Runoff impoundment for supplemental irrigation: An economic assessment

F. G. Scrimgeour and G. W. Frasier

Abstract. *Water harvesting technologies capture surface water runoff and recycle it for productive use. Despite the long history of water harvesting and the renewed interest in many places in the world, the technology has not been widely adopted in the United States, in part because of a lack of understanding of its economic benefits. We developed a simulation model for the economic evaluation of water harvesting systems that combines agronomic, engineering, and economic factors and daily meteorological data. The simulation model was used to investigate the economic feasibility of using a water-harvesting, supplemental irrigation system for grain sorghum production over a 44-year period at two locations in Texas. Water harvesting combined with supplemental irrigation was most successful where the precipitation is the highest. However, the net benefits were extremely variable from year to year. The modeled technique could not take advantage of the potential additional water in the wet years and did not harvest sufficient water in dry years to make water harvesting more economically attractive than conventional dryland farming. This does not mean that runoff farming cannot be of economic benefit, depending on local conditions. Widespread adoption of the technology is constrained by the limited profit potential, the variability of the profits, and the knowledge required to use the technology successfully. The simulation model was a useful and simple tool for dealing with the complexity of the issues.*

Key words: water-harvesting, runoff-farming, drought, dryland-farming, model, simulation

Introduction

In many places irrigated agriculture is no longer economically feasible because of declining ground water levels. The reduced ground water supply has increased the interest in other potential water sources and various water conservation practices. These practices include conservation tillage, conservation bench terraces, fallowing, furrow disking, limited irrigation dryland system, skip row production, and reservoir storage with supplemental irrigation (water harvesting). They vary in their cost, effectiveness, and practicality. Conservation tillage, fallowing, furrow disking, and skip row production are relatively cheap. However, conservation tillage requires a high level of chemical use for weed control; furrow dikes must be rebuilt after each cultivation and may cause water logging in wet seasons; and fallowing and skip row production take land out of a yearly production cycle. Conservation bench terraces and reservoir storage for excess surface runoff with supplemental irrigation are more costly investments. With all techniques, benefits will vary because of fluctuations in precipitation characteristics, such as storm size and annual amount, and in economic conditions.

Krishna et al. (1987) showed that in east Texas, based on annual averages, a runoff farming system with a water impoundment reservoir for supplemental irrigation was promising for increasing and stabilizing crop yields, gross income, and profits. The system is described as: "The collection of surface runoff from cropped land into on-farm impoundments and subsequent application of this water as supplemental irrigation to crops on the same watershed during periods of crop water stress."

Economic feasibility requires that a cropping system be able to provide an adequate return on a yearly basis. The performance of any runoff farming system depends on the timing and quantity of individual precipitation events. For economic sustainability, the stochastic nature of rainfall and evaporative demand make it important to consider the operation of the farming system, within any one year and from year to year. This paper evaluates the yearly economic potential of using a runoff farming, supplemental irrigation system for growing sorghum (*Sorghum bicolor*) at two locations, Bushland and Temple, Texas. This analysis is accomplished through simulation modeling.

Simulation adds practical plausibility to investment analysis and is useful for exploring possible investment strategies and their uncertain consequences. This exploration of the stochastic dependence resulting from the joint dependence of some variables is a great advantage. It is particularly useful where investments are complex and the distributions are not normal (Anderson et al., 1977).

There are many farming systems that potentially are suitable for a given area. This analysis considers one approach to illustrate how yearly climatic conditions can affect yearly profit or loss and is not meant to promote or discourage any type of farming operation. Scrimgeour (1989) considers the use of four different water harvesting technologies at two sites in Texas.

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Model and site description

Model

The simulation model used is based on the conceptual design of an economic evaluation of water harvesting systems developed by Scrimgeour (1989). The model incorporates all available hydrological, biological, and economic information necessary for the calculation of costs, benefits, and risks of runoff farming systems under different environmental conditions, such as precipitation, and economic conditions, such as crop price. This approach accounts for the joint dependence of the stochastic variables.

