in the dam is shown as half an elliptical cone of height H, length L and width W.)

as a logical way to overcome the severe rainfall limitations to dryland cropping (Weston 1971).

The topography of the Mitchell grass plains is well suited to furrow irrigation and to storing ephemeral runoff from native pastures in shallow but expansive farm dams. Many graziers in the region have considered using these shallow farm dams for growing irrigated grain and forage supplements that can

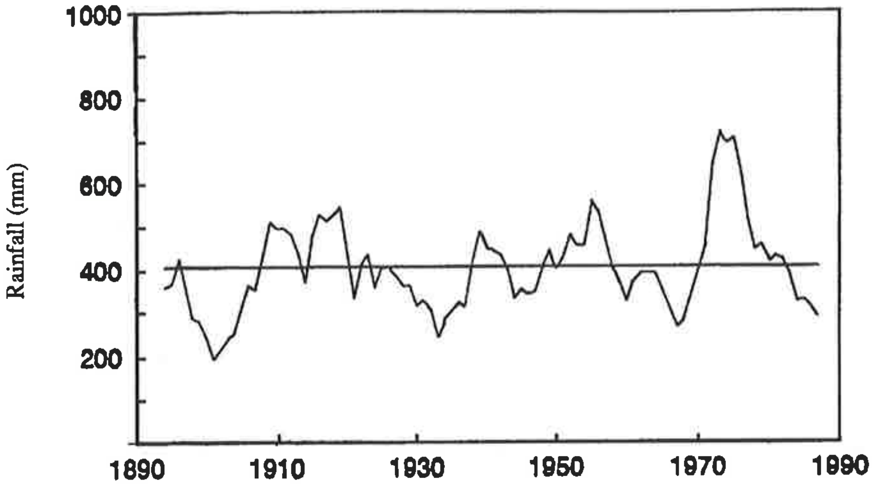

Fig. 2. Five year moving average of summer rainfall at Richmond, Queensland. The location of Richmond is shown in Fig. 6. Long term summer average rainfall is 404 mm.

boost wool and beef production. The use of such dams for irrigation of crops is termed "shallow storage irrigation".

Shallow storage irrigation systems are characterised by: (i) a native pasture catchment area producing ephemeral runoff; (ii) rapid evaporation losses of water temporarily stored in a shallow dam; (iii) strategic use of water stored in the dam for irrigation of crops such as grain and forage sorghum; and (iv) growing crops such as forage sorghum in the bed of the dam when it is not covered by water. This latter feature is termed "ponded-area" cropping and is practised by planting successive strips of crop around the edges of the dam as the dam's water line recedes due to irrigation and evaporation.

The following sections describe the field experiments, mathematical models, simulation experiments and the approach used by Clewett (1985) to evaluate shallow storage irrigation.

Field Experiments

The mathematical model of shallow storage irrigation developed by Clewett (1985) was based on data from field experiments conducted at the Queensland Department of Primary Industries' Richmond Shallow Storage Research Project in north-west Queensland from 1968 to 1977. The topography and soils of the experimental site are typical of the Mitchell grass plains. The experiments included: (i) daily observations of climate, free water evaporation from the dam, and runoff from a 160 ha native pasture catchment; (ii) regular observations of soil moisture on the catchment and under crops; (iii) investigations of the effects of irrigation strategy and plant density on the components of grain sorghum yield; and (iv) investigations of factors affecting the growth of ponded-area forage sorghum crops.

Modelling the System

The shallow storage irrigation system model comprises: (i) four physical component models to estimate catchment runoff, water storage in the dam, irrigated grain sorghum production, and ponded-area forage sorghum production; and (ii) a financial accounting model to estimate annual costs of crop production.

A water balance sub-model (Fig. 1) is included in each of the physical component models to account for: rainfall inputs to all components; runoff from the catchment forming stream flow into the dam; outflow from the dam; evaporation and irrigation losses from the dam; irrigation inputs to crop; evapotranspiration losses from pasture and crop; and deep drainage losses from all components with drainage from the dam as input to ponded area soil moisture. The physical shape of water storage in the dam is modelled as half an elliptical cone, and this was found to quite accurately estimate changes in the dam's volume, depth and surface area.

Different approaches are used to estimate changes in soil moisture for: (i) the catchment; and (ii) the cropping areas. Where infiltration via cracks is observed as an important process, a daily time step is used to estimate soil moisture changes in three soil layers for the catchment. Because of the significant influence that temporal changes in pasture biomass were observed to have on infiltration and runoff, the catchment runoff model includes a pasture biomass sub-model.

An event stepping procedure is used in the crop soil water balance sub-models, where changes in soil moisture status are related to cumulative evaporative demand. The step length is determined by changes in the phasic development of crops or when rainfall exceeded 3 mm. The event stepping procedure uses only 30% of the computing time required for daily simulation. Whilst modelling of infiltration via cracks is necessary for the catchment area, this process is not necessary for the irrigation-area due mainly to the disruption of cracks by cultivation.

The most important sub-model is the catchment water balance. Calibration of this model against observed data was carried out in three steps: (i) calibration of evapotranspiration parameters and estimated soil moisture against 33 observations of soil moisture in three soil layers; (ii) second-round calibration of estimated daily runoff against 32 observed values of daily runoff from a 160 ha weir gauging station; and (iii) third-round calibration of daily runoff. The third-round calibration was carried out after two daily runoff values were excluded due to spatial variability of rainfall. These values were excluded on the basis that it was deemed more appropriate to use a model which gave close agreement to observed runoff in a large number of cases, than to use a model which gave a mediocre fit to all observations. This calibration strategy is likely to be necessary in those cases for which the amount of runoff is the most important variable because the magnitude of runoff is small (1% of rainfall on average) compared to other processes, such as evapotranspiration. An important step towards simplifying model calibration in cracking clay soils is reported by Clewett (1984). This paper shows that field estimates of volumetric soil moisture can be satisfactorily calculated from observed gravimetric soil moisture without need to change bulk density in response to changes in soil moisture content.

