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Review

Perspectives on deficit irrigation

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Abstract

An analysis of deficit irrigation in three quite different situations was conducted to better understand the potential benefits and risks associated with this irrigation strategy. Existing crop yield functions and cost functions, developed independently of the present research, were used to estimate the levels of applied water that would produce maximum net income in each situation. These same functions were also used to estimate the degree to which the three crops could be under-irrigated without reducing income below that which would be earned under full irrigation. The analysis encompassed wheat production in the northwestern USA, cotton production in California and maize production in Zimbabwe. Results suggest that (1) deficits of between 15% and 59% would be economically optimal, depending on the circumstances, and (2) the estimated margin for error in these estimates is quite wide.

Keywords: Deficit irrigation; Efficiency; Economics; Risk

1. Introduction

Deficit irrigation, the deliberate and systematic under-irrigation of crops, is a common practice in many areas of the world (e.g. Tyagi, 1987; Trimmer, 1990; English et al., 1990; Jurriens and Wester, 1994). Governmental agencies in water-short countries such as India and the Republic of South Africa have implicitly endorsed the concept of deficit irrigation by recommending that irrigation planning be based on a '50% dependable' supply of water (Chitale, 1987). However, in the academic world, deficit irrigation it is not usually treated as a practical alternative to full irrigation. A review of recent text books dealing with irrigation system design found that formal design

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procedures were always predicated on full irrigation. Some texts explicitly stipulated that the system should deliver enough water to meet full crop water demands (cf. Walker and Skogerboe, 1987, p. 25; American Society of Civil Engineers, 1990, p. 268). In other texts the design procedure was based on a maximum allowable soil water depletion. The maximum depletion level would be chosen by the designer, but the depletion levels recommended in the design texts all implied full irrigation (cf. James, 1988, p. 6; Keller and Bleisner, 1990, p. 32). Only one of the texts reviewed for this paper even mentions the concept of partial irrigation (Cuenca, 1989). Cuenca suggests that under some circumstances the designer might allow for greater soil water depletion, which could result in reduced yields as an economic tradeoff against the higher costs of more intensive irrigation. However, Cuenca then cautions the reader that this approach entails a risk of "serious yield reduction due to unexpected equipment failure or extremely dry meteorological conditions".

The apparent reluctance to fully explore the concept of deficit irrigation in the formal context of text books may be due to a concern that the potential benefits of this technique may not justify the associated risk. The goal of this paper is to develop a clearer perspective on this issue. This paper utilizes past research to assess the benefits and risks of deficit irrigation in a variety of real-world situations involving different crops, soils, weather and economic circumstances.

2. The concept of deficit irrigation

A number of researchers have analyzed the economics of deficit irrigation in specific circumstances and have concluded that this technique can increase net farm income (e.g. Dudley et al., 1971; Stewart et al., 1974; Howell et al., 1975; Gulati and Murty, 1979; Kumar and Khepar, 1980; Martin et al., 1989; English, 1990). The potential benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water (English et al., 1990). Fig. 1(a) and Fig. 1(b) illustrate the concept. The discrete data shown in Fig. 1(a) are yields of winter wheat per unit of irrigated land. These data, which are from field experiments in eastern Oregon (English and Nakamura, 1989), were used to derive a quadratic production function, $y(w)$, which relates applied water to crop yields. (This functional relationship will be used later in the analysis of Case 1.)

Estimated revenue from irrigation of this field can be represented by a revenue function relating gross income to applied water. The revenue function would be the product of the production function and the crop price, defined by the equation:

$$R(w) = P_c y(w) \tag{1}$$

where $R(w)$ is revenue per hectare, $y(w)$ is the crop production function, w is the depth of water applied and P_c is the price per unit weight paid for the crop. The revenue function is shown as the curved line in Fig. 1(b). The straight line in Fig. 1(b) is a simple cost function, with an intercept that represents fixed costs and a slope that represents operating costs. [1] Profit, which is calculated by subtracting costs from revenues, is indicated by the vertical difference between these two lines.