Input data for the model include daily rainfall data, monthly pan evaporation, costs of production, and grain prices. The model consists of five components: catchment (runoff), impoundment (water storage), soil, crop, and economic. The model simulates production and generates a range of outcomes (maximums, minimums, averages, and standard deviations) and shows how yields, costs, and profits vary by years (seasons) for a given farming system design and decision rule. The model simulates final outcomes and predicts input supply and demand in intermediate time periods. Some of the important components of the biophysical system that are calculated for each time period are runoff, drainage, overflow, irrigation water applied, and crop water consumption.

The submodel components are specified by the following equations:

$RO_d = 0.4\ (RF_d - 6.35)$ (1)

where RO_d is the daily runoff (mm) and RF_d is the daily rainfall (mm);

$D_d = D_{d-1} + ADD_d - S_d - RE_d - O_d - IA_d$(2)

where D is the volume of water in the reservoir, ADD is the additions to the reservoir, S is the seepage losses from the reservoir, RE is the evaporative loss from the reservoir, O is the overflow loss from the storage, and IA is the quantity of irrigation water applied (all in m^3), and d is the time (days);

$ADD_d = RO_d * CA$ (2a)

where CA is the water collection area (ha);

$S_d = .006\ (WST_d)$, (2b)

where WST is the wetted surface area of the reservoir (m^2);

$RE_d = 0.618\ (PE_d * RA)$, (2c)

where PE is the pan evaporation (mm) and RA is the reservoir area (ha);

$PAW_s = PAW_{s-1} + RF_s + I_s - DD_s - ET_s$ (3)

where PAW is the plant available water, DD is the water lost by deep drainage, ET is the water lost by evapotranspiration, and I is the depth of irrigation water applied (all in mm), and s is the growing season;

$Ecum = 3.05\ (DSR)^{.5}$ (3a)

where Ecum is the cumulative evaporation (mm) and DSR is the number of days since the last rain;

$$E_d = Ecum_d - Ecum_{d-1} \quad (3b)$$

$$RF_d = \sum_{d=1}^{n} RF_d \quad (3c)$$

where n is the length of the growing season (days).

$$I_s = \sum_{d=1}^{n} 0.1\ (IA_d\ /\ AC) \quad (3d)$$

where AC is the irrigated area (hectares);

$$DD_s = \sum_{d=1}^{n} DD_d \quad (3e)$$

$$ET_s = \sum_{d=1}^{n} E_d \quad (3f)$$

$Yld = 0\ (PAW_s < 152)$ (4)

$Yld = 15.44\ (Paw_s - 152)$, $(152 < PAW_s < 635)$ (4a)

$Yld = 4.41\ (Paw_s - 635) + 7448$ $(635 < PAW_s)$ (4b)

where Yld is the crop yield (kg/ha). There are other yield subroutines from other models such as EPIC (Williams et al., 1988) and IBSNAT (Thornton and Dent, 1987) which may be applicable.

$Profit = (P * Yld) - VC - FC$, (5)

where P is the grain price ($/kg), VC are the variable costs, and FC are the fixed costs.

Sites

Runoff farming systems with supplemental irrigation were modeled for two sites, Bushland and Temple, Texas. Both locations are USDA-ARS research laboratories with detailed soil, climate, and crop production data. The results are compared to an analysis of a conventional dryland farming system at both locations.

The Bushland, Texas, climate is classified as semiarid with high evaporation rates (1900 mm annually from free water surfaces) and low average annual rainfall. Annual rainfall averages 470 mm but is highly variable in both amount per year and per storm. During the study period (1941-1985), annual precipitation ranged from 240 mm to 830 mm. Seventy-five percent of the rainfall normally occurs during the six-month growing season, April through September. Temperatures range from a January average minimum of -5 C to a July average maximum of 33 C (USDA-ARS, undated).

Temple, Texas, has a wetter climate than Bushland. The annual rainfall average is 840 mm, ranging from 340 mm to 1270 mm during the study period. Approximately 55 percent of the rain falls during the six months from April through September. Free water surface evaporation is 1470 mm annually. Temperatures range from a February average minimum of 5 C to an August average maximum of 36 C (Bloodgood et al., 1954).