The irrigated grain sorghum production model includes sub-models for: planting strategy (time and area); irrigation strategy (area, frequency and timing); phasic development; and yield. Grain yield is calculated from its components (grain number, grain size and lodging losses) with the components being estimated from plant density, evapotranspiration rates and temperature. Estimates of grain sorghum yield from the model were found to agree favourably with the observed grain yield used in model calibration (Fig. 3). No independent data sets were available for the Mitchell grass plains to test the model. However, the spatial homogeneity of climate, soils and topography of the Mitchell grass plains suggests that the model would be relevant to other locations in the region.

The ponded-area forage sorghum model includes sub-models for planting strategy (timing and area) and dry matter yield. Cumulative evapotranspiration and temperature were used as predictors of forage yield. The accounting model includes all operating costs, depreciation and interest on capital investments but excludes labour costs. Costs and prices are calculated to those applicable in 1978.

Simulation Experiment Methods

The system's model and long-term (60 year) weather records of daily rainfall and mean monthly temperature from the Richmond Post Office were used in a series of computer simulation experiments to determine long-term means of runoff and crop production, and to determine the probability distributions of these attributes.

Comparison of Experimental and Simulation Data

The simulation experiments showed large changes in crop production and costs of production due to: (i) climatic variability; (ii) changes in irrigation management; and (iii) changes in the system's design. The single most important factor affecting crop production was the effect of changes in the frequency and magnitude of catchment runoff on the availability of water for irrigation.

During the experimental period (1968-77), the mean and median depth of annual runoff from the catchment were measured to be 76 and 50 mm respectively. In contrast, the mean and median depth of annual runoff over the 60-year simulation period were only 35 and 5 mm respectively. This large difference in the probability distributions of annual runoff between the short-term experimental period and the long-term simulation period (Fig. 4) occurred because the field experiments coincided with a period of generally above-average rainfall. The average summer rainfall for the experimental period was 553 mm (36% above the long-term mean).

During this period there was sufficient runoff for irrigated cropping in eight out of the ten years, but in the 60-year simulation the frequency of sufficient water supplies was much less (42% of years), and in one period of eight years (1942 to 1949) there were seven years in which runoff was negligible. Average summer rainfall during this latter period was 326 mm (19% below the long-term average).

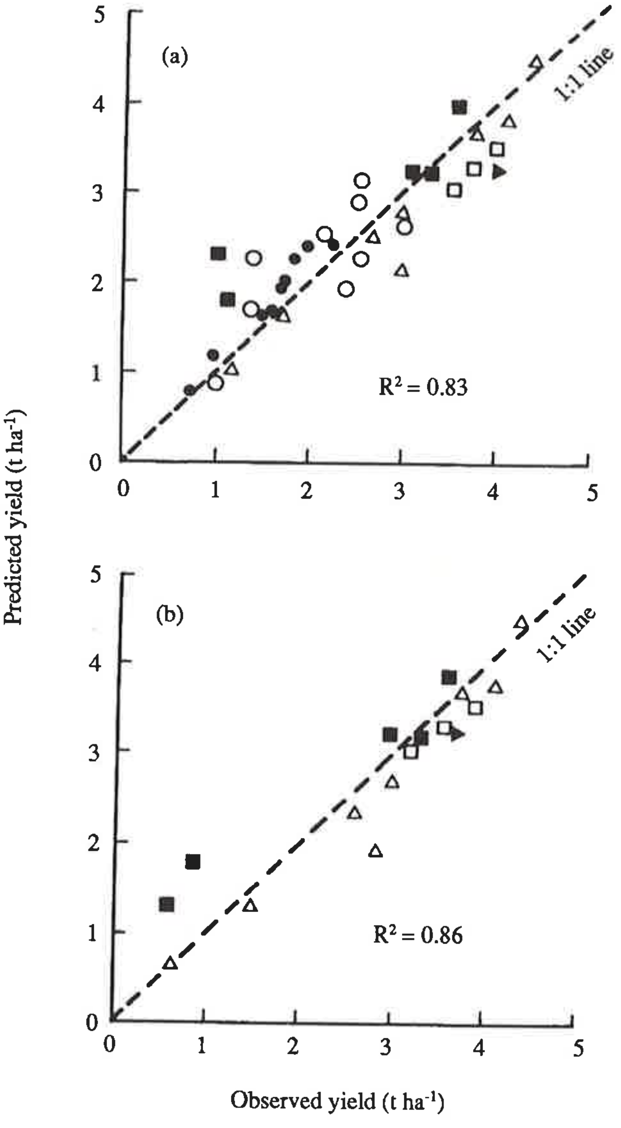

Fig. 3. Comparison of predicted and observed grain sorghum yield: (a) before lodging losses are deducted; and (b) after lodging losses are deducted. Data points with the same symbol were recorded from the same experiment.

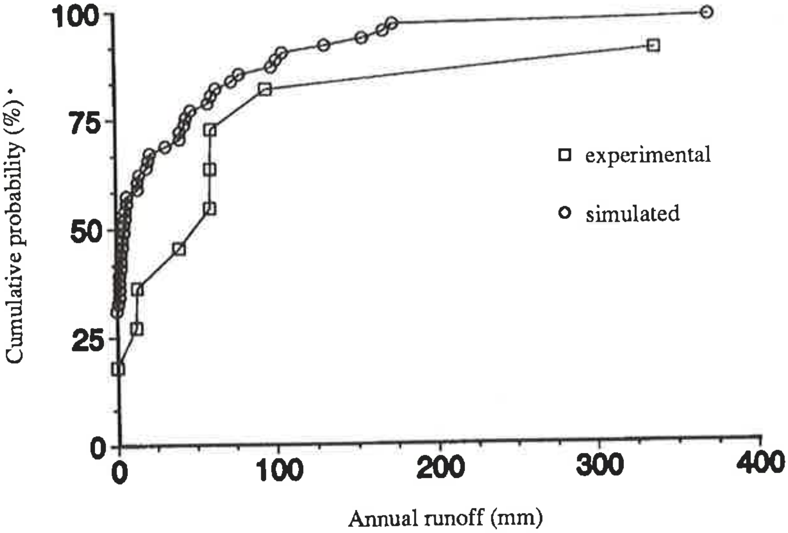

Fig. 4. Cumulative frequency distribution function for annual runoff from the gauged native Mitchell grass pasture catchment at Richmond. Both recorded data during a ten year experimental period 1968 to 77, and a 60-year simulation period 1918 to 1978 are shown.

