Irrigation Practice and Infrastructure Design in the Variable Monsoonal Climate of Lombok (Indonesia)

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Keywords: *Irrigation, climate, water balance, Indonesia*

EXTENDED ABSTRACT

Rainfall in southern Lombok is highly variable, mainly due to variability in the monsoon. Irrigation infrastructure for the dry season in southern Lombok consists of small ponds (embung) used to irrigate small areas of crop. This study explores the potential benefits of constructing larger storages, as might be shared by several small farms. The proposed capacities are tens to hundreds of times larger than the ponds being used now.

Water balance simulation was used to assess the capture, storage and re-use of excess wet season rainfall in the dry season. These simulations indicate that runoff during the wet season ranged from an average of 102 to 161 mm, depending on the crop and soil type. However, a high percentage of years have no excess rainfall. Frequency distributions of the amount of water that could be stored were calculated for the main crops and a range of pump capacities (e.g. Figure 1).

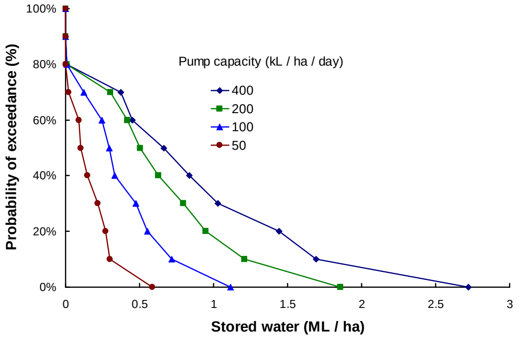


Figure 1. Pump capacity affects water storage. The data are for soybeans grown on permanent raised beds, 1973 to 2006.

Irrigation demand in Phase 2 (April to July) is typically 300 to 400 mm per season. Without irrigation, transpiration and crop yields are low. To ensure that the irrigation supply is substantial, the area cropped in Phase 2 must be kept small in relation to the catchment area cropped in Phase 1 (e.g. 0.1 ha per 1 ha). Benefits that may be obtained with such storages are shown in Figure 2.

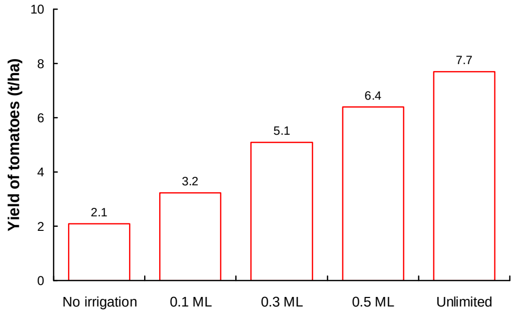
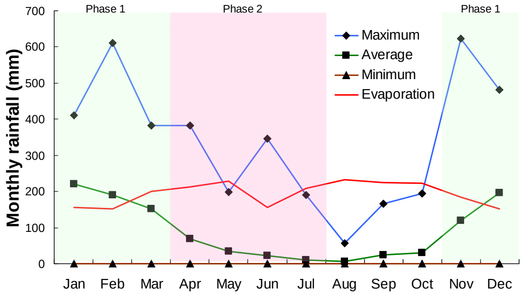


Figure 2. Average tomato yield (t DM/ha) for a range of store sizes (assumed full at the start of the season). Fresh weight ≈ 7 × dry matter.

1. INTRODUCTION

Rainfall in southern Indonesia is mainly associated with the monsoon, and is quite variable from year to year (Figure 3). This leads to difficulty in planning irrigation supply and demand at scales from farm to catchment.



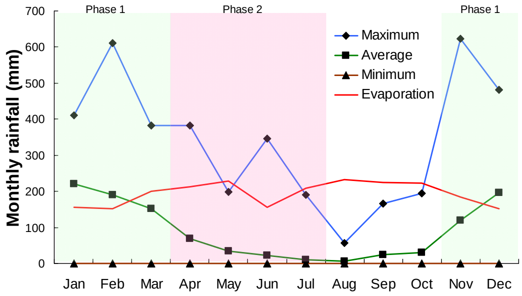
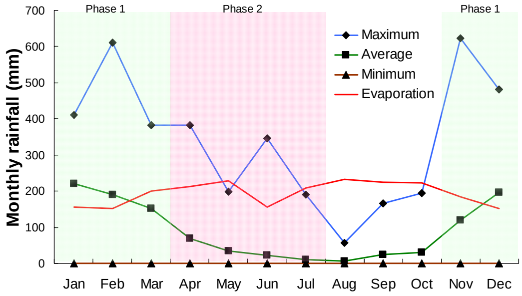
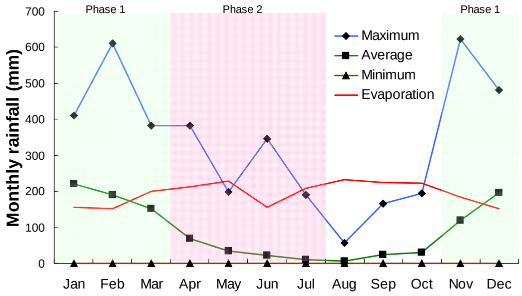