W_m is the yield maximizing level of applied water. At that point the marginal water use efficiency is zero, since the application of additional water will produce no additional yield. On the other hand, if the amount of water applied is something less than W_m the marginal efficiency of the last increment of water will be greater than zero since an increment of water will produce some increment of yield, and the marginal efficiency will become progressively greater as water use is further reduced. This illustrates the first factor, the increasing efficiency associated with deficit irrigation.

Profit per unit of land will be maximized when the level of applied water reaches W_l, at which point the slope of the cost line equals the slope of the revenue line. At levels higher than W_l the cost line is steeper than the revenue line, so total costs are increasing faster than revenues. In the range between W_l and W_m the farmer can benefit from reduced costs (the second factor). Additionally, a decision to use less water may enable the farmer to reduce capital and other fixed costs.

It is difficult to illustrate the third factor, the opportunity cost of water, with Fig. 1(b), but a heuristic argument may suffice. Because efficiency and profit are both increased with reduced levels of applied water, the net income per unit of applied water is increased. If the water saved by reducing the depth of irrigation is then used to bring additional land under irrigation with the same increased profit per unit of land, the total farm profit is increased still more. The net income from the additional land represents the opportunity cost of water. If additional land can be irrigated, the profit maximizing water use strategy would be to irrigate at a level below W_l, indicated by W_w in Fig. 1(b).

Two other important points are shown in Fig. 1(b). If applied water is reduced enough, a point will be reached at which the vertical difference between the cost and revenue lines is again equal to the difference at W_m. That point is illustrated by W_{el} for the land-limiting case and W_{ew} for the water-limiting case. The range of applied water between either of those points and W_m might be referred to as the range of profitable deficits, since the net income associated with any deficit within that range will result in greater net income than would be realized with full irrigation.

There are circumstances where deficit irrigation is not appropriate. For example, in the case of potatoes in the northwestern USA, soil moisture deficits that have little effect

[1] The reader should note that some of the earlier analyses cited above accounted only for the direct costs of irrigation and did not account for other production costs. Such incomplete cost analyses lead to underestimation of the magnitude of deficit that would be optimal and the potential gain in net income that would be realized. It is important to keep in mind that reductions in applied water, and the accompanying reductions in yields, will usually imply reductions not only in the costs of irrigation but also in the costs of seed, fertilizers, harvest and other factors of production, and may also imply reduced capital costs for water delivery and application systems. English and Nuss (1982) analyzed potential savings that could be achieved by designing a system specifically for partial irrigation of a field of winter wheat in Oregon. The savings were partitioned into three categories: (1) reduced irrigation costs (energy, labor and maintenance), which accounted for 37% of savings; (2) reduced fixed costs (primarily capital costs), which accounted for 36% of savings; (3) reductions in other production costs (cultural operations, chemical application, harvest and other costs) which accounted for 27% of savings.