It is clear that evaluation of optimum practices for shallow storage irrigation without reference to long-term weather records to normalise field data could give misleading conclusions.

Optimising Shallow Storage Design and Management

The number of factors effecting design and management prevents full factorial field and simulation experiments. The initial approach adopted (Clewett 1985) was to use a sequential optimising strategy of: (i) optimising the design of the dam and cropping system; (ii) optimising the management operations of irrigation and planting strategy; and (iii) reducing the conclusions to a set of simple decision rules for management and simple design equations amenable to easy calculation.

Optimum shallow storage design. In designing a shallow storage irrigation system, the first decision concerns the scale of operation. There needs to be a balance between the size of the irrigation area and the water supply as determined by catchment area and size of the dam. Topography at the dam site (measured by the gradient of the stream bed) is also important, as this has a major influence on the proportion of water lost from the dam by evaporation. The optimum balance between these factors is dependant on climatic variability.

A series of simulation experiments was conducted to determine the effects of change in shallow storage design on crop production and costs of production. The designs tested were those likely to cover the range of shallow storage irrigation systems to be encountered on the Mitchell grass plains, and included: catchment areas ranging from 400 to 4000 ha; stream gradients ranging from 1:125 to 1:2000; dam sizes ranging from 20 to 2000 ML; and size of irrigation-area ranging from 20 to 400 ha. These design changes were examined using an experimental design suited to response surface analysis.

Changes in crop production resulting from the above designs were found to be non-linear and interactive. Despite this complexity, it was found that two simple equations could be used to calculate the optimum shallow storage design. Response surface analysis of simulated crop production and costs of production showed that the optimum size of the irrigation area (A(opt),ha) and the optimum dam size (D(opt),ML) that minimised the cost per tonne of crop production could be closely approximated from:

$$A(opt) = 0.727\,P + 120\,P/C - 29.5 \qquad (1)$$

$$D(opt) = 3.19\,A(opt) - 721\,A(opt)/C + 0.360/G - 113 \qquad (2)$$

where: P is required level of long-term mean crop production (t); C is catchment area of the dam (ha); and G is gradient of the stream bed.

A general principle derived from the analysis was that dams should be constructed large enough so that, after accounting for evaporation losses, they hold just enough water to irrigate the entire irrigation-area twice without further recharge from runoff. This design characteristic should apply to most farm dam irrigation schemes in the semiarid tropics which use grain sorghum as the irrigated crop.

A typical situation for a shallow storage irrigation system on the Mitchell grass plains would be a catchment area of 2000 ha and a stream gradient at the dam site of 1:1000. If a long-term mean crop production level of 200 t was required from such a system, then the above equations give 128 ha as the optimum size for the irrigation-area, and 609 ML as the optimum storage capacity of the dam. When full, this dam would hold 30 mm of catchment runoff, store water to a maximum depth of 2.3 m, cover a ponded-area of 80 ha, and store 4.8 ML per ha of crop. If the irrigation strategy uses two irrigations at 30 and 60 days after the dam fills, then all water in the dam would be used with approximately half the water being lost to evaporation. This optimum design is used in the analysis given below.

Optimum irrigation management. The effect of irrigation timing and frequency on grain crops has been well documented from a qualitative point of view (e.g. Salter and Goode 1967). However, when seeking the optimum management of an irrigation system, it is necessary to quantitatively define relationships so that the outcome of competing processes can be determined.

Dryland grain sorghum yield was estimated to range from 160 to 3190 kg ha^{-1} with yield in excess of 1200 kg ha^{-1} (the estimated economic "break-even" yield) occurring in only 32% of years. Grain yield was found to increase with increasing irrigation frequency up to a maximum yield of 4387 kg ha^{-1} when three irrigations were applied. The relief of water stress by irrigation between panicle emergence and flowering was found to be more effective in reducing yield losses, than irrigation at other growth stages. The application of one supplementary irrigation timed to occur at early flowering was estimated to give a long-term mean yield of 3154 kg ha^{-1}.

In the absence of rainfall after planting, the effect of a single irrigation on grain yield was found to increase as the timing of irrigation was delayed until panicle emergence (Fig. 5a). In contrast, the area of land that could be irrigated was rapidly reduced as the time of irrigation was delayed due to evaporation losses from the dam and an increasing soil water deficit. The dominant relationship in these competing processes was found to be grain yield versus time of irrigation. Thus grain production increased as the timing of irrigation was delayed until panicle emergence and thereafter declined rapidly (Fig. 5b).

Optimum irrigation management was found to require a flexible approach to irrigation scheduling because of the large year to year variation found in water supplies from the dam. The cost per tonne of grain was minimised when the frequency and area of irrigation were altered according to conditions. This flexible strategy requires an initial scheduling of three irrigations (at the floral initiation, panicle emergence and grain filling phenophases). However, if water supply is limited, priority should be given to maximising the area of irrigation at panicle emergence. If there is enough water to irrigate the entire irrigation-area at panicle emergence, but not enough to apply three irrigations, then priority should be given to irrigation at floral initiation rather than during grain filling.

Estimating future water storage evaporation losses and crop soil moisture deficits up to 30 days in advance are key parts of this scheduling procedure. In the analysis given here, it is assumed that rainfall will not occur in the forecasting period and that evaporative demand continues at the same daily rate.

The flexible irrigation strategy defined above, is a simple but robust set of decision rules that will optimise water use irrespective of changes in shallow storage design and planting strategy.