Figure 3. Monthly maximum, minimum and average rainfall (mm) at Mankung, Lombok, from January 1973 to December 2006.

At present, water storages in southern Lombok carry a small, though useful, supply through from the wet season to the dry season. The storages (embung) are typically a few hundred litres and the crop is typically a few tens of square metres.

It is expected that crop production in the dry season can be increased by expanding such schemes and modifying their management. This is because the climate of southern Lombok is conducive to high crop yields if irrigation water is available. Temperatures are warm to hot, and radiation levels are high. While the moisture deficit (rainfall less evaporation) in the wet season is usually low (Phase 1, November to March, Figure 3), variability in rainfall is high (Figure 3), and therefore some months and years will have substantial rainfall deficits while others will have rainfall excesses. The second growing period (Phase 2, April to July) includes the onset of the dry season, and the average moisture deficit is approximately 550 mm. Irrigation demand in Phase 2 is usually less than 550 mm due to moisture carried over from the wet season in the soil.





In this study, a water balance model was used to investigate water availability for storage and crop irrigation. Modelling had low cost relative to field studies, and provides estimates of some components of the water balance that are difficult to measure directly or via proxies. In particular, runoff estimates were required for calculating probability distributions of the amount of water that could be stored in the wet season for use in the dry season. Such distributions, combined with estimates of the yield responses of cropping systems to water supply, provided a basis for assessing engineering, agronomic and economic options concerning irrigation systems.

2. METHODS

A daily time-step model (HowLeaky?, Rattray *et al.* 2004) was used to simulate crop growth and the components of the water balance. It is derived from the PERFECT model (Littleboy *et al.* 1996, 1999). HowLeaky? simulates irrigation, rainfall infiltration, runoff, moisture re-distribution within the profile, and deep drainage. Weather records from Mankung, in south-central Lombok, provided data from 1973 to 2005.

Crop development was simulated using the growing degree days to crop maturity method (GDDM, C). At a nominated proportion of GDDM, the crop achieved maximum leaf area index (LAI), which, without temperature or water stress, was equal to the potential LAI. Stress-induced reductions in leaf area development reduced radiation interception and both dry matter accumulation (through radiation use efficiency), and yield (from dry matter and a harvest index).

Irrigation was simulated when a nominated deficit in water availability was exceeded. Irrigation occurred in either permanent raised beds (PRB) and paddies (ponds). For Phase 1 (Nov-March), irrigation in the PRB occurred at 40 mm of deficit, and in the paddy at 20 mm. In Phase 2 (Apr-Jun), all irrigation was in PRB, and occurred with 25 mm of deficit.

2.1. Soil parameters

The deep, basalt-derived soils are equivalent to the Black and Brown Vertisols of Australia (Stace *et al.* 1968). Some parameters for two soil types simulated in this study are shown in Table 1. The data were derived from the Soil Survey Report

(1996) and J. Tisdall *et al.* (pers. comm.) for soils in southern Lombok.

Table 1. Some soils parameters used in the simulations. PAWC is the plant-available water capacity to 120 cm depth. Moisture is shown in volumetric units.

Depth (cm)	Lower limit (%)	Upper limit (%)	Total porosity (%)	Maximum drainage (mm/day)
Black Vertisol (PAWC = 185 mm)				
0-10	14	35	51	50
10-30	18	34	46	12
30-60	21	33	38	8
60-120	24	32	35	5
Brown Vertisol (PAWC = 111 mm)				
0-10	16	33	47	25
10-30	14	31	41	10
30-60	20	30	35	6
60-120	24	29	32	3

Other parameters included the USDA curve numbers for estimating infiltration (Williams and LaSeur 1976). These were 75 for the Black Vertisol, and 78 for the Brown Vertisol. The soil evaporation model is that of Ritchie (1972), as used in PERFECT, and the evaporation parameters for both soils were set to U = 8 mm/day and Cona = 4 mm/day$^{0.5}$.