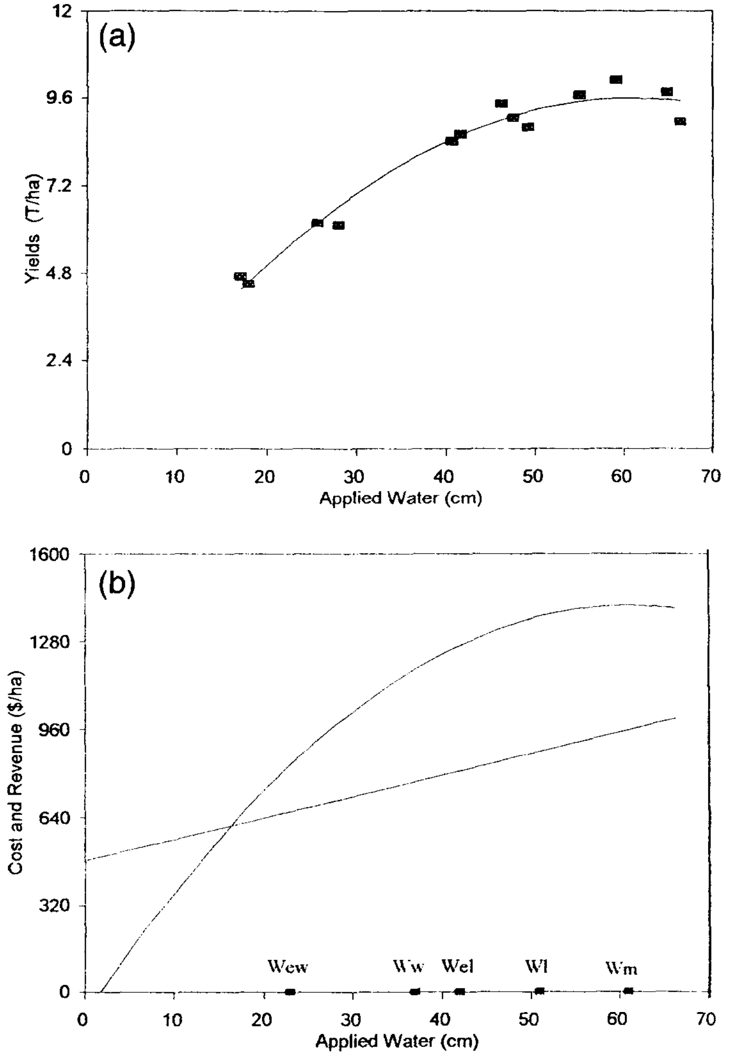

Fig. 1. (a) Yield versus applied water: Case 1, winter wheat in Oregon. (b) Cost and revenue functions: Case 1, winter wheat in Oregon.

on yield may cause significant changes in tuber shape, an important determinant of quality (Robbins and Domingo, 1956; Sparks, 1958). Larsen and McMaster (1965) found that early season moisture stress which caused a 15% reduction in total yield of Russet Burbank potatoes resulted in a 27% decline in the highest valued component of yield. Conversely, water stress may enhance quality in other crops. For example, deficits may improve the protein percentage of wheat and other grains, increase the fiber length and strength of cotton, and increase the sugar percentages in grapes, sugar beets and other crops (Krieg, 1986; Musick and Porter, 1989).

3. Optimal levels of water use

The foregoing discussion outlines four levels of applied water that could be defined as optimal in one sense or another, and which might therefore be interesting to an analyst. They are:

- the level of applied water at which crop yields per unit of land are maximized;
- the level at which net income per unit of land is maximized;
- the level at which net income per unit of water is maximized;
- the level at which yields per unit of water are maximized.

The optimum level of applied water for a particular situation will be that which produces the maximum profit or crop yield, per unit of land or per unit of water, depending on whether the goal is to maximize profits or food production and whether the most limiting resource is water or land. Additionally, as discussed above, there are two other levels of applied water which, though not optimal, should be of interest. They are the deficit levels at which net returns will be equal to those which would be realized by full irrigation.

English (1990) has derived equations for each of the application levels described above. The first equations presented in the original paper are completely general. The specific forms of those equations depend upon the forms of the cost and production functions that are utilized. For the particular case of a quadratic production function of the form

$$y(w) = a_1 + b_1 w + c_1 w^2 \tag{2}$$

and a linear cost function of the form

$$c(w) = a_2 + b_2 w \tag{3}$$

the following specific equations were also derived:

(a) for the yield maximizing level of water use, W_m:

$$W_m = -\frac{b_1}{2c_1} \tag{4}$$

(b) for the profit maximizing level when land is the limiting resource, W_l:

$$W_l = \frac{b_2 - P_c b_1}{2P_c c_1} \tag{5}$$

(c) for the profit maximizing level when water is the limiting resource, W_w:

$$W_w = \left(\frac{P_c a_1 - a_2}{P_c c_1}\right)^{1/2} \tag{6}$$

(d) for the level of deficit irrigation at which net income will equal that at full irrigation when land is limiting, W_{el}:

$$W_{el} = \frac{b_2 - P_c b_1 + Z_1}{2P_c c_1} \tag{7}$$

where

$$Z_1 = \left[(P_c b_1 - b_2)^2 - 4P_c c_1 \left(\frac{P_c b_1^2}{4c_1} - \frac{b_1 b_2}{2c_1} \right) \right]^{1/2}$$

(e) for the level of deficit irrigation at which net income will equal that at full irrigation when water is limiting, W_{ew}:

$$W_{ew} = \frac{-Z_2 + \left[Z_2^2 - 4P_c c_1 (P_c a_1 - a_2) \right]^{1/2}}{2P_c c_1} \tag{8}$$

where

$$Z_2 = \frac{P_c b_1^2 - 4a_2 c_1 + 4P_c a_1 c_1}{2b_1} \tag{9}$$

The reader is referred to the original paper by English (1990) for the derivation of both the general and the specific equations presented above.

