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EFFECT OF VARIABLE WATER SUPPLY AND QUALITY ON DESIRABLE CROP PRODUCTION PATTERNS

by J.A. GROENEWALD and J. VAN ZYL*

ABSTRACT

Availability of resources, including water, is a major consideration in the choice of irrigated crops. This problem is compounded by variations in water supplies.

For maximum profit, the marginal revenue to water applications must at the last usable unit be the same for all crops or uses. With abundant water, profit is maximized with expansion of high water requirement crops relative to water-economising crops. Empirical evidence shows that profit maximization is achieved if returns to the scarcest, most limiting resources available are at a maximum. Thus, in certain situations, land or water resources may have to be left idle to maximize profit.

Imperfect knowledge arising from unpredictable variability leads to risk in agricultural production. Rational decision-making under risk is choice consistent with the decision maker's beliefs about the uncertainty he faces and with his preferences for possible consequences. With uncertain water supplies, the manager could adopt more conservative estimates. An optimal risky decision is one that maximizes the decision-maker's subjective expected utility. This can be determined by using stochastic efficiency analysis, mean variance analysis or simulation.

INTRODUCTION

Problems involving water availability and water quantity and the effect thereof on irrigated agricultural production are many-faceted. Some questions obviously centre around decision-making at farm level. Given that a farmer is in control of some tract of irrigable land, and given also that he is in a certain defined financial situation (especially net worth, solvency, liquidity and access to loan funds), given furthermore that a certain class and amount of infrastructure exist, the question is, how should he use his resources, including irrigation water, to maximize his likely return to these resources? This question will inevitably involve crop selection; physical and financial yields to different resources and resource mixes vary among different crops. Varying availability of a major resource such as water in irrigation farming, may complicate this decision.

*University of Pretoria, January 1984

PROBLEM DEFINITION

Relationships involving crops, climate, water and soil are complex; many biological, physiological, physical and chemical processes are involved. Much research information is available in relation to water (Doorenbos and Kassam, 1979); for practical application this knowledge must however be reduced to a manageable number of major components to allow a meaningful analysis of crop response to water at the field level.

Different crops have different water requirements as well as differences in the timing of these water requirements during the growth period. A careful selection of the crop and the variety most suited to a given environment is of paramount importance for obtaining high and efficient production.

Availability of water and also other resources form a major consideration in the choice of crops to be grown under irrigation. These problems are compounded by what is certainly one of the biggest problems in the South African water economy, namely variations in total water supplies, consisting of variations in irrigation water and rainfall.

It is well known that different crops yield different revenues per unit of area and per volume unit of water. Table 1 presents gross margins per hectare and per 10 cubic metres of water for selected crops and localities. The "COMBUD" routine (Department of Agriculture, 1984 a) was used to generate gross margins per hectare. Water requirements were based on the publication "Besproeiingsbehoeftes van gewasse in Suid-Afrika" (Department of Agriculture, 1984 b) and another by Doorenbos and Kassam (1979).

THEORY OF SCARCITY

In this discussion, maximization of profit from irrigation farming is assumed to be a major goal. This goal appears to be generally acceptable albeit constrained by other considerations including some of personal, social or institutional nature.

Profit maximization is achieved by maximizing the economic return to the farmer's total resources mix - long, medium and short term capital, land, water, labour and management. This in turn occurs if and only if returns to scarcest, most limiting resources available to management are at a maximum.

Under some simplified conditions the

TABLE 1 - Water requirements and gross margins of selected crops, 1984

Crop	Locality	Water requirement (m³/ha)	Gross margin per hectare (R)	Gross margin 10 m³ irrigation water (R)
Wheat	Vaalharts	3 682	667,40	1,84
	Douglas	4 188	619,89	1,48
	Theunissen	3 960	581,98	1,47
	Van der Kloof	3 423	465,48	1,36
	Barkley-West	3 572	760,95	2,13
Peanuts	Theunissen	3 677	540,57	1,47
	Barkley-West	2 865	988,35	3,45
	Vaalharts	3 110	1 026,90	3,30
Lucerne	Barkley-West	9 718	787,15	0,81
	Vaalharts	10 203	1 112,11	1,09
Cotton	Vaalharts	3 701	843,86	2,28
	Van der Kloof	3 366	891,92	2,65
Maize	Van der Kloof	4 910	618,53	1,26
	Barkley-West	3 574	707,67	1,98
	Vaalharts	3 700	677,05	1,83
Green peas	Vaalharts	3 250	643,42	1,98
	Barkley-West	8 745	970,73	1,11
Cabbage	Theunissen	5 020	2 293,60	4,57

determination of an economically optimal system can be very simple and straightforward. Let us assume we have two different crops: Wheat and lucerne, with water requirements and gross margins as shown for Vaalharts in Table 1. If 300 000 m³ of water is available and all other resources, including land are unlimited, then returns will be maximized by using all water and by maximizing returns per m³ of water: 81,5 ha of wheat will be produced, yielding a total gross margin of R55 222.