The simulated farm layout consisted of an 80 hectare area (Figure 1). Runoff water was collected from the entire 80 hectare area and stored in an impoundment reservoir for later application in two supplemental irrigations to a 53 hectare crop area within the farm. The remaining 27 hectare area was primarily used as a water contributing area planted to a dryland grain sorghum that would provide some grain production in the wetter years.

Based on studies by Frasier (1975), the total annual water yield (runoff) from the area was estimated as 40 percent of any daily rainfall in excess of a threshold of 6.4 mm. Seepage losses from the impoundment were assumed to be 6 mm per day of wetted perimeter (Laing, 1975). Evaporation losses from the storage reservoir, reduced by the use of evaporation suppressants (Cooley, 1975), were assumed to be 40 percent of open

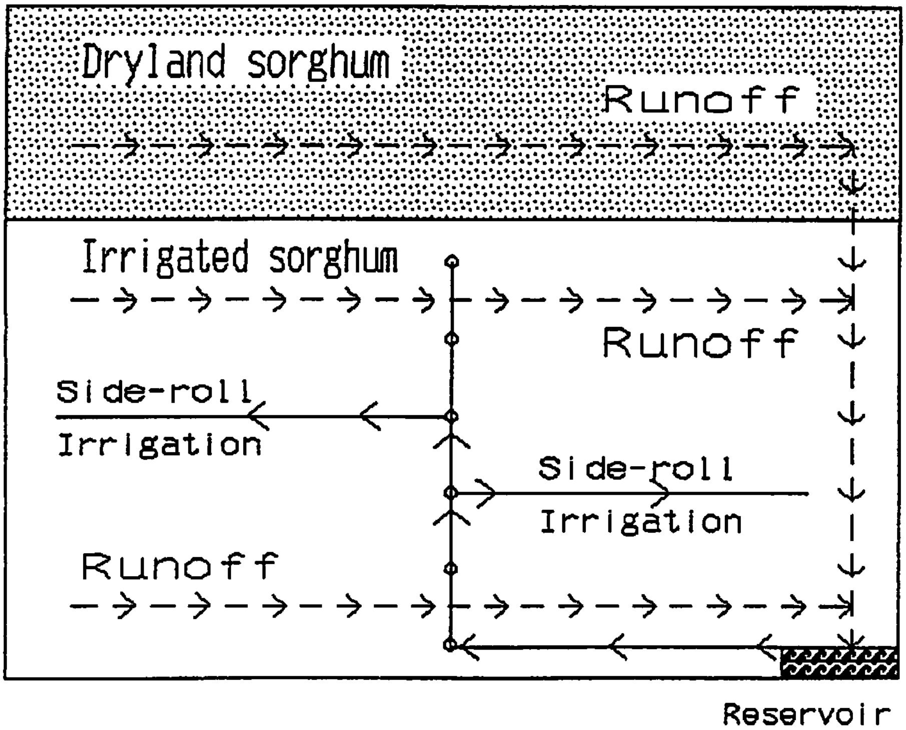

Figure 1. Sketch of simulated farm layout.

pan evaporation.

The optimal reservoir size is determined by the tradeoff between the added benefit from a larger storage versus the cost of the additional storage. Following Krishna et al. (1987), the pond size used was sufficient to store, at any single time, a volume of water equivalent to a depth of 58 mm over the irrigated area. The collected water, up to a total of 116 mm, was applied in two irrigations (two full storages) to the irrigated area at a total cost of $57/ha. The cost of irrigation includes the total interest and depreciation for the year. Any collected water in excess of 116 mm but less than 175 mm (three storages) was applied in a third irrigation at a cost of $25/ha. Where a third application of water was made, there was no interest or depreciation charge.