4. The risk associated with deficit irrigation

There is uncertainty associated with the above estimates of optimal water use. The production function, $y(w)$, cannot be known a priori, since yields will be affected by a number of unpredictable factors, including such things as climate, irrigation system failures, germination rates and the incidence of disease. Consequently, the production function used in the above equations will only be an estimate of the true relationship. The cost function and crop price may be relatively more predictable, but will be uncertain nevertheless. Use of these uncertain functions in the foregoing equations implies that the resulting estimates of optimum water use will also be uncertain, and these uncertainties imply risk.

The fact that there is risk does not preclude using deficit irrigation. English (1981) has shown that farmers will adjust their water use to reduce risk, but will accept some degree of risk in exchange for potential economic gains. Nevertheless, the concern for risk implies that crop yield models should be used not only to predict yields but also to quantify the uncertainty of yield predictions. While we cannot know the true yield functions a priori, we can use our estimates of these functions to develop some sense of the associated risk. Let us focus on W_m, the yield maximizing level of water use, and W_{el} or W_{ew}, the levels of deficit irrigation at which net income is just equal to that at full irrigation. In the range of water use between these levels, net income will be at least as great as it would be at full irrigation. The probability of being outside that range, with reduced income as a consequence, is a risk that a farmer takes by adopting a deficit irrigation strategy. The extent of this range of profitable deficits is therefore a qualitative indication of potential risk. If the profitable deficit range is narrow there is little margin for error in estimation of optimum water use. If the range is wide there is greater margin for error. One goal of this paper is to develop some perspective on this range of profitable deficits.

5. Case studies

Case studies are presented below to illustrate the potential economic benefits of deficit irrigation and the range of profitable deficits in three different circumstances. The first case concerns wheat farming in the northwestern USA; the second is concerned with cotton farming in California; the third involves subsistence maize farming in southern Africa.

These analyses required appropriate cost and production functions. For the first two cases, quadratic production functions were derived directly from local field experiments, which made it possible to use Eqs. (4)–(9) to determine the optima. The production function for the third case was a fourth degree polynomial taken from the literature (Solomon, 1985), so a numerical search procedure was used to derive the optima.

Linear cost functions were derived from estimates of typical production costs for each case. Because these cost estimates were drawn from a variety of sources, they are presented in a variety of formats. In each case the estimates were used to calculate total production costs, first with irrigation at a specified level, and then with no irrigation. The resulting two calculations were used to derive linear cost functions.

5.1. Case 1: wheat farming in the Columbia Basin

The first case study involved irrigation of winter wheat on a large, family operated farm in the Columbia Basin, an arid region in eastern Oregon. It is an area with limited water and abundant land, and the farm in question has an opportunity to irrigate additional land if water becomes available. This is, therefore, a water-limiting case.

The wheat production function used in this case was derived from local field experiments (English and Nakamura, 1989) in which alternative strategies for deficit irrigation of a common, local variety of winter wheat were tested: (1) by irrigating at intervals ranging from 2 days to 4 weeks, and (2) by irrigating with different levels of applied water at 2 day and 7 day intervals. The results of that earlier study were used in Fig. 1(a). The following quadratic production function was derived from these data by linear regression:

$$y(w) = -0.5348 + 0.3326w - 0.00273w^2 \tag{10}$$

In this case, w is expressed as cm, and y as kg ha^{-1}.

A cost function was derived from an earlier analysis of irrigation on this same farm (English and Nuss, 1982). Cost figures presented in that earlier analysis are summarized in Table 1, and from those figures the following linear cost function (in \$ ha^{-1}) was derived:

$$c(w) = 482.30 + 7.79w \tag{11}$$

Crop price was assumed to be \$147.00 per US metric ton. Costs and revenues are expressed as US dollars.