Optimum planting strategy. There is a basic choice to be made with respect to time of planting. The first option is to plant as soon as sufficient rain occurs to assure crop establishment. The second option is to delay planting until sufficient runoff has occurred to provide enough irrigation water so that crop production is assured. The choice between these two options was not adequately resolved in the study by Clewett (1985). Planting on the first available rains was shown to have the higher long-term mean production. However, this strategy also had a much higher variability of production because irrigation water was not available in many years that crops were planted.

In this present study, we approach optimisation of planting strategy by examining changes in the probability distributions of rainfall and crop production that are associated with fluctuations of the Southern Oscillation. However, in order to derive general conclusions from our case study, it is necessary to firstly consider the impact and generality of the Southern Oscillation on summer rainfall at a statewide level.

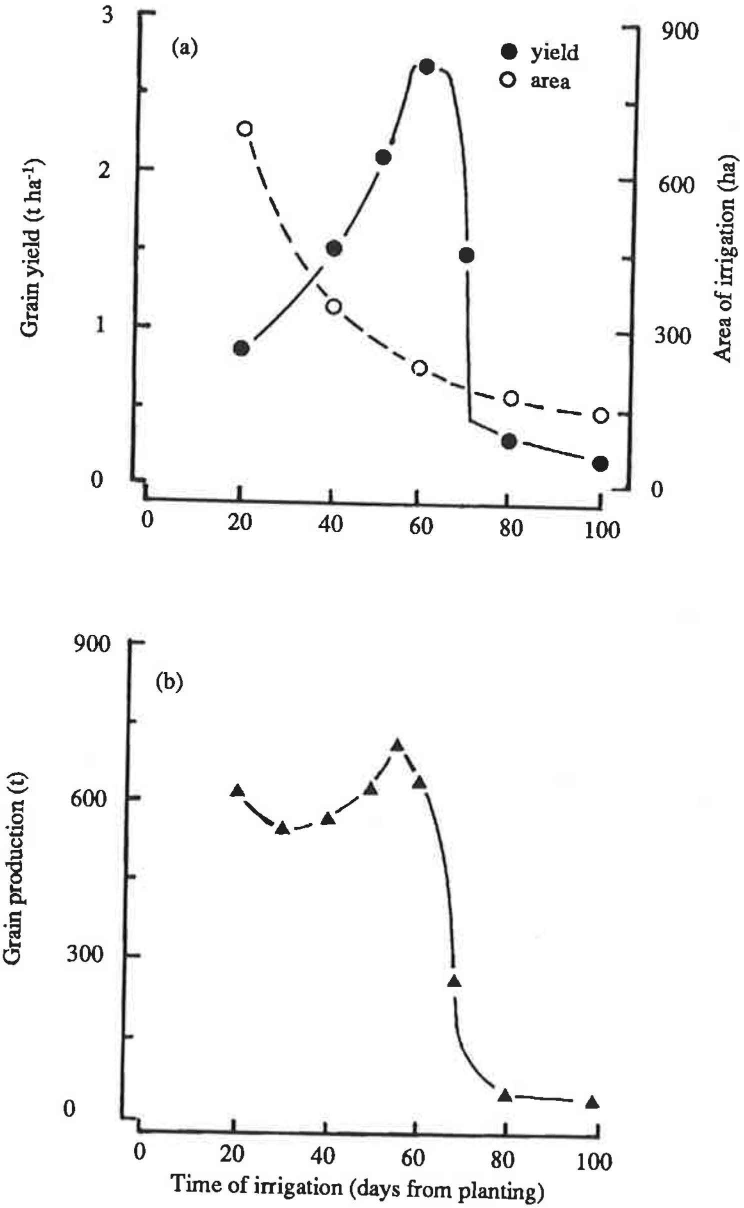

Fig. 5. Effect of: (a) time of irrigation on grain sorghum yield and area of irrigation; and (b) time of irrigation on grain production (i.e. yield x area), assuming soil moisture is at field capacity, the dam (600 ML, 2.3 m deep) is full at planting, no rainfall occurs after planting, and flowering occurs on day 60.

Effects of the Southern Oscillation on Rainfall

The Southern Oscillation can be measured by the Southern Oscillation Index (SOI) which is the normalised difference in atmospheric pressure between Tahiti and Darwin (Coughlan 1988; Nicholls 1991). Previous rainfall analyses (McBride and Nicholls 1983; Coughlan 1988) have concentrated on using the SOI to provide "outlooks" of above- or below-average rainfall in geographic areas where the correlation of summer rainfall with the SOI exceeds 0.4. At Richmond, there are positive correlations of summer rainfall to the SOI when either concurrent summer values of the SOI are used (r=0.42, n=98), or when values of the SOI from the previous spring are used (r=0.36, n=98). The strong persistence of the SOI from spring to summer makes the SOI a useful predictive tool.

In this paper, we use a different approach by examining probability distributions of rainfall related to classes of the SOI. Clewett *et al.* (1988) found that an effective analysis of the relationship between SOI and summer rainfall was obtained, when years were split into three approximately equal-sized categories based upon seasonal SOI values. The three categories were those seasons with SOI strongly negative (less than -5), between -5 and +5, and strongly positive (greater than +5). Analysis of rainfall throughout Queensland for these three SOI classes has not been previously reported.

The effects of the Southern Oscillation on summer (November to April) rainfall totals throughout Queensland were determined in this study using a database of 260 stations with long-term (i.e. 100 years or more) monthly rainfall records. At each location, the summer rainfall totals were divided into three groups based upon the SOI classes described above. These classes were formed from average values of the spring SOI (August to October). The number of springs with an average SOI in the three SOI classes (strongly negative, -5 to +5, and strongly positive) in the 100 year period from August 1888 to April 1989 was 31, 38 and 31 respectively. At all locations, the mean summer rainfall derived for each SOI class was input to a geographic information system to produce isohyet maps of Queensland. The maps have a predictive basis because spring SOI is used to plot summer rainfall.

The analysis shows a consistent shift of all isohyets across Queensland in a south-westerly direction as the SOI changed from strongly negative to strongly positive (Fig. 6). For example, in south-west Queensland, the 300 mm summer rainfall isohyet moves 300 km further west when the spring SOI changes from strongly negative to strongly positive. Similarly, in Central Queensland, the 500 mm isohyet moves about 300 km westward when the SOI shifts from strongly negative to strongly positive.

