

SOUTHERN AFRICA: FOOD SECURITY POLICY OPTIONS

Correct citation:

Mandivamba Rukuni and Richard H. Bernstein, eds. 1988. *Southern Africa: Food Security Policy Options*. Proceedings of the Third Annual Conference on Food Security Research in Southern Africa. 1-5 November, 1987. University of Zimbabwe/Michigan State University Food Security Research Project, Department of Agricultural Economics and Extension, Harare.

Library of Congress # HD9017.567

REFLECTIONS ON TWO DECADES OF RESEARCH ON
SORGHUM-BASED FARMING SYSTEMS IN NORTHERN
NIGERIA AND BOTSWANA

D.W. Norman, H. Sigwele, and D. Baker

235

SECTION 4: ACCESS TO FOOD

THE ROLE OF THE GOVERNMENT OF BOTSWANA IN
INCREASING RURAL AND URBAN ACCESS TO FOOD

K. F. Mokobi and S. Asefa

257

THE ROLE OF NONFARM ACTIVITIES IN THE RURAL
ECONOMY

P. Kilby and C. Liedholm

275

**SECTION 5: COMMUNAL MAIZE PRODUCTION, STORAGE,
AND MARKETING IN ZIMBABWE: IMPLICATIONS FOR
POLICY MAKERS**

THE GROWTH OF SMALLHOLDER MAIZE PRO-
DUCTION IN ZIMBABWE (1979-1985):
IMPLICATIONS FOR FOOD SECURITY

D. D. Rohrbach

307

POLICY IMPLICATIONS OF HOUSEHOLD GRAIN
MARKETING AND STORAGE DECISIONS IN ZIMBABWE

J. L. Stanning

329

**SECTION 6: WHEAT PRODUCTION AND IMPORTS IN
THE SADCC REGION: WHAT ARE THE TRADE OFFS?**

THE POLITICAL ECONOMY OF WHEAT CON-
SUMPTION AND PRODUCTION WITH SPECIAL
REFERENCE TO SUB-SAHARAN AFRICA

D. Byerlee and M. L. Morris

361

WATER-USE EFFICIENCY ON COMMERCIAL
WHEAT FARMS IN ZIMBABWE

S. Tembo and A. Senzanje

389

ACKNOWLEDGEMENTS

This proceedings of the Third Annual Conference on Food Security Research in Southern Africa is the product of close cooperation between social scientists, technical scientists, government officers, and donor agencies in Southern Africa. The studies reported in the proceedings are part of a comparative analysis of food security in Sub-Saharan Africa that is directed by Michael Weber of Michigan State University's Department of Agricultural Economics. The UZ/MSU food security research programme is being carried out through a sub-contract with Michigan State University.

In the Ministry of Lands, Agriculture, and Rural Resettlement, we acknowledge the generous support provided by Sam Muchena and John Dhliwayo who are responsible for the close collaboration between the food security research project and the SADCC Food Security Technical and Administrative Unit--responsible for developing and managing SADCC's Food Security Programme. They have been particularly helpful in identifying relevant research themes that complement the SADCC programme.

The research supporting the preparation the proceedings papers was financed by the U.S. Agency for International Development, Bureau of Science and Technology; Bureau for Africa; and the Southern Africa Regional Programme; under a *Food Security in Africa* cooperative agreement (DAN-1190-A-00-4092-00) with the Department of Agricultural Economics, Michigan State University and a sub-contract with the Department of Agricultural Economics and Extension, University of Zimbabwe. We are grateful to the following present and former USAID officials for their support to the project's efforts to strengthen indigenous research capacity for food security policy research: Don Anderson, Curt Reintsma, Thomas Mehen, Calvin Martin, David Atwood, Ernesto Lucas, Michael Yates, Roy Stacy, Dale Pfeiffer, Pamela Hussey, and Janet Schulman. We are particularly appreciative of the support provided by Allison Herrick, Eric Witt and Joshua Mushauri of the Southern Africa Regional Programme, Harare.