The relevant levels of applied water, derived using Eqs. (4)–(9), are summarized in Table 2. Although water is the limiting resource in this case, an analysis of both water-limiting and land-limiting situations was carried out. For the water-limiting case, maximum net farm income would be realized by reducing applications from W_m to W_w. The resulting application would be 37 cm, a 39% deficit. At that point, net return per

Table 1
Production costs

Cost categories	Costs ($\$$ ha^{-1})
Case 1: winter wheat, Oregon	
Fixed costs (annualized)	
Field machinery	116.23
Field operations (tillage, planting, etc.)	114.73
Irrigation equipment	152.36
Variable costs: without irrigation (1950 kg ha^{-1})	
Nitrogen: 22.5 kg ha^{-1}	28.70
Seed	6.92
Harvest	63.36
Variable costs: irrigated (8138 kg ha^{-1})	
Irrigation at 42.2 cm	137.59
Nitrogen: 117.9 kg ha^{-1}	150.44
Seed	29.65
Harvest	109.76
Total costs	
Unirrigated	482.30
Irrigated (42.2 cm)	810.76
Cost function: $482.30+7.79w$	
Case 2: cotton, California	
Fixed costs: includes land preparation, etc.	529.42
Partially variable costs (assumed 50% of the following costs are variable)	
Fertilizers	86.48
Defoliation materials	42.00
Harvest	254.51
Post-harvest shredding	24.71
Irrigation operations (100 cm)	74.13
Cost of water (100 cm)	489.34
Total fixed costs	770.34
Total variable costs (100 cm water applied)	730.26
Cost function: $770+7.30w$	
Case 3: maize, Zimbabwe	
Variable costs: unirrigated (2.8 US tons ha^{-1})	
Field preparation, planting	55.00
Fertilizer	245.00
Insecticide	2.00
Labor	330.00
Transport	52.00
Subtotal	684.00
Capital at 13% (except labor)	46.00
Total	730.00

Table 1 (continued)

Cost categories	Costs ($\$$ ha^{-1})
Variable costs: irrigated (5.8 US tons ha^{-1})	
Field preparation, planting	165.00
Fertilizer	610.00
Insecticide	120.00
Labor	500.00
Transport	120.00
Irrigation (600 mm)	30.00
Subtotal	1545.00
Capital at 13%	135.00
Total	1680.00
Cost function: $730+1.58w$	

unit of water would be increased from 0.0745 $\$$ m^{-3} to 0.1110 $\$$ m^{-3}, a gain of 49%. The lower limit of the range of profitable deficits for this case would be a deficit of 62%. Note that values of W_l and W_{el} which would apply to a land-limiting case are also shown in Table 2 for added perspective.

Table 2
Analysis of alternative levels of applied water

	Water use		Net returns		Profit increase at optimum	
	Applied (cm)	Deficit (%)	To land ($\$$ ha^{-1})	To water ($\$$ m^{-3})	Land-limiting (%)	Water-limiting (%)
Case 1: wheat/Oregon						
W_m	61	–	453.70			
W_l	51	16	491.51	0.0964	8.3	
W_w	37	39	414.81	0.1110		49.0
W_{el}	42	31	453.70	0.1080		
W_{ew}	23	62	170.90	0.0745		
Case 2: cotton, California						
W_m	164	–	682.87	0.0416		
W_l	139	15	774.96	0.0558	13.2	
W_w	118	28	711.97	0.0603		44.1
W_{el}	114	30	682.87	0.0599		
W_{ew}	85	48	353.00	0.0415		
Case 3: maize, Zimbabwe						
W_m	52.5	–	1651	0.315		
W_l	44.5	15	1713	0.385	3.8	
W_w	21.5	59	1137	0.529		68
W_{el}	36.6	30	1651	0.450		
W_{ew}	9.8	81	329	0.315		

5.2. Case 2: cotton production in California

The second case concerns a corporate farm in the San Joaquin Valley, the arid central valley of California. Water supplies are limited, but there is no opportunity to expand irrigated acreage even if more water were available. This is therefore a land-limiting case.The following quadratic production function was derived by Cuenca (1989) using experimental data collected at a nearby research station of the University of California:

$$y(w) = -781.1 + 29.85w - 0.091w^2 \tag{12}$$

The units of applied water and yield are cm and kg ha^{-1}, respectively.