Collected water in excess of 175 mm per irrigated hectare was lost as overflow from the storage. The soil profile was assumed to be saturated when a total of 254 mm of water was accumulated by irrigation and/or rainfall. Excess infiltrated water was lost through deep drainage. Evaporation from the soil during the fallow period was assumed to vary as the square root of the number of days after rain, with evaporation on the first day equal to 3 mm. This approximates the results of Ritchie (1972). The water necessary to establish a crop was assumed to be 152 mm. Each additional mm of available water was assumed to increase the crop yield by 15.4 kg per hectare (Stewart et al., 1983) up to 7448 kg per hectare with 635 mm of plant available water. Beyond this, the addition of each mm of water was assumed to increase the yield by 4.4 kg per hectare.

The growing season was assumed to be March to June in Temple, Texas, and from June to September at Bushland, Texas. Despite the climatic differences at the two sites, it is assumed that the differences in soil, temperature, and other environmental factors do not alter the relationship between plant available water and crop yield.

Variable costs of crop production (cultivation, seed, fertilizer, labor, weed and pest management, and harvest expenses) were assumed to be $175 per hectare for the dryland sorghum and $195 for the supplementally irrigated sorghum (Texas Agricultural Extension Service, 1988). The capital costs for constructing the water harvesting system were assumed to be $26,215 for the impoundment and $20,000 for the irrigation equipment. This is equivalent to an annual cost of $96/ha for the 53 irrigated hectares using 9 percent interest, a 20-year life for the irrigation system, and an infinite life for the water impoundment facility, with annual maintenance charges of $520. Sorghum price was assumed to be $0.10 per kilogram.

Table 1. Comparison of model results with published data.

		Model	Published
Runoff (% of rainfall)	Minimum	0	22 [a]
	Average	13	–
	Maximum	40	32
	Standard deviation	11	–
Fallow Efficiency	Minimum	0	12 [b]
	Average	19	24
	Maximum	39	43
	Standard deviation	10	7
Grain yield (kg/ha)	Minimum	0	880 [c]
	Average	1640	1710
	Maxium	4710	2450
	Standard deviation	1260	425

[a] Frasier, 1975
[b] Steiner, 1989
[c] Lansford et al., 1986.

Model validation and procedures

The model results were validated by comparison of computed catchment runoff efficiencies and the fallow efficiency and yields to published results from other studies (Table 1). The catchment runoff efficiencies were derived from experimental watersheds in Arizona (Frasier, 1975). The fallow efficiency and yield results were from studies of a fallow farming system at Bushland, Texas. Fallow efficiency is defined as the percentage of fallow period rainfall stored in the soil profile at the end of the fallow period. The results reported by Steiner (1989) were based on the effects of different residue levels on soil water evaporation. The results of Lansford et al. (1986) on grain yields are based on the averages for groups of counties in Texas. There was a reasonable similarity between the model results and the published data.

Results and discussion

At both locations over the 44-year simulation period, there was an average increase in available plant water of approximately 30 percent (Table 2); but the amount of the increased water varied considerably from year to year (Figure 2). In wet seasons, water overflowed from the impoundments and was lost from any beneficial use. In dry seasons there was insufficient rainfall to fill the impoundments, limiting the amount of water available for supplemental irrigation.

At Bushland the simulated grain yields with supplemental irrigation ranged from zero to more than 7400 kg/ha. At Temple with supplemental irrigation the range was from 1240 kg/ha to more than 8400 kg/ha (Figure 3). The supplemental irrigation did not significantly reduce the risk of total crop failure compared to a conventional dryland farming system. However, without water harvesting in 2 of the 44 years, yields were less than 1120 kg/ha, but with water harvesting the minimum yield in any year was 1120 kg/ha. At Bushland the supplemental irrigation increased yields by more than 1120 kg/ha in 23 of the 44 years and at Temple in 39 of the 44 years.