2.2. Crop parameters

The crops simulated were rice (paddy and PRB), soybeans, tomatoes and melons. Rice has the largest value for growing-degree days to maturity (GDDM, Table 2) and so is the last to mature for a given planting date. Typically, in Phase 1, rice takes 115 days to mature in Lombok (Mahrup et al. 2005). Soybeans are the first to mature, in about 100 days. Each crop develops maximum LAI, and therefore demand for water, at 60 to 75% of their total development time. Table 2 shows the full range of crop parameters for rice.

Decomposition of crop residues was simulated according to a simple model of daily rainfall and temperature. This was based on the relevant section of the SWAT model (Schomberg *et al.* 1994, Steiner *et al.* 1999).

Table 2. Crop parameters for rice.

Parameter	Units	
Growing degree days to maturity (GDDM)	C	2400
Radiation use efficiency	g/ MJ PAR/ m^2	2.5
Optimum temperature	C	30
Potential leaf area index (LAI)	m^2 leaf/m^2 ground	6
Time of maximum LAI	% GDDM	60
1st development stage	% GDDM	15
	% potential LAI	5
2nd development stage	% GDDM	50
	% potential LAI	75
Senescence coefficient	(unitless)	1.0
Harvest index	Proportion of dry matter	0.5
Maximum root depth	mm	600
Root extension	mm/day	20
Dry matter at full cover	t/ha	10

2.3. The farming systems

Phase 1 (November to March):

Sowing of all crops was simulated on the first occurrence of more than 60 mm of rainfall over a 7 day period, during a "window" beginning 14 November and ending 14 December. If sowing had not occurred by 15 December, then sowing and irrigation is simulated. Pre-plant tillage was also simulated.

Phase 2 (March to June):

Sowing was simulated on April 1 in all years, because Phase 1 crops mature in mid to late March. Due to its advantages in terms of irrigation efficiency (Mahrup *et al.* 2005), all crop options in Phase 2 are based on the use of permanent raised beds.

As well as full irrigation, scenarios in Phase 2 included no irrigation, and irrigation from limited supplies. The amount of storable water was calculated from the amount of runoff from PRB rice from 1 January to 31 March. Amounts less than 1 mm were considered uncollectible, and an upper limit was also applied (the "pumping capacity"). Scenarios included capacities of 50, 100, 200 and 400 kL/ha/day. In these scenarios, for each day that there is water in the store, a small amount is considered lost as leakage (0.2 mm/day).

The final analysis estimates responses in the components of the water balance and crop yield for tomatoes grown on water held in storages of different sizes. The storage is assumed to be full (1 m depth) on the planting date (1 April). During crop growth, further runoff is collected from the catchment farms, up to a daily limit of 200 kL/ha (20 mm) and direct "topping up" from rainfall.

3. RESULTS AND DISCUSSION

Phase 1 (November to March):

The components of the simulated water balances for the four options are shown in Table 3. Key results include: (i) irrigation demand varies from 107 to 236 mm, depending on the combination of crop and soil type, (ii) irrigation demand by paddy rice is substantially more than for PRB rice, due to more evaporation and deep drainage. This effect is greater on the Black Vertisol than the Brown Vertisol, and (iii) similar amounts (+/- 10%) of excess water (for the ponded systems) and runoff (for the PRB systems), regardless of the crop type on each soil type.

Irrigation demand is higher for all options on the Black Vertisol. This is because the extra PAWC (185 mm vs. 111 mm) frequently results in higher irrigation demand at the commencement of the season, when the soil is "wet up". Also, the Black Vertisol has better structure, resulting in more deep drainage. Less runoff from the Black Vertisol only partially offsets these effects.

It is not surprising that average irrigation demand is only 1 to 2.5 ML/ha, given the modest moisture deficits that are typical for this period. Under non-limiting water supply, actual transpiration of each crop is similar to the potential evaporation rate, due to the rapid development of the crop canopy (data not shown).