A cost function was derived from cost estimates (Table 1) provided by Northwest Economic Associates (R. McKusick, NEA, personal communication, 1989), a consulting firm which had conducted an earlier analysis of water use on the farm in question. The NEA figures were presented in three broad categories: (1) fixed costs, which are independent of the level of production; (2) partially variable costs, which depend to some extent on production levels; (3) costs of water. For purposes of this analysis, the partially variable costs were arbitrarily partitioned equally between fixed costs and variable costs. The resulting cost function (in \$ ha^{-1}) was:

$$c(w) = 770 + 7.30w \tag{13}$$

The crop price used for this case was \$1.59 kg^{-1}.

Results of this second analysis are presented in Table 2. Maximum yield would occur at 164 cm of applied water. The economic optimum level of applied water for the land-limiting case (W_l) would be 139 cm, a deficit of 15%. The deficit level at which income would equal that at full irrigation (W_{el}) would be 114 cm, a 30% deficit.

5.3. Case 3: subsistence maize farming in Zimbabwe

The third case involves an irrigation scheme on communal lands near Mutoko, Zimbabwe. This is an area of small-holding, subsistence farming. The farm in question has 1 ha of irrigated land and some additional land which could be irrigated if water were available, so this is a water-limiting situation.

No local field data were available from which to derive production functions directly, so the following generic production function (in metric tons ha^{-1}) for maize was taken from the literature (Solomon, 1985):

$$y(w) = 6.0\left(-0.84 + 0.43W_R - 3.52W_R^2 + 1.11W_R^3 - 0.18W_R^4\right) \tag{14}$$

where $W_R = (w + [\text{rain}])/(W_{max})$

The rainfall used in the analysis was 156 mm, an amount that would just begin to produce a harvestable yield. W_{max}, the total available water (irrigation plus rainfall), was estimated to be 685 mm. The coefficient 6.0 represents an estimate of maximum attainable yield.

The costs of production for this third case were derived from various local sources, as discussed by English and Stoutjesdyke (1992). The resulting costs, shown in Table 1, are consensus figures for dry land and fully irrigated maize production. These two estimates

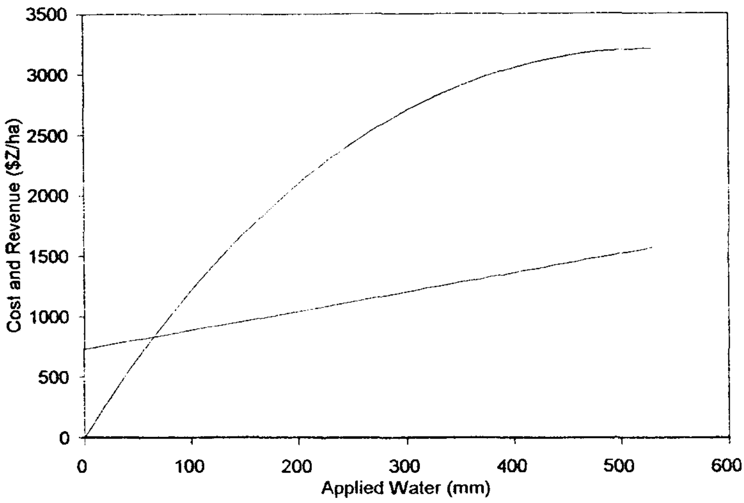

Fig. 2. Cost and revenue functions: Case 3, small-scale maize farming in Zimbabwe.

were used to develop the following linear relationship between production costs and applied water ($ ha^{-1} mm^{-1}):

$$c(w) = 730 + 1.58w$$

Labor costs shown in Table 1 are based on the potential earnings of a laborer who leaves the farm to find other work. But there is some question about whether labor costs should be included in the analysis, since farm labor is often provided by family members who have no such outside labor opportunities. However, in the course of this analysis, it was found that labor costs did not appreciably influence the optimal levels of applied water for Case 3.

The units for applied water and yield in this case were mm and metric tons ha^{-1}, respectively. The cost and revenue functions for Case 3 are illustrated in Fig. 2. Costs and income are expressed as Zimbabwe dollars. [2] Maximum net income would be ZIM$ 1713.