If, on the other hand, land is the only limited resource and 80 hectares are available, while all others (including water) are unlimited, returns will be maximized by planting all 80 hectares to lucerne, yielding R88 969 as total gross margin, using 816 240 m³ of water.

These situations are merely illustrations of Liebig's Law of the Minimum. Blanchet (1974) formulates this law simply as: "A factor can act only to the extent that some other is not exactly limiting".

However, with the exception of special laboratory cases, production/resource relationships are not as simple as this. In practice one does not have limitations in only one or two resources; a large number of resources is used, and these can become relatively scarce or relatively abundant to various degrees, relative to the others. For example, as water becomes more abundant, it does so relative to soil, plant nutrients, labour, tillage capacity and other factors, which in turn become scarcer relative to water. The presence of each of a multitude of factors in what has been emphasized to be in variable proportions (Friedman, 1962) causes relationships among inputs, among products and between inputs and products to be curvilinear, except under very unusual situations which can only be created artificially. Using basically this line of reasoning Mitscherlich (1909) identified the Law of the Minimum to be a special case of Diminishing Marginal Returns which as implied by Friedman (1962) should more appropriately be called the Law of Variable Proportions.

The relationship between any two crops, given the availability of a certain array of resources, is the typical textbook relationship portrayed in Figure 1 for crops Y_1 and Y_2. Curve ABC is the production possibilities curve, a frontier showing all the technically most efficient combinations in which Y_1 and Y_2 can be produced on the particular farm. Line HI depicts the highest obtainable iso-revenue line assuming a certain ratio between prices of products Y_1 and Y_2. This price ratio Py_1/Py_2 forms the slope of the straight line HI. Profit is maximized at point B where the iso-revenue line HI is tangential to the production possibilities curve ABC. Thus, OL of Y_1 and OK of Y_2 should be produced for maximum