The differences in irrigation requirements between paddy and PRB-grown rice on the two soils were 41% and 30% (Table 3). These data are broadly consistent with the results of a field experiment in southern Lombok reported by Mahrup *et al.* (2005). They found that PRB reduced water requirements of rice by an average of 44% and 50% at two sites. Borell *et al.* (1998) has previously reported an average reduction in water use of 32% with PRB.

Table 3. Components of the water balance during crop growth in Phase 1on two soil types.

	Paddy rice	Rice	Soybeans	Tomatoes
		Black Vertisol		
Rainfall (mm)	641	641	541	569
Irrigation (mm)	236	155	107	129
Runoff (mm)	123	121	102	107
Transpiration (mm)	340	342	237	268
Evaporation (mm)	164	120	126	125
Evapotranspiration (mm)	504	462	363	393
Deep drainage (mm)	174	165	121	158
		Brown Vertisol		
Irrigation (mm)	193	135	95	113
Runoff (mm)	161	158	137	142
Transpiration (mm)	340	342	237	268
Soil evaporation (mm)	164	119	125	124
Evapotranspiration (mm)	504	461	362	392
Deep drainage (mm)	129	122	94	118

Due to limited rainfall in Phase 2 (April to July), the primary source of irrigation water will be runoff stored from Phase 1. This supply is highly variable from year to year (Figure 4). In the example shown, there is almost no excess water available for storage from 1988 to 1991. On the other hand, in some years sufficient rainfall will fall during Phase 2 (in the small catchment area) for runoff to also contribute to the supply from Phase 1. This effect is included in the analysis of crop yields in Phase 2, below. Figure 4 also shows that irrigation demand and excess have an inverse relationship, with a moderate amount of correlation (-0.51).

In Phase 1 transpiration by soybeans and tomatoes on PRB are less than for rice (Table 3) due to the shorter growing season and less leaf area (data not shown). Soybeans also have less simulated deep drainage than tomatoes, due to their deeper root system (900 and 600 mm, respectively).

At the end of Phase 1, soil moisture was nearly at the drained upper limit for both soils with most crops. For example, the mean for the Black Vertisol was 92% of the PAWC for PRB rice and 98% for paddy rice, and slightly higher for the Brown Vertisol. To simplify the analyses in Phase 2, plant-available soil moisture was set to 90% of PAWC at planting (1 April) for all scenarios. For brevity, the results shown below are only for the Black Vertisol. Because the Brown Vertisol generates more runoff (Table 2) the potential for storing water is greater than for the Black Vertisol.

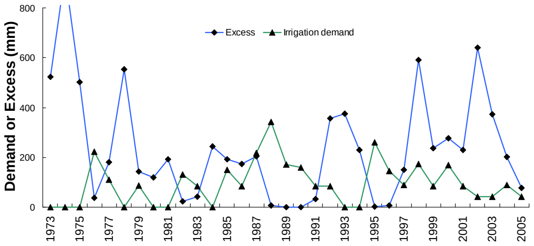


Figure 4. Annual simulated irrigation demand (blue) and excess rainfall (runoff, blue) for soybeans in Phase 1 on a Black Vertisol soil.

Phase 2 (April to July):

The components of the water balance for fully irrigated crops on the Black Vertisol are shown in Table 4. These data are quite different to the corresponding values for crops in Phase 1 (Table 3). Some of the differences include: (i) far greater demand for irrigation, (ii) less runoff, and (iii) less deep drainage.

Table 4. Average components of the water balance during crop growth (Phase 2, April to June) with full irrigation on a Black Vertisol soil.

	Soy-beans	Tomatoes	Melons
Rainfall (mm)	126	127	127
Irrigation (mm)	340	438	334
Runoff (mm)	9	11	9
Transpiration (mm)	340	379	303
Evaporation (mm)	114	144	137
Evapotranspiration (mm)	454	523	441
Deep drainage (mm)	17	32	28

Average irrigation demand for tomatoes, a common crop, is almost 440 mm for the season, equivalent to 4.4 ML/ha. To supply this amount of irrigation water to significant areas of crop in southern Lombok would require a radical change in irrigation infrastructure and management. Traditionally, the ponds (embung) have small catchments and small capacities – typically hundreds of litres rather than kilolitres or megalitres. Hence the area of crop irrigated in Phase 2 has been correspondingly small - typically tens to hundreds of square metres.