Table 2. Simulated plant available water

	Bushland		Temple	
	Mean	(Range)	Mean	(Range)
	(mm)		(mm)	
Water stored in profile	58	(0-150)	166	(7-254)
Rainfall (growing season)	199	(81-374)	249	(101-487)
Plant available water (no irrigation)	257	(119-258)	415	(182-679)
Supplemental irrigation	83	(0-175)	124	(41-175)
Plant available water (w/irrigation)	340	(133-633)	539	(233-854)

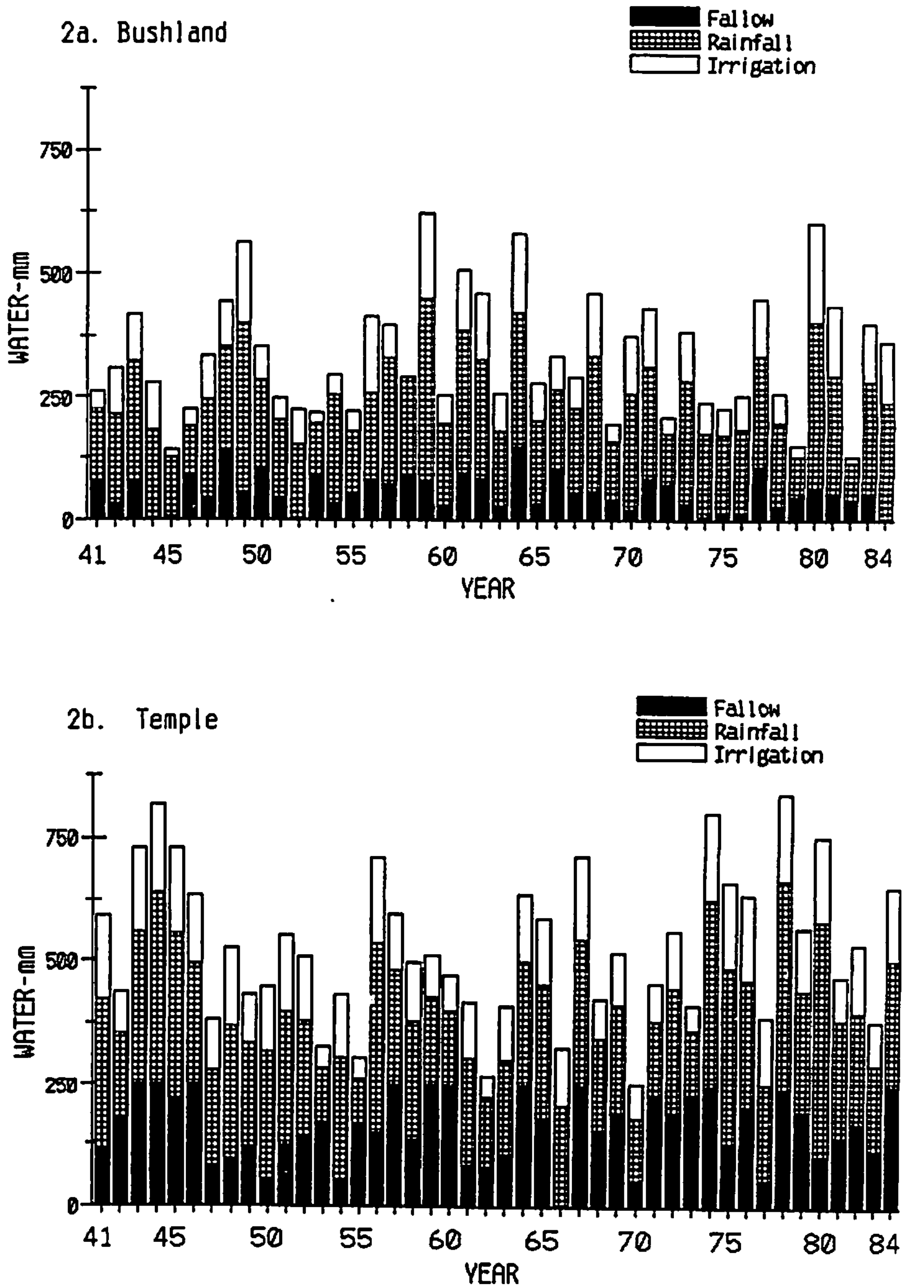

Figure 2. Simulated yearly quantities of water available for plant growth from fallow carryover, rainfall during the growing season, and supplemental irrigation for the 44-year study period at Bushland (2a) and Temple (2b), Texas.