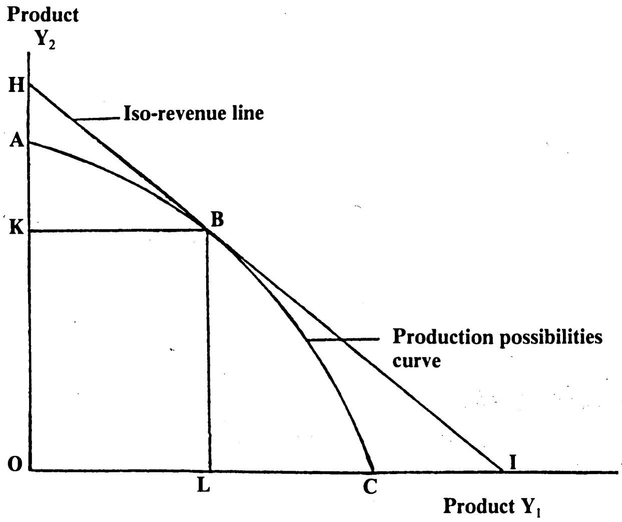

FIG. 1 - Production surface for two crops

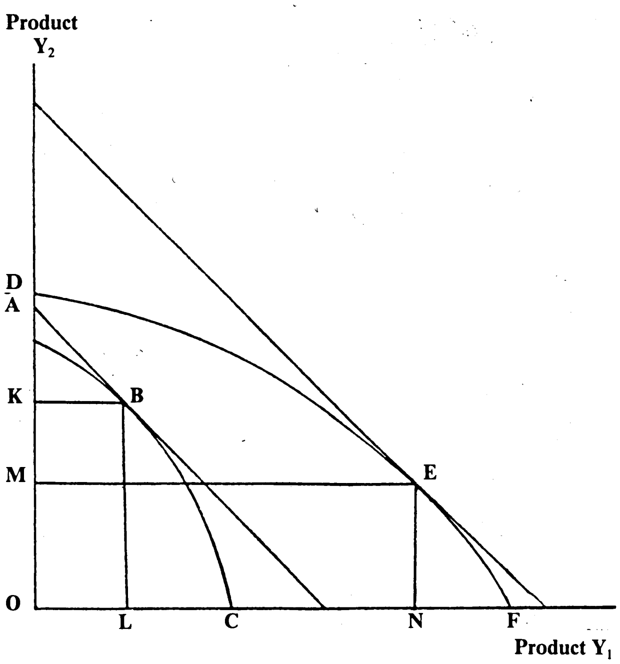

FIG. 2 - Effect of change in water availability on production surface for two crops

profit. In the linear programming approach such curves are divided in linear segments for purposes of using existing algebraic algorithms (Dorfman, 1974).

The following equation holds at this optimum situation:

$$\frac{dY_2}{dY_1} = \frac{Py_1}{Py_2}$$

$$\text{or } dY_1 \,.\, Py_1 = dY_2 \,.\, Py_2$$

Taking water (W) as one resource and dividing the entities at both sides of the equal sign by dW, it becomes:

$$\frac{dY_1}{dW} \cdot Py_1 = \frac{dY_2}{dW} \cdot Py_2 \quad ^{1)}$$

Thus, the marginal products of the two products to water multiplied by their prices must be equal. Thus again, the marginal revenue to water applications must at the last usable units be the same for all crops or uses. This, in reality, is only an example of the equi-marginal principle which according to many authors (e.g. Hischleifer *et. al.*, 1975) should be the guiding principle in all water allocation decisions.

When more than two crops are considered profit will be maximized if, with n possible products.

$$\frac{dY_1}{dW} \,.\, Py_1 = \frac{dY_2}{dW} \,.\, Py_2 = \frac{dY_3}{dW} \,.\, Py_3 = \ldots\ldots \frac{dY_n}{dW} \,.\, Py_n$$

It also follows that a situation with a shortage of high-quality irrigation water, is a situation in which marginal returns on water will have to be high for profit maximization. This will favour water-economising crops, i.e. crops with a high return per unit of water or, otherwise stated, with a low-water requirement relative to product value.

As water becomes more abundant, lower marginal returns will define the situation of economic optimum. This will also mean a movement away from water-economising crops to crops that yield lower returns per unit of water. As water becomes less scarce, returns to other scarce resources such as land, labour, mechanical power, short-term capital items, management etc., become important relative to returns to water. This phenomenon is illustrated in Figure 2.

Consider two crops Y_1 and Y_2. Y_1 has a higher water requirement than Y_2. Y_2 is the water-economising crop. Water thus places a more serious production constraint on the production of Y_1, relative to constraints emanating from other inputs such as labour and/or land.

Product Y_2, as compared to Y_1, has low water requirements; thus water is less constraining on Y_2 production, relative to constraints by the other resources (e.g. land and/or labour) than is the case with Y_1.

Thus, the production possibilities curve may be ABC in a watershort situation, with water availability constraining Y_1 fairly severely. As more water becomes available, Y_1 can be expanded more than Y_2, since limitations to the land/labour resources gradually become bigger impediments to expansion of Y_2 than Y_1. This will cause slopes of the production-possibility curves associated with much water to differ from the slopes of curves in a water-short situation. Curve DEF defines production possibilities in a situation with more abundant water. Therefore, in a situation of abundant water, profit will be maximized with an expansion of high water requirement crops relative to water-economising crops.

In Figure 2, assuming that the price ratio Py_1/Py_2 remains unchanged, the economically optimum combinations will be as follows:

Water shortage: OL of Y_1 and OK of Y_2

Water abundance: ON of Y_1 and OM of Y_2

It can, and in fact often does happen, that increased water supply will call for an absolute reduction in production of water-economising crops. This is, however, certainly not inevitable. What will be inevitable, is a reduction in production of water-economising crops *relative* to other crops.

Some other situations may also change water use, land utilisation and crop selection. Changes in methods of applying water - e.g. flood, overhead or microjet irrigation will bring about a change in water availability and hence, its optimum allocation among crops.

Water-quality differences will have similar effects. If irrigation water has a high degree of salinity, for example as reported in the Great Fish River (Tordiffe & Botha, 1981; Backeberg, 1984), then this obviously becomes a more limiting factor than would otherwise be the case, and saline-resistant crops are called for.