Storage-limited irrigation in Phase 2:

A typical example of the annual time course of water stored from runoff from a soybean crop on PRB is shown in Figure 5. These results are for soybeans and a daily pumping limit of 200 kL. As noted above, inter-annual variability is high, and the period includes 4 consecutive years without any stored water. Data equivalent to that shown in Figure 5 were calculated for a range of pump capacities. As capacity increases, the mean and median amounts of water stored increases, but there is a also a tendency for the increases to be small in drier years and larger in wetter years.

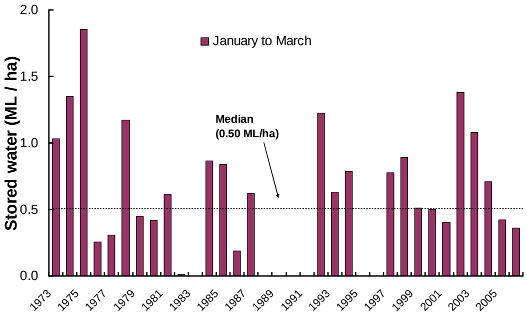


Figure 5. Annual water storage from soybeans grown on PRB in Phase 1, assuming a collection limit of 200 kL/day.

Converting the annual collection data shown in Figure 5 to a probability distribution produces the results shown Figure 6 for the case of 200 kL/ha/day (indicated by green squares). Similar data were derived for a range of pump capacities, and are shown. These curves again highlight the temporal variability and non-linearity of responses in stored water to pumping capacity. For example, no water is available in the driest 20% of years, regardless of pump capacity (i.e. at probabilities of exceedance of 80% and above). However, there is a large response in storable water in the wettest 30% of years. A change from 50 kL/ha/day to 100 kL/ha/day almost doubles the amount of water stored in this range of probabilities.

The following scenarios are for a 1 ha catchment cropped in Phase 1 that continues to generate some runoff in Phase 2, and which is then used to irrigate a 0.1 ha crop. Such a ratio (10:1) between catchment and cropped area allows meaningful rates of irrigation to be supplied. For example, a store of 0.3 ML, filled to capacity, supplies 300 mm (+ capture and – losses) of irrigation to 0.1 ha.

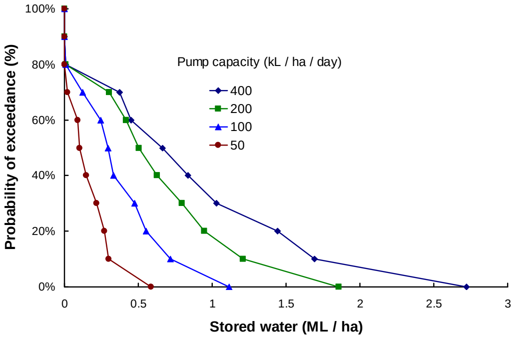


Figure 6. Pump capacity affects water storage. The data are for soybeans on PRB, 1973 to 2006.

With an unlimited supply of irrigation water, amounts of 25 to 35 mm are applied throughout the season, because 25 mm of soil water deficit is the "trigger" for irrigation. This demonstrated for a tomato crop in a typical year in Figure 7. Irrigation is less frequent if rainfall meets crop demand. Typically, rainfall frequency and amounts decline, and crop leaf area reaches a maximum mid to late in the period. Both factors maximise irrigation demand at the end of the period. Figure 7 shows that an irrigation supply limited to 0.3 ML is unable to meet much of the demand late in the season.

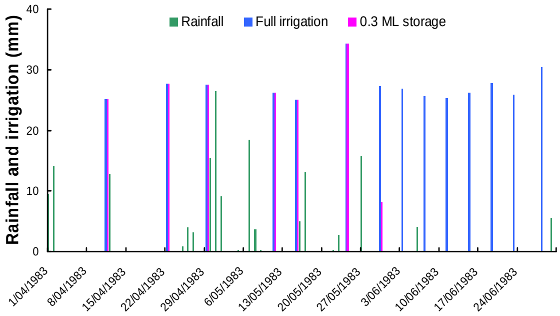


Figure 7. Daily rainfall and irrigation for tomatoes during Phase 2 in 1983. Irrigation events are shown for scenarios of unlimited irrigation and 0.3 ML of storage.

The mean effects of limited irrigation storage on irrigation, transpiration and other components of the water balance are shown in Figure 8. Comparison of the nil irrigation scenario and unlimited irrigation shows that the increases in runoff and deep drainage were 18% and 25%, respectively. In terms of absolute amounts, the change in these components is negligible (1 mm and 9 mm, respectively). Transpiration is the fate of almost all of the extra irrigation water applied as the simulated storage is increased (Figure 8).