We convey special thanks to Thembi Sibanda for an excellent job in organizing the Third Annual Conference, and to the many individuals who helped to make the conference a success: Murie Hutchison, Lovemore Nyabako, Maxwell Chiwashira, Samson Maguhudze, George Nyamatemba, Ronald Sagwete, Pete Hopkins, and Andrew Barnes.

We are especially indebted to Mrs. Corinne Smith for her patience, skill, and dedication in word processing the numerous drafts of the chapters included in this proceedings. Her persistence in mastering the word processing and laser printer technology has been exceptional.

Finally, we thank Chris Wolf and Elizabeth Bartilson for providing technical support for the laser printing technology used to print the proceedings.

WATER-USE EFFICIENCY ON COMMERCIAL WHEAT FARMS IN ZIMBABWE

S. Tembo and A. Senzanje¹

INTRODUCTION

Wheat is grown commercially in Zimbabwe as a fully-irrigated winter crop (May-September) in the highveld, middleveld and lowveld on medium-to-heavy textured soils. Approximately 75% of the commercial wheat farmers are located in the Hunyani and Mazowe Valleys of the highveld (mean elevation of 1442m) and the rest are scattered in the middleveld and lowveld, with a significant concentration in the lowveld (mean elevation of 443m).² In Zimbabwe, winter wheat is irrigated by overhead sprinkler systems. Virtually all farmers hand move their irrigation equipment, although about four farmers are experimenting with low-pressure centre pivot systems.

Zimbabwe's wheat industry has grown rapidly over the past 20 years. The first commercial wheat was planted in 1965 in the southeastern lowveld, which marked the beginning of a pronounced increase in wheat production. During the early years, the wheat area expanded mainly in the lowveld, which in 1968 accounted for more than 60% of the country's wheat production (Edwards, 1974). Since 1968, the most rapid expansion has occurred in the highveld. The wheat is grown mainly on large-scale commercial farms, which presently contribute about 94% of the crop. About 4% is produced on state farms, and at most 2% by the communal sector, mostly for home consumption or local markets.

In 1965, Zimbabwe produced only 4,571 mt of wheat, which represented only 4% of its annual wheat consumption requirements. As a consequence of both an expansion of irrigated area--from slightly over 2,000 ha in 1965 to 42,000 ha in 1985--and the release of input responsive varieties; production

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² The Department of Research and Specialist Services of the Ministry of Agriculture and the Agricultural Research Trust have embarked on research into summer wheat. Many years of research will be necessary to overcome the numerous problems (i.e., rust, low yields, etc.) associated with growing wheat during the summer months. Therefore this paper focuses only on winter wheat.

increased to almost 200,000 mt per year by the early 1980s. Average yields increased from 2.5 mt/ha in 1965 to over 5.0 mt/ha in 1985 (Table 1). These dramatic increases in production have had a marked effect on national self-sufficiency, which increased from 4% in 1965 to the current level of 80%, with a slight surplus in 1975-1976 due to an increase in producer prices and favourable rainfall.

This paper focuses on the commercial wheat sector which includes approximately 470 large-scale commercial wheat farms, with from 30 to 2,000 ha allocated to wheat, but with an average wheat area of 45 ha. The paper draws on the results of a survey of commercial wheat farmers, presented by Longmire, Ngobese, and Tembo at the 1986 conference on Food Security in Southern Africa, held in Harare (Longmire, *et al.*, 1986). After summarizing findings of the wheat survey, the paper reviews current irrigation design methods, scheduling procedures, and the costing of energy and water. Based on this discussion, energy and water saving methods are identified. Available evidence suggests that adoption of the proposed water-saving methods would enable farmers to expand their irrigated wheat hectares, without investing in new water storage facilities.

REVIEW OF FINDINGS FROM THE WHEAT SURVEY.