In other situations, the most limiting factor on an irrigation farm may be management and/or labour and/or capital. In such cases, a situation may arise where both land and water resources have to be left idle in order to maximize profit. If for example capital is severely limiting, a farmer will be wise to produce in such a way that he maximizes returns on capital producing crops requiring low capital inputs. Then all the capital will be utilised, but not necessarily all land and all water.

EMPIRICAL EVIDENCE

Little has evidently been published on relationships between water quality or quantity and optimum crop selection. Some studies may, however, be cited to substantiate remarks made earlier.

In a study at the Hartebeespoort scheme, Hancke and Groenewald (1972) divided a period of 10 years into three groups: "good" years consisted of the four years with the highest water availability, followed by the three "medium" years, and, of course, the three "poor" years had least water available. Linear programming was used to obtain optimum crop combinations on an 18 morgen unit[2] for each of the three classes of year, using both flood and sprinkler irrigation. The model allowed for the purchase of as much labour as would be associated with maximum profit. The model also allowed for a variety of cash crops and a dairy herd utilising irrigation-produced feeds.

In the results, high water-use crops such as cotton and lucerne, both with fairly high gross margins per unit area were included in the optimum organisation only if water availability was at its most favourable. Tobacco, the crop with the highest gross margins both per morgen of land and per m^3 of water - in all three year types - appeared consistently in the solutions (almost at the maximum level allowable under rotation constraints) while wheat, having high gross margins per morgen and per m^3 of water in "good" years but less so in other years, was prominent in "good" years and absent in "poor" years. In a year with very limited water, one simply cannot afford to use it on crops with a low return per m^3. Another noticeable feature was that in "poor" years, considerable land should be kept idle.

Some time later, Van Rooyen (1973), also at Hartbeespoort, did an analysis on optimum farm organisation under four different situation types, each of which had in fact occurred before. Water release to farmers, and hence water availability, is determined by the amount of water in the dam. He determined optimum organisation with an almost empty dam (dam level = 3 m), a moderately empty dam (dam level = 6 m), a moderately full dam (dam level = 12 m) and a full dam (level = 18 m). He applied parametric programming to labour. He also found water availability at the lower levels to be very limiting, necessitating the adoption of crops which had high returns per m^3 of water, such as tobacco and potatoes. Wheat is unimportant in terms of profit maximization at very low water availability, except in cases where labour is too scarce to handle crops such as tobacco or potatoes. Wheat increases in importance as water becomes more abundant. The same was the case with other crops with relatively low yields per m^3 of water.

Van Rooyen (1973) also found that as water became more abundant, more of other inputs - such as labour - should be employed. If this was not possible, these inputs rather than water, would be the limiting - thus scarce - factors. According to his results, land is not a limiting factor at Hartbeespoort, even with a full dam. Water remains scarce relative to land.

One should, however, not generalise by extrapolating this finding to all other possible irrigation-farming areas. In a linear-programming study at the water-rich Malelane-Komatipoort area, land was found to be scarce relative to water. In a normal year, land had to be, practically speaking, fully used, and in no single month of the year would more than 65% of available water be needed. In this case, increased water availability would obviously not have any advantageous effect on farm income or organisation (Brotherton & Groenewald, 1982).

Another question involved with crop selection concerns managerial action when conditions change during a growing season. While lamenting the absence of sufficient documentation on yield-reducing effects when less irrigation water is applied than had been claimed, Anderson (1968), designed and demonstrated a simulation program which may be used for adaptations of this nature. In other words if more irrigation water, or particularly less water is available than originally anticipated, which crops should bear the brunt, and which crops should still receive water? If more water is available, which, if any, should receive increased applications?

This obviously depends largely on different crops' water-production functions as influenced also by levels of some other inputs - such as seed and fertiliser - which can shift water-production functions. This will in future place a premium on parametric water use research efforts of the type done at the University of California - Los Angeles (Burt *et. al.*, 1981). It has been indicated (Zusman & Amiad, 1965) that as the year changes and seasons follow on each other, the following are about to change: the state of the system - soil, moisture and growth conditions to date, and hence the condition of the crop; the probability of different availability levels of moisture (and, one should add, other needed resources) - and hence probable growth conditions. One could add to this probable prices. Such changes should obviously continuously be taken into account in farm management. It may, for example, become advisable to plough under some crops, neglect others, and persevere with even some others. In this, the guiding principles should still be those of the theory of scarcity, together with some principles of risk decision-making.