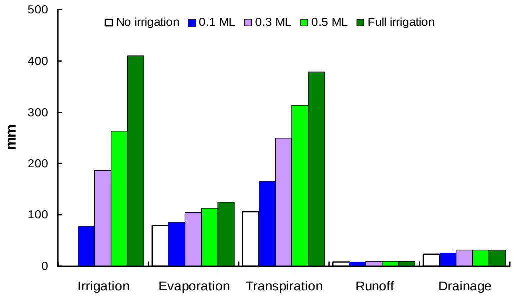


Figure 8. Responses in the water balance of a 0.1 ha tomato crop in Phase 2 to irrigation from storages of different capacities. The storages are assumed to be full at planting.

Yield is likely to be nearly proportional to transpiration. The high correlation between the two ensures that transpiration efficiency (kg of yield per mm of transpiration) is relatively constant, and is therefore a valuable tool for estimating crop yields. It is likely that the increase in transpiration that may be obtained from larger storages will proportionally increase yield. However, this will not be equally true for all crops. The relative impact on crop yield will probably be least for crops that "avoid" drought by having less leaf area, shorter durations and deeper root systems. Temporal patterns of radiation interception and conversion efficiency also play a role.

Figure 9 shows the simulated yields of tomatoes for three storage scenarios. Yield increases for the other crops followed a broadly similar pattern, and were similar to the pattern of response in transpiration shown in Figure 8.

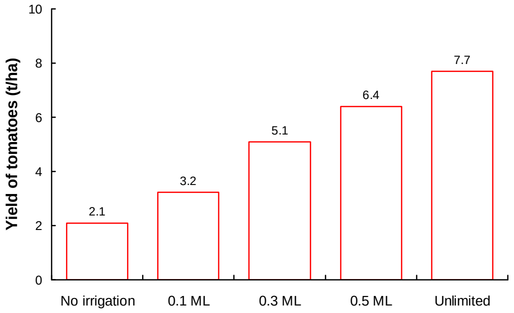


Figure 9. Average tomato yield (t DM/ha) in Phase 2 with a range of irrigation capacities, assumed full at the start of the season. Fresh weight is approximately seven times the yield.

4. CONCLUSIONS

In Phase 1 (Nov to March) paddy rice requires more irrigation than any of the crops grown on PRB, including soybeans. Non-sodic, wellstructured soils require more irrigation than sodic, poorly-structured soils. These results might provide a useful guide to irrigation efficiency in areas and in years when the supply is limited in Phase 1.

Runoff during Phase 1 was equally variable. No significant runoff occurred in some systems for consecutive years. This presents a significant problem for irrigation development because there is a high opportunity cost of setting aside land for water storage during Phase 1, when rice yields are high and the area of available land is a major constraint to production. To set aside land for storage and have it remain unused in dry years may be unacceptable to farmers. Perhaps the base of these storages could be planted with crops that would be sacrificed if runoff water becomes available.

Important information can be obtained about potential returns from developing water storages by coupling the probability distributions of stored water (Figure 6) and relationships between yield and storage (Figure 9). Correlations between the climate of Phase 1 and 2 may also be important (i.e. are Phase 1 supply and Phase 2 demand coupled?).

There is high inter-annual variability of irrigation supply and demand, leading important trade-offs in management and infrastructure design between increasing losses of crop yield in Phase 1 and increasing yields in Phase 2 as the size of the store increases.

Water balance modelling has provided low-cost insights into management options for irrigated agriculture in southern Lombok. However, the results and have not been validated, and are based on "best bet" parameterisation of the model. The accuracy of the results might be improved through better parameterisation, especially concerning: (i) crop characteristics and management, (ii) leaf area index, radiation interception, dry matter yield and the economic yield of crops, (iii) soil characteristics, particularly the hydraulic conductivity of the subsoil.

Overall, the agronomic, engineering and economic problems studied are not simple ones. There is a complex array of combinations of pumping rates and types, storage configurations and sizes, irrigation systems, crop types and other factors. This analysis provides a basis for further analysis and decision-making.

5. ACKNOWLEDGMENTS

This work was partly funded by ACIAR project through project SMCN/2002/033.

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