The difference in mean summer rainfall across Queensland between years with a strongly positive SOI and years with a strongly negative SOI is shown in Fig. 7a. A change in the spring SOI from strongly negative to strongly positive was found to cause increases in mean summer rainfall ranging from less than 50 mm for areas in the south-west to greater than 400 mm for areas on the "wet coast" near Cairns and Mackay. To express this difference in terms of the "normal" rainfall regime experienced at any particular location, the absolute rainfall difference due to SOI class was divided by the long-term average rainfall.

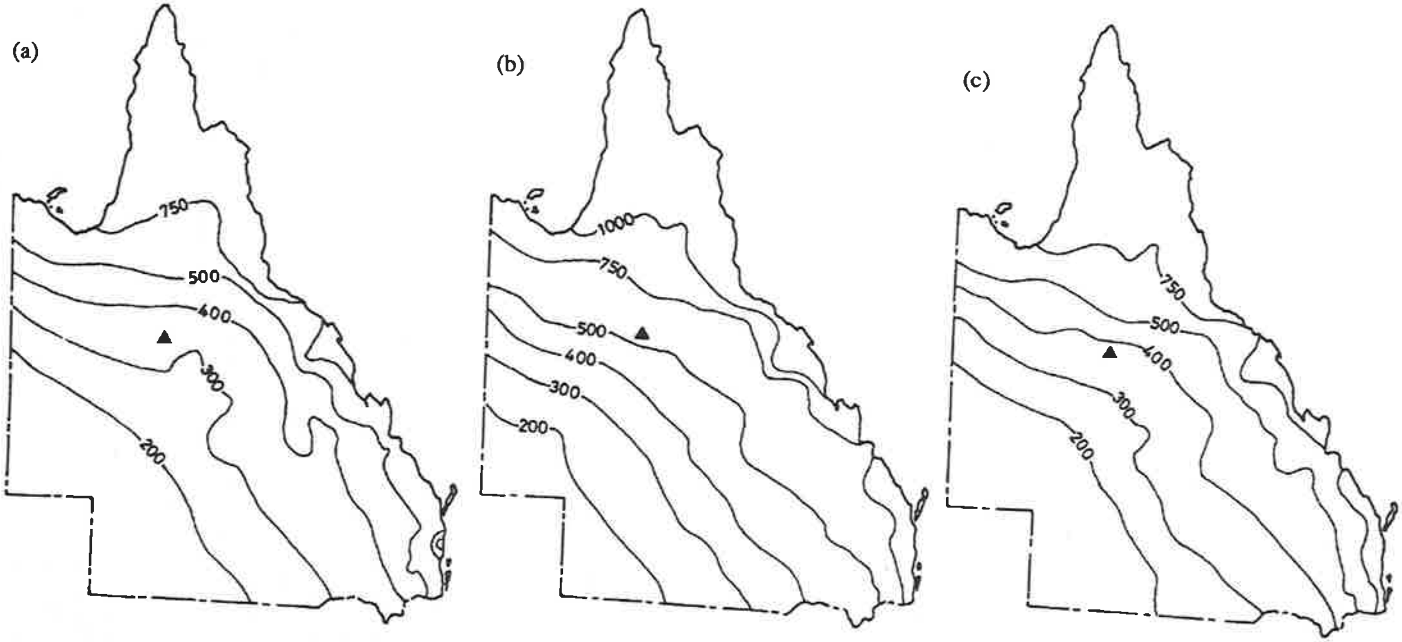

Fig. 6. Isohyets of mean summer rainfall (November to April) across Queensland for years when the mean value of the SOI in spring (August to October) was (a) less than -5, (b) more than +5, and (c) between -5 and +5. (▲ shows the location of Richmond).

Fig. 7b shows that the difference in summer rainfall associated with SOI class was greater than 30% of the long-term mean for most of Queensland and was less than 20% for only small areas in the south-east.

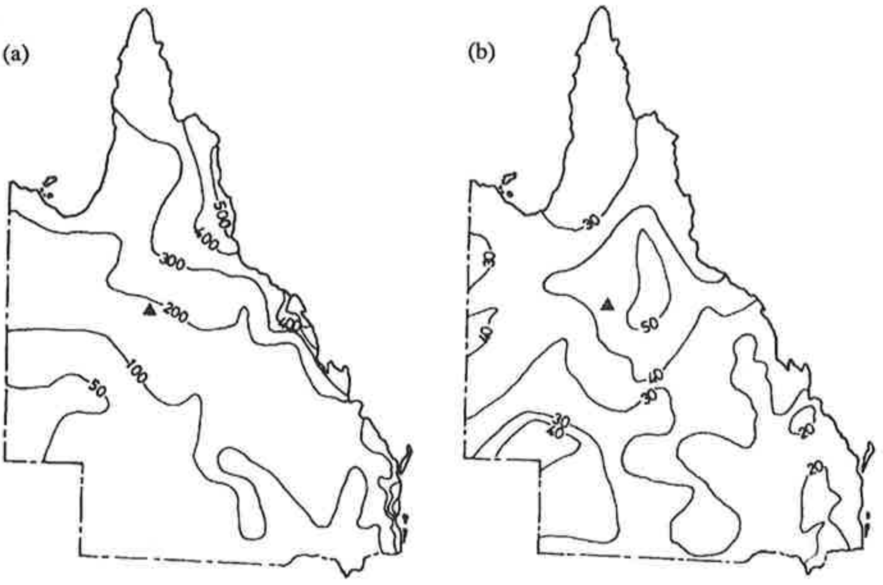

Fig. 7. Isolines of: (a) the differences in mean summer rainfall (mm) between years when the spring SOI was greater than +5, and years when the spring SOI was less than -5; and (b) this difference expressed as a percentage of the long-term average summer rainfall.