Optimal levels of applied water and the associated yields and net incomes were determined by a simple search procedure. The results of the analysis are summarized in Table 2. The optimum level of applied water would be 21.5 cm, a deficit of 59%. The equivalent deficit level, W_{ew}, would be 9.8 cm of water, an 81% deficit.

It is interesting to also consider total food production, which is a primary concern in the communal lands of Zimbabwe. As water use is reduced additional land can be brought into production, with a consequent increase in total food production. The results,

[2] The exchange rate in 1992 was approximately 5 Zimbabwe dollars for 1 US dollar. The maximum net income from this 1 ha farm would therefore be equivalent to US$ 343.

Table 3
Alternative levels of applied water: subsistence maize production in Zimbabwe

	Water use (cm)	Yield (US tons ha^{-1})	Irrigated land (ha)	Total yield (US tons)
W_m	52.5	6.0	1.0	6.0
W_w	21.5 (59% deficit)	4.13 (31% deficit)	2.44	10.1 (68% increase)
W_{el}	9.8 (81% deficit)	2.23 (63% deficit)	5.36	11.9 (99% increase)

shown in Table 3, suggest that total food production could be nearly doubled without reducing net farm income by irrigating at the W_{el} level.

6. Discussion

Three analyses of deficit irrigation in real world situations have been presented. The crop production functions and cost functions, which are critical to the analyses, were derived from independent work of other individuals as well as earlier research by the present authors. These relationships were used to explore the potential benefits and the margin for error in deficit irrigation.

In land-limiting situations the estimated optimal deficits were 15% or 16%, which represents appreciable water savings. The resulting gains in profit would range from 8% to 13%. Optimal deficits were much larger in the water-limiting cases, ranging from 28% to 59%, with associated gains in total farm income between 44% and 68%. The magnitude of these optimal deficits is consistent with earlier research by Martin et al. (1989), English (1990) and others.

The potential benefits of deficit irrigation appear to be significant in these three cases. A central concern of this paper, however, is the risk the farmer takes in adopting such a strategy. This was addressed in a limited way by studying the range of irrigation deficits which would have been at least as profitable as full irrigation. That range was found to be quite wide. Deficits averaging 64% were found to be economically equivalent to full irrigation in the water-limiting cases, and deficits averaging 30% were found to be equivalent to full irrigation in the land-limiting cases. These results suggest that the margin of error in determination of optimum water use may be rather wide.

It should be noted that we have only considered one aspect of the issue of risk, the range of profitable deficits, which represents in a general way the margin for error. The magnitudes of possible errors in estimates of optimum applications have not been analyzed in this paper although other researchers have addressed some aspects of this question. For example, Martin et al. (1989) evaluated the variability of W_m for three crops in Nebraska and found variations on the order of $\pm 25\%$ in W_m from one season to another.

7. Conclusions

Existing production functions and cost functions were used to examine the potential economic benefits of deficit irrigation for three very different sets of circumstances. In situations where irrigable land is abundant and water is scarce, the optimum strategy would be to under-irrigate by 28% to 59% in the three cases studied. Even where water supplies are not limited the optimum strategy would entail deficits on the order of 15%.

Since the relationship between water use and crop yield is intrinsically uncertain, the margin for error in determination of optimum levels of water use was examined. Using the same production and cost functions it was found that net incomes would not be reduced by deficit irrigation unless the deficits are substantial, on the order of 30% when water is not limited and as much as 48% to 81% for the water-limiting cases considered.

The conclusions presented here should not be regarded as either universal or absolute. Any analysis that employs the cost and production functions presented in this paper will arrive at essentially the same results, but alternative functions might reasonably have been used and would have produced different numbers. Likewise, the circumstances of these three case studies cannot be regarded as representative of all irrigated agriculture. Finally, the analyses were based on model estimates, and although the models were derived from field research they are still intrinsically uncertain. Such uncertainty is, in fact, a basic tenet of this paper. Nevertheless, the results of these analyses are compelling enough to warrant serious attention. The potential advantages of deficit irrigation appear to be quite significant, particularly in a water-limiting situation, and the associated risks may be quite acceptable.

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