RISK MANAGEMENT

Imperfect knowledge arising mainly from unpredictable variability leads inexorably to risk in agricultural production. Although static theory embodies the knowledge of farm management and production economics, the shortcomings of the static equilibrium theory have been recognised throughout the postwar period (Jensen, 1977).

The effect of uncertain resource supplies on decision-making can be illustrated by a simple production-possibility boundary as depicted in Figure 3, showing feasible production levels of two crops, Y_1 and Y_2, with respect to available supplies of land, machinery and water. The manager knows the available quantity of land and machinery but is not sure of water supplies. Assume that only two possible quantities of water are possible: W_1 and W_2, with W_2 exceeding W_1. The production possibilities curve would be either ABCD or EFCD. If the ratio Py_1/Py_2 is the slope of the price line aa, the most profitable point on either production possibility boundary is C, and water will always be in surplus supply, and the production program can be planned completely independently of water availability and uncertainties involved. However, should the price ratio be such that water is a limiting factor of production the uncertainty about water availability will affect production decisions.

Using the price line bb, the optimum crop combination is F with water supply equal to W_2, but B if it equals W_1. If the manager knows at the beginning of the season which water supply will be received he can choose the profit-maximizing plan. If complete knowledge about the supply of the water resource does not exist, however, the situation is completely different.

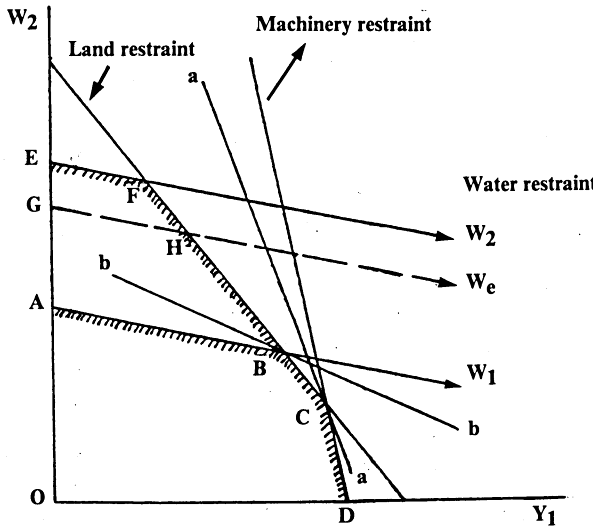

FIG. 3 - Production with uncertain resource supplies

If the manager decided on the product combination at point B in Figure 3, his production decision would be feasible regardless of which of the two levels of water supply eventuated. This product combination would maximize profits should water supply equal W_1, but with water supply W_2 the manager would have a surplus of water which could have been used profitably. Alternatively, if he decided on the product combination at point F his decision would be feasible and optimum should the water supply equal W_2, but with supply W_1 his program would be impracticable. Modifications, perhaps at a considerable cost, would be necessary to overcome this water shortage-induced problem.

In cases of uncertain resource supplies, the manager could adopt a more conservative estimate. If we assume the expected supply of water to be W_e the expected production possibilities curve becomes GHCD and point H denotes the 'expected' profit-maximizing crop combination. Should water supply W_2 materialise some surplus water would exist, but this surplus is less than that associated with the crop combination at point B. Should water supply W_1 result, a cost will be incurred due to the impracticability of the chosen plan, but this cost would be less than that associated with the crop combination at point F. Clearly some managers would consider H to be a safer 'plan' than F; some managers might be so averse to risk that they might choose only the safest plan of all, plan B. The manager must decide at what point between B and F any further increase in the cost of achieving feasibility outweighs any possible increase in profitability.

Decision-making under risk conditions is rational if the choice is reconcilable with the decision-maker's beliefs about the uncertainty he faces and with his preferences for possible consequences. Beliefs can be measured as subjective probabilities. Rationality also requires consistency in subjective probability judgements. Preferences can be encoded via utility functions. An optimally risky decision is defined as one that maximizes the decision-maker's subjective expected utility.

The analysis of decision problems into separate assessments of beliefs and preferences requires first that some way be found of measuring the decision-maker's beliefs. Subjective probabilities have been proposed for this purpose (Savage, 1954). The subjective nature of probabilities as statements of belief makes them essentially personal judgements. This means that two individuals can reasonably assign different probabilities to the same uncertain outcome. The personal nature of the measurement of beliefs as subjective probabilities thus emphasises the sovereignty of the decision-maker in choices that affect his welfare. It is the decision-maker who must bear the consequences of his decision and therefore his beliefs are relevant to the analysis of his choice.