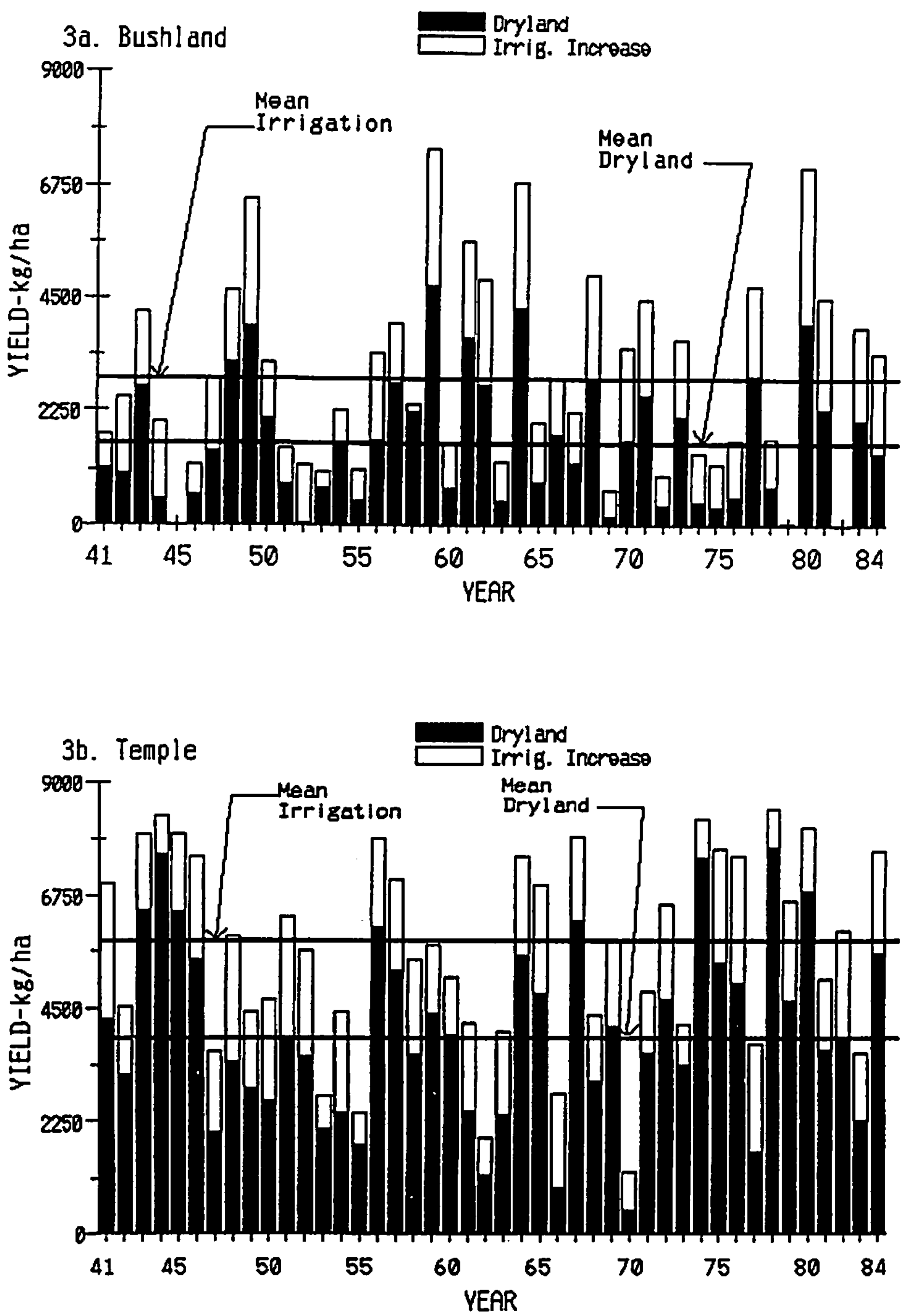

Figure 3. Simulated yearly yield of grain sorghum grown under dryland and supplemental irrigation for the 44-year study period at Bushland (3a) and Temple (3b), Texas.