Probability distributions of summer rainfall in the three SOI classes were found to be very different in Central Queensland (Clewett 1988). Median summer rainfall (October to March) increased 47% (from 346 to 510 mm) when the SOI in October changed from strongly negative to strongly positive. At Charters Towers, Queensland, 70% of dry summers (rainfall less than decile 3) have occurred when the SOI was strongly negative, but only 4% occurred when the SOI was strongly positive (McKeon *et al.* 1990). For wet summers (rainfall greater than decile 7) these proportions were 4% and 63% respectively.

At Richmond, the probability distributions of summer rainfall (Fig. 8) show that both dry and wet summers may be expected when the spring value of the Southern Oscillation is strongly negative or positive. However, in years when the spring SOI was strongly negative, the median summer rainfall was only 305 mm compared with 531 mm in years when the spring SOI was strongly positive. This difference is 60% of the long-term median rainfall. Summer rainfall has been less than the long-term median rainfall (379 mm) in 67% of years, when the spring SOI is strongly negative. In contrast, there have been only 31% of summers with rainfall less than the long-term mean, when the spring SOI has been strongly positive.

The above analysis shows that the Southern Oscillation has large and relatively consistent effects on the mean, median and probability distributions of summer rainfall for Queensland. It therefore follows that the SOI could be a useful guide when seeking optimum management decisions in cropping systems.

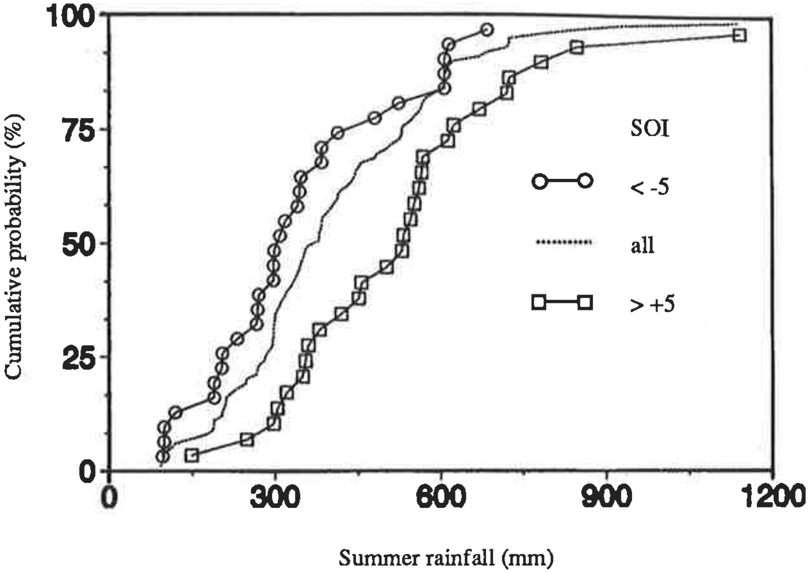

Fig. 8. Effect of Southern Oscillation on the cumulative distribution function for summer rainfall at Richmond.

Use of the SOI to Optimise Management

To determine the relationship between the productivity of shallow storage irrigation systems and the Southern Oscillation, the simulation results from each year of the 60-year simulation were grouped using the three SOI classes described above. The analysis was on a predictive basis because the SOI values used were the average SOI values for the two months before planting of crops. For example, if planting was estimated to have occurred in January, then the average November/December value of the SOI was used. Planting dates were estimated in each year as the first occasion after 1 December that rainfall recharged the surface 30 cm of the soil profile to capacity. If planting did not occur due to the lack of suitable soil moisture conditions, then the average value of the SOI in November/December/January was used. The number of years in each SOI class were 16, 25 and 19 in the strongly negative, -5 to +5, and strongly positive classes, respectively.

The effect of the Southern Oscillation on rainfall was found to carry through to both runoff from native pastures, and the yield of dryland grain crops as shown by the probability distributions in Table 1. These data, and the frequency data in. Table 2, show that strongly negative SOI values indicate higher risk of crop failure due to the lack of planting rains, lower yields from dryland crops, and lack of water supplies for irrigation. These factors have an additive effect on grain production from the system.

Table 1. Effect of SOI class on the probability distributions of annual runoff from the native pasture catchment area, and dryland grain sorghum yields.

	SOI class			Cumulative probability			Mean
		10	30	50	70	90	
Runoff (mm yr^{-1})	Less than -5	0	0	2	13	74	15
	-5 to +5	0	0	7	50	141	37
	More than +5	0	2	5	41	174	49
	All years	0	0	5	38	106	34
Grain Yield (mm yr^{-1})	Less than -5	0	0	199	248	2036	505
	-5 to +5	0	0	625	1420	2068	821
	More than +5	0	727	1023	1766	2172	1153
	All Years	0	188	672	1563	2070	844

Table 2. Effect of SOI class on planting frequency and supplies of irrigation water.

SOI class	SOI less than -5	SOI from -5 to +5	SOI greater than +5	All years
% of years with crops not planted due to lack of planting rains.	44	32	11	28
% of years with nil irrigation due to failure of catchment runoff.	13	12	5	10
% of years with limited water supplies for irrigation (not enough water to irrigate half the irrigation area)	25	16	47	27
% of years with a significant water supply (sufficient to water more than half the irrigation area)	18	40	37	35

When rates of evaporative demand were analysed with respect to the three classes of SOI, it was found that evaporative demand in January, February and March were 16% less in seasons when the SOI was strongly positive compared to seasons when the SOI was strongly negative. This can make a difference of 1 ML d^{-1} in the rate of evaporative loss from shallow storage dams (such as the optimum design described previously) and hence can make a significant difference to the area of land that can be irrigated. Similarly, McKeon *et al.* (1990) showed that the Southern Oscillation also affected plant growth through its effect on the efficiency of plant water use. In seasons for which the SOI was strongly positive, the atmospheric vapour pressure deficit was found to be lower and the efficiency of plant water use was higher in terms of dry matter growth per unit of water transpired. The reverse occurred in seasons with a strongly negative SOI. Thus the effects of the Southern Oscillation on plant production systems should be larger than its effect on individual climatic variables such as rainfall.