Research work on supply behaviour of farmers, incorporating consideration of their responses to changes in risk, by Behrmann (1968), Just (1974) and Anderson *et al.*, (1980), amongst others, has generally confirmed the existence of widespread risk aversion.

Problems involving many individual decision-makers arise in agriculture. These problems can only be addressed by recognising the effects of risk and farmers' attitudes to it. The difficulty is that farmers vary in their attitudes to risk, so that the concept of one universally optimal choice is not valid.

A certain segregation of alternative risky prospects can be achieved without detailed knowledge of the utility functions of the target population using the method of stochastic-efficiency analysis (Anderson, 1974; Anderson, Dillon and Hardaker, 1977). By assuming, for example, that farmers generally prefer more income to less and that most of them are averse to risk, it is possible to partition a set of risky prospects into those that are risk-efficient and those that are not. Since this process is quite a lengthy one for complex decision problems, ways of lessening the analytical burden would be useful. One such way is mean-variance (E-V) analysis, which removes the need to estimate the utility function.

The major assumption of the (E-V) approach is that the utility of any act is summarised adequately by two statistical measures: the mean (E) of the probability distribution of outcomes, and the variance (V) of that distribution. A decision-maker's choice among acts will usually depend upon the size of the expected advantage and how variable he considered this advantage.

Given these assumptions, a farmer should rationally restrict his choice among those farm plans for which the associated income variances are minimal for the expected income levels. An efficient boundary over the set of all feasible plans can thus be defined.

Since short-run planning models assume farm overhead costs to be constant for the length of the planning horizon, the income distribution of a farm plan is totally specified by the total gross margin distribution. The optimal (E-V) farm plan can be obtained by quadratic-risk programming or linear-risk programming (Hazell, 1971).

Experience obviously has an important influence on a person's feelings of uncertainty and his degrees of belief. To begin the elicitation procedure, it is often useful to array pertinent historical data in a form that can help to sort out beliefs. Data may be formed into frequency diagrams such as a histogram or processed into statistics such as sample moments and/or fractiles (Schlaifer, 1969), or a frequency curve fitting exercise may be entertained. The best approach will depend upon the problem, the amount of data and the statistical services available (Anderson, 1974). Once a frequency curve has been fitted, simulation can be used to derive optimum farm plans and crop combinations (Zusman & Amiad, 1965; Anderson, 1968).

Simulation has been widely used to forecast water supply and to derivate monthly reservoir release policies (Young *et. al.*, 1980; Bhaskar and Whitlatch, 1980). However, with the exception of Zusman & Amiad (1965) and Anderson (1968), no studies could be found relating variable water supply to optimum farm plans and crop combinations. This may partly be attributed to a lack of information concerning variable water supplies and water requirements of plants.

CONCLUSION

The paucity of research on the effect of changes in water quantity and quality on both the optimal choice of crops and their optimal production levels is indeed unfortunate. Some irrigation dams, forming the bulk of many South African irrigator's water supplies, have very recently contained less than 10% of their total water-holding capacity. These same dams have in the past, and will in future, overflow. Under such conditions farmers need more and better analysis and advice on optimal production patterns than are presently available. Water being one of its scarcest resources, South Africa can ill afford to persevere in not producing the know-how to use it optimally, or at least better, at all levels. Research needs obviously span over a wide variety of scientific disciplines. More co-operation among researchers, more multi-disciplinary research and also more inter-disciplinary research are urgently needed in this respect.

REFERENCES

1) This holds in cases where the amount of water applied does not have sufficient influence on product quality to affect product prices. If prices of one or more products are affected in this way, the relationship becomes more complex mathematically. The conceptual principal, however, remains unchanged.
2) 1 hectare =1,167 499 morgen

BIBLIOGRAPHY

ANDERSON, J.R., 1974. Risk efficiency in the interpretation of agricultural production research. *Review of Marketing and Agricultural Economics* 42(3)

ANDERSON, J.R., BLITZER, C. & CANCHORS, T., 1980. *A Dynamic Simulation Model of the World Jute Economy.* World Bank Working Paper No. 391, Washington, D.C.