Table 3. Simulated profit

	Bushland		Temple	
	Mean	(Range)	Mean	(Range)
	($ /ha)			
Annual Profit:				
Without supplemental irrigation	−15	(−178, 292)	225	(−131, 585)
With supplemental irrigation	−45	(−285, 339)	227	(−188, 505)

The increases in yield do not translate directly into increased profitability because of the fixed costs of the investment and the additional variable costs of more fertilizer and seed applied to the irrigated crop. The average annual cost per hectare of supplemental irrigation is $1.86 per mm at Bushland and $1.32 per mm at Temple. At Temple, the water harvesting investment resulted in no significant change in average profitability, with an average annual net benefit from the investment of $2 per hectare. At Bushland, the water harvesting, supplemental irrigation system investment had an annual net loss of over $30 per hectare (Table 3). The net benefit varied greatly from year to year. In some years the water harvesting resulted in a net loss compared with the absence of the investment (Figure 4).

There is more variation in the net benefit than there is in the yield or the rainfall. This variation is measured by the coefficient of variation (standard deviation/mean) (Table 4). These results indicate that water harvesting may reduce the probability of crop failure, but it does not reduce the variability in profitability. The analysis did show a sensitivity to grain prices. A $0.10/kg increase in grain price resulted in a significant increase in profit at both test sites with and without the supplemental irrigation system (Table 5). A similar analysis was conducted using a playa lake or other existing water storage facility rather than a new reservoir. If water storage construction costs could be reduced to 25 percent of the cost of constructing a conventional reservoir, the annual profit improves by approximately $5 per irrigated hectare (Table 6).

Conclusions

For the criteria used, supplemental irrigation from a water harvesting system did not increase the profitability of sorghum grain production at two locations in Texas. Water harvesting combined with supplemental irrigation was most successful in the location where the volume of water harvested was greater, i.e., where precipitation was higher. However, the net benefits were extremely