The probability distributions of grain production from the irrigation-area in our case study for the positive and negative SOI classes showed a much wider separation around the median than the corresponding distributions for rainfall. The median grain production for years with a strongly positive SOI before planting was 264 t (average yield of 2063 kg ha^{-1}, Fig. 9a), whereas, the median grain production for years with a strongly negative SOI before planting was 29 t (average yield of 226 kg ha^{-1} which includes zero yield in 44% of cases). This difference in grain production due to the Southern Oscillation is 132 % of the median grain production from all years (compared with 60% for rainfall).

The impact of the Southern Oscillation is also highlighted when profits are examined. The gross margin data (Fig. 9b) show that when the SOI is negative before planting, a loss is likely to occur in 70% of years. However, when the SOI is positive in the months leading up to planting, then a loss is likely to occur in only 30% of years. This large shift in profitability could cause a major change in crop optimal management.

Farmers have different attitudes to risk, but we suggest that many would accept a 30% risk of crop failure in any one year but not a 70% risk of failure. This has important implications for planting strategy. In years when the spring SOI is strongly positive, it would be sensible to proceed with land preparation during spring so that planting could occur on the first opportunity at which planting rains occurred after mid December. In contrast, in years when the spring SOI is strongly negative, it would be prudent to avoid the costs of land preparation until catchment runoff occurred and water supplies in the dam were assured. This delay in land preparation and consequent delay in planting would be likely to cause further changes, such as the need to irrigate at planting, or a switch from grain sorghum to winter crops or forage.

DISCUSSION

This study shows the importance of assessing crop production and management decisions over long periods of time. A feature shown by the 60-year simulations is the number of long periods where average gross margins were negligible, e.g.

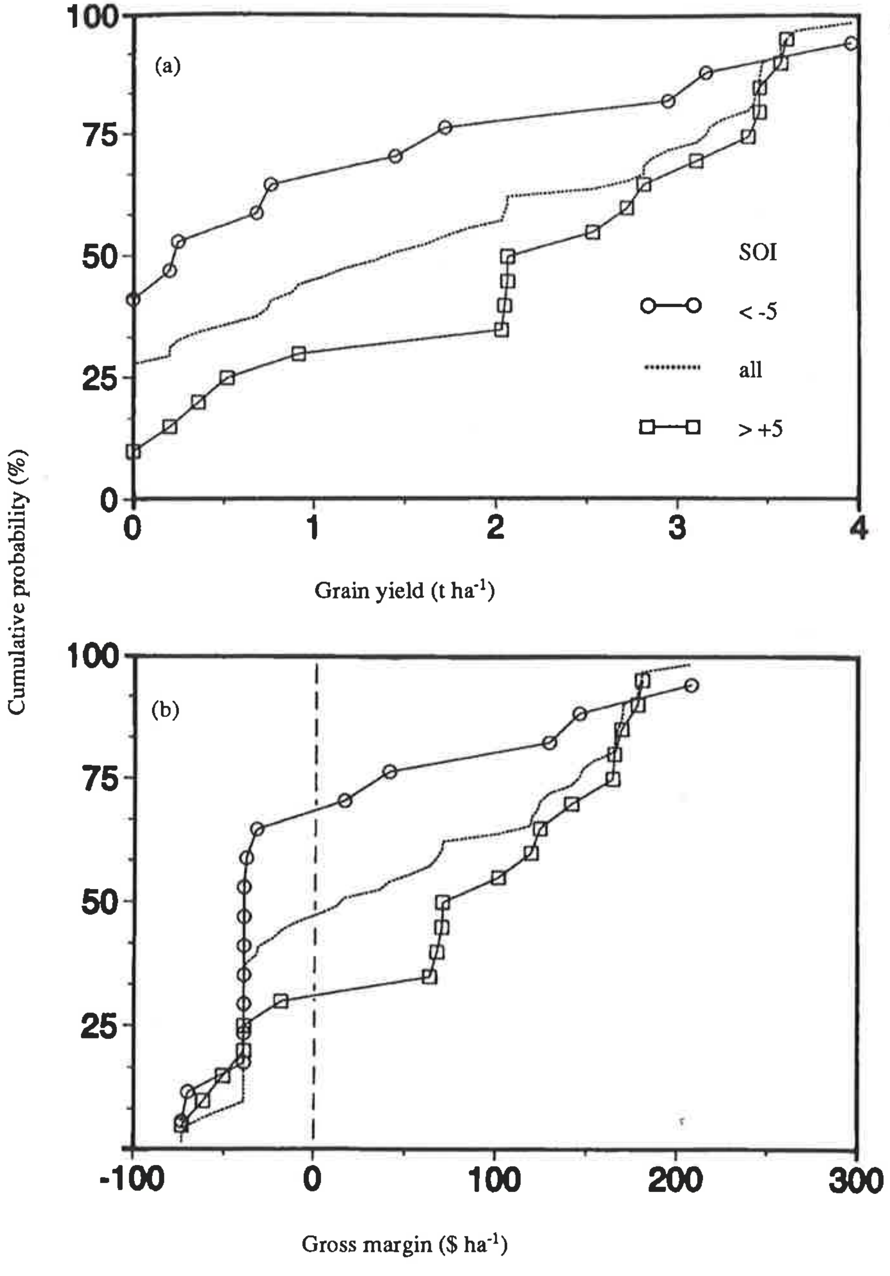

Fig. 9. Effect of the Southern Oscillation on the cumulative distribution functions for: (a) irrigated grain sorghum yield; and (b) gross margin.

1928-1937 ($-3 ha^{-1}); 1940-1949 ($6 ha^{-1}); and 1958-1967 ($-1 ha^{-1}); and the number of periods where average gross margins were high, e.g. 1947-58 ($105 ha^{-1}) and 1968-77 ($118 ha^{-1}). This finding is consistent with the general pattern of summer rainfall in eastern Australia (Russell 1981, 1988) and with evaluation of other cropping systems elsewhere in Queensland (e.g. Hammer *et al.* 1987). When all years of the 60 year simulation were considered, the overall risk of a negative gross margin in any one year was 46% (Fig. 9b). We suggest that most primary producers would be unlikely to accept this high risk of financial failure and would therefore reject the whole concept of shallow storage dam irrigation for crop production.