ANDERSON, J.R., DILLON, J.R. & HARDAKER, J.B., 1977. *Agricultural Decision Analysis.* Iowa State University Press, Ames

ANDERSON, RAYMOND L., 1968. A simulation program to establish optimum crop patterns on irrigated farms based on preseason estimates of water supply. *Amer. J. Agr. Econ.* 50: 1587-1590

BACKEBERG, G.R., 1984. *Besproeiingsontwikkeling in die Groot-Visriviervallei.* M.Sc(Agric) thesis, University of Pretoria

BEHRMAN, J.R., 1968. *Supply Response in Underdeveloped Agriculture.* North-Holland, Amsterdam

BHASKAR, N.R. & WHITLATCH, E.E., 1980. Derivation of Monthly Reservoir Release Policies. *Water Resources Research*, Vol. 16, No. 6

BLANCHET, R., 1974. Fertilizer use and ecological factors. In: Fernandez, V. Hernando (Ed), *Fertilizers, crop quality and economy.* Amsterdam, Oxford & New York

BROTHERTON, I.A. & GROENEWALD, J.A., 1982. Optimal organisation on developed irrigation farms in the Malelane-Komatipoort area, *Agrekon* 21(2):22-30

BURT, J.E.; HAYES, J.T.; O'ROURKE, P.A.; TERJUNG, W.H. & TODHUNTER, P.E.,1981. A parametric crop water use model. *Water Resources Research* 17: 1095-1108

DEPARTMENT OF AGRICULTURE, 1984 a. *Bedryfstakbegrotings vir besproeiingsgewasse.* Direktoraat Landbou produsie-ekonomie, Departement van Landbou, Pretoria

DEPARTMENT OF AGRICULTURE, 1984 b. *Besproeiingsbehoeftes van gewasse in Suid-Afrika.* Departement van Landbou, Pretoria

DOORENBOS, J. & KASSAM, A.H., 1979. *Yield Response to water.* FAO Irrigation and drainage paper No. 33, Rome

DORFMAN, ROBERT, 1975. Mathematical or "linear" programming: A non-mathematical exposition. In: Mansfield, Edwin (Ed) *Microeconomics, 2nd Ed.* New York: W.W. Norton & Co

FRIEDMAN, MILTON, 1962. *Price Theory.* Chicago: Aldine

HANCKE, H.P. & GROENEWALD, J.A., 1972. The effect of resource availability on optimum organization in irrigation farming. *Agrekon.* 11(3): 9-16

HAZELL, P.B.R., 1971. A linear alternative to quadratic programming for farm planning under uncertainty. *Amer. J. Agric Econ.* Vol. 53(4)

HIRSCHLEIFER, JACK; DE HAVEN, JAMES & MILLIMAN, JEROME, 1975. The allocation of water supplies. In: Mansfield, Edwin (Ed), *Microeconomics, 2nd Ed.* New York: W.W. Norton & Co

JENSEN, H.R., 1977. Farm management and production economics, 1946-70. In: *A survey of Agricultural Economic Literature.* Vol. 2. University of Minnesota Press, Minneapolis

JUST, R.E., 1974. *Econometric Analysis of Production Decisions with Government Intervention.* Giannini Foundation Monograph No. 30, Berkeley, California

MITSCHERLICH, E.A., 1909. Das Gesetz des Minimums und das Gesetz des abnehmenden Bodenertrages. *LandW Jahrbuch* 38: 537-552

SAVAGE, L.J., 1954. *Foundations of Statistics.* Wiley, New York

SCHLAIFER, R., 1969. *Probability and Statistics for Business Decisions.* New York: McGraw-Hill

TORDIFFE, E.A.W. & BOTHA, B.J.V., 1981. The relationship between macrotopography and the groundwater quality of the Great Fish River Basin, Eastern Cape Province. *Water S.Afr.*, Vol. 7

VAN ROOYEN, C.J., 1973. *Die gebruik van proefboerderyresultate vir die beplanning van boerderye by die Hartbeespoortbesproeiingskema.* M.Sc(Agric) thesis, University van Pretoria

YOUNG, G.K., BONDELID, T.R. & DALEY, S.A., 1980. Methods for water supply forecasting. *Water Resources Research.* Vol. 16, No. 3

ZUSMAN, PINHAS & AMIAD, AMOTZ, 1965. Simulation: a tool for farm planning under conditions of weather uncertainty. *Amer. J. Agric Econ.* 47: 574-594