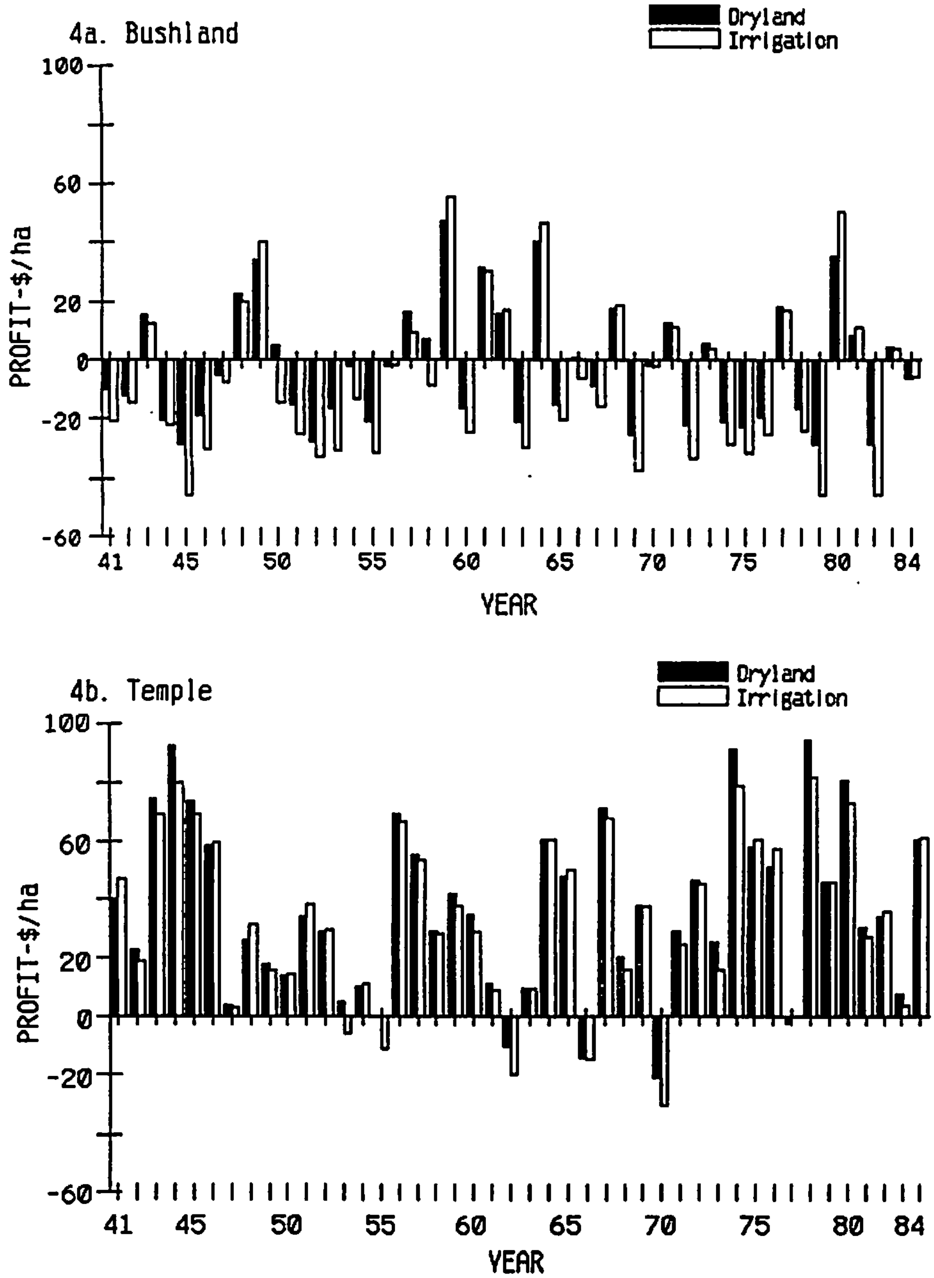

Figure 4. Simulated yearly net profit (loss) of growing grain sorghum under dryland and supplemental irrigation for the 44-year study period at Bushland (4a) and Temple (4b), Texas.

Table 4. Variation in results

	Bushland			Temple		
	Mean	sd	cv	Mean	sd	cv
Rainfall: (mm)						
Annual	469	117	.25	835	194	.23
Growing season	199	68	.34	249	85	.34
Plant Available Water: (mm)						
Without irrigation	257	85	.33	415	119	.29
With irrigation	340	125	.37	539	152	.28
Yield: (kg/ha)						
Without irrigation	1643	1291	.79	4034	1807	.45
With irrigation	2911	1916	.66	5655	1908	.34
Profit: ($/ha)						
Without irrigation	−15	126	8	225	180	.81
With irrigation	−45	161	4	227	209	.92

Table 5. Profit as a function of grain price

	Sorghum Prices	
	$0.10/kg	$0.20/kg
	($/ha)	($/ha)
Bushland:		
Without irrigation	−15	148
With irrigation	−45	200
Temple		
Without irrigation	225	626
With irrigation	227	733

Table 6. Annual profits as a function of reservoir costs

	Natural Reservoir	Constructed Reservoir
	($/ha)	($/ha)
Bushland:		
With irrigation	−37	−45
Temple		
With irrigation	235	227

variable from year to year. The modeled water harvesting technique was not able to take advantage of the potential additional water in the wet years and did not harvest sufficient water in dry years to make water harvesting more economically attractive than conventional dryland farming. For the water harvesting system to be more profitable on a yearly basis than dryland sorghum farming, there must be a yield increase of about 1600 kg/ha or more with the supplemental irrigation system. To achieve this yield increase, the runoff farming system must consistently harvest sufficient water to provide an additional 110 mm of supplemental irrigation to the irrigated area. This does not mean that there are not situations or conditions where runoff farming would be of economic benefit. The model did show that the net profit benefit was significantly increased with an increase in grain prices.

Water harvesting is a complex technology that has benefits in some locations. Each situation needs to be evaluated on its own merit and conditions. Widespread adoption of the technology is constrained by the limited profit potential, the variability of the profits, and the knowledge required to successfully use the technology. The simulation model used in this evaluation was found to be a useful and simple tool for dealing with the complexity of the issues.

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