One method of enhancing the viability of shallow storage irrigation would be to choose only those catchments on laterite or limestone formations. These catchments are known to produce more runoff than Mitchell grass catchments, but they are relevant to only a small proportion of properties in the region (about 2%). A second method of increasing catchment runoff would be to denude the catchment area by over-grazing. However, this is undesirable in terms of soil conservation and probably animal production.

Expectations of summer rainfall decrease in a south-westerly direction across the Mitchell grass plains, and therefore expectations of runoff are also likely to decrease in this direction. Because Richmond lies on the northern boundary of the Mitchell grass plains, it is in a position of comparatively high summer rainfall. Therefore, the probability distribution of annual runoff (Fig. 4) found for the shallow storage experimental site at Richmond is likely to have a runoff expectation that is slightly higher than most catchments on the Mitchell grass plains. Therefore, shallow storage irrigation is likely to be less feasible at other locations on the Mitchell grass plains, than was found for Richmond. It is concluded that shallow storage irrigation is a non-viable option for property development on the Mitchell grass plains.

In extending information on shallow storage irrigation to primary producers, the direct use of results from field experiments has been of useful but limited value. Producers have had problems integrating isolated pieces of information to assess their impact on the whole system. In contrast, results from the simulation experiments (i.e. time-series and probability distributions of crop yields, profits and losses) have had an immediate impact, because the information is in a form pertinent to management decision making. The Richmond case study provides an example of the value of agricultural simulation models. Not only is the cost of simulation low compared to the field experimentation (Table 3), but the conclusions are judged to be more useful.

The SOI is most useful to management where the outcome of a decision occurs over a few months. Consequently, the SOI is useful in optimising time of planting but not for management of irrigation strategy where the outlook is several weeks, or for optimising shallow storage design where the outlook is over several years. Other aspects of management where the SOI may be useful include selection of crop cultivar, planting rate and fertiliser use. Whilst farm planning horizons for property development are typically 7 to 10 years, the timing of capital investments can be important. For example, it may be prudent to delay the purchase of new farm machinery if the SOI is strongly negative.

Table 3. Comparison of costs incurred for the field experiments at the Richmond shallow storage research project and the costs incurred for simulation modelling (salary and administrative costs excluded).

Cost	Field experimentation	Simulation modelling
Man years	22	4
Capital and operating costs	$89000	$6000

The percent difference in rainfall between strongly negative and positive phases of the SOI is amplified when runoff, cropping frequency, crop production and financial returns are considered. The analysis also shows the Southern Oscillation to be a useful predictor of summer rainfall, and to have large and relatively consistent effects on the mean, median and probability distributions of summer rainfall throughout Queensland. We therefore suggest that the effects of Southern Oscillation would be amplified in many plant and animal production systems throughout the tropics and subtropics of eastern Australia.

This conclusion can be substantiated by the grazing studies of McKeon *et al.* (1990) and the probability distributions of dryland grain sorghum yields developed by Hammer and Muchow (1991). For example, at Emerald in central Queensland, Hammer and Muchow (1991) show that when the SOI changes from strongly negative to strongly positive, there is a change in the median grain yield from 1.3 to 2.2 t ha^{-1}. This difference is 60% of the long-term median yield (1.5 t ha^{-1}). The same calculation for rainfall gives a 44 % difference, but the difference for gross margin increases to 102% (S. McMinimum, pers. comm.).

CONCLUSIONS

The approach using mathematical modelling and computer simulation in conjunction with long-term historical climate data is shown to be useful and efficient for the evaluation of agricultural systems. In comparison to the direct assessment of short-term field experiments, the interpretation of field data with modelling and long-term simulation is shown to: (i) be relatively cheap; (ii) provide better estimates of the mean, median and probability distribution of production; (iii) provide analyses outside the bounds of field experimentation; (iv) provide simple guidelines to the design and management of the crop production systems; and (v) provide information that is more relevant to the decision making processes of producers. The conclusion from these points is that mathematical modelling and computer simulation over long periods of time to determine probability distributions of outcomes are essential steps in defining optimal agronomic practices in the semiarid tropics where rainfall is highly variable.

The Richmond case study and consideration of the implications elsewhere in Queensland lead us to suggest a structure for future analysis of agricultural systems. The models developed in the Richmond case study were necessarily empirical given the unique properties of the Mitchell grass plains and the need to complete the evaluation before detailed crop models were available. The subsequent development of process-based models for runoff (e.g. Littleboy *et al.* 1989) and crop products (e.g. Hammer and Muchow 1991) provides the opportunity and capacity for evaluation of farm dam irrigation systems for a greater range of locations, climates and crops.

With the benefit of these models, we now suggest that simulation analysis should precede detailed collection of data for projects investigating the management of agricultural systems. The method should be to, initially, identify the major components of the system and the factors which are most important in influencing the behaviour of the whole system. If detailed data collection is required before an evaluation can be completed, we suggest that results from modelling and simulation should be used to establish priorities on the kinds of measurements to be taken, and the experiments to be conducted. If this approach had been possible with evaluation of the shallow storage system at Richmond, then greater emphasis would have been given to catchment runoff studies.

The implications of the Southern Oscillation on rainfall, agricultural production and agricultural decision making are greater than previously recognised. We have shown the SOI to be a powerful asset to management decision making. Therefore, in evaluating agricultural management there is a need to not only recognise climatic risk as a factor influencing optimum management practices, but there is also a need to develop decision rules which respond to changes in climatic risk caused by fluctuations of the Southern Oscillation.

The aim of optimisation studies should be to define for each area of management a set of simple rules with each set independent of other components within the system. For example, the management rules proposed for system design, irrigation and planting strategy are simple and not dependent on one another. Searching for globally optimum management rules is not very useful, if the result is complex and difficult to apply in practice.

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