In their survey of wheat growers in Zimbabwe, Longmire, Ngobese and Tembo (1986) identified five major points:

- o By 1986 the demand for wheat products had outstripped supply. The major constraint to increasing wheat production was the availability of water.
- o All readily accessible water sources in the wheat-growing areas had been either fully allocated and developed, or restricted for urban and industrial purposes.
- o Despite the obvious water constraint, wheat farmers were not managing water efficiently. Data collected indicated that they seemed to apply more water than needed to carry the wheat crop to maturity (Stewart and Hagan, 1972, 1973).
- o Zimbabwean research institutions have not sufficiently addressed the issue of efficient water utilization in wheat production, perhaps because water has been readily available and cheap, or because demand was not expected to reach the current high level.

Table 1. Zimbabwe wheat production trend, 1965 - 1985, Zimbabwe.

Year	Farm count (large-scale)	Area planted (000 ha)	Yield (mt/ha)	Total output (000 mt)	Domestic consumption (000 mt)	Self sufficiency (%)
1965-66	NA	1.7	2.69	4.57	84	4.0
1966-67	NA	4.5	2.23	10.04	108	10.4
1967-68	NA	5.2	2.81	14.61	99	16.0
1968-69	105	7.3	3.37	24.60	109	22.0
1969-70	193	11.4	3.48	39.67	114	33.0
1970-71	198	13.6	3.67	49.91	116	50.0
1971-72	278	20.6	4.02	82.81	119	78.6
1972-73	338	21.9	3.73	81.69	111	78.0
1973-74	276	21.1	3.94	83.13	130	65.0
1974-75	360	25.8	3.71	95.72	141	68.0
1975-76	460	30.6	3.95	120.87	146	88.2
1976-77	491	32.7	4.31	140.94	120	123.4
1977-78	578	41.9	3.93	164.67	125	137.1
1978-79	597	44.8	4.53	202.94	144	147.1
1979-80	464	34.3	4.46	152.98	169	93.8
1980-81	424	32.6	4.75	154.82	205	79.5
1981-82	504	36.6	5.01	183.44	223	89.3
1982-83	485	37.3	5.14	191.72	234	91.1
1983-84	304	21.5	5.16	110.96	227	54.6
1984-85	271	16.9	5.20	87.81	220	44.8
1985-86	371	42.0	5.24	219.99	248	86.5

NA indicates data not available

Source: Adapted from CSO and GMB Data.

- o In the analysis of data collected from 45 commercial farms, no strong relationship could be established between net water applied and yield, although the lack of a relationship was perhaps due to measurement error associated with farm survey data.

The Longmire, Ngobese and Tembo (1986) paper concluded that water, not land, is the limiting production factor. Therefore, as water supplies become limited and irrigation and input costs increase, the producers' management objective should shift from optimizing production per unit area to optimizing production per unit of water applied. Optimizing production per unit of water applied implies accepting some yield loss in order to optimize water-use efficiency (WUE)³.

Longmire's *et al.*, (1986) analysis showed how a farmer can maximize returns to water by applying 440 mm/ha (a total of 176,000 m³). This would enable him to increase his production from 244 mt on 40 ha to 330 mt on 60 ha through efficient water application. Even after deducting interest and investment costs of expanding the wheat area, net returns would increase from Z\$13,370 to Z\$21,120 (1986 prices), an increase of over 50%.

The analysis showed that by saving water through "fine tuning" irrigation scheduling, farmers could bring additional land under irrigated wheat without additional water. In conclusion, the authors argued that improved water scheduling is one of the least costly options open for achieving Zimbabwe's stated objective of self-sufficiency in wheat production.

WATER-USE EFFICIENCY.

The two components of water use efficiency are "crop water-use efficiency" and "field water-use efficiency". Crop water-use efficiency is the ratio of crop yield to the amount of water depleted by the crop through evapotranspiration. Field water-use efficiency is the ratio of crop yield to the total amount of water used on the field. The two differ by the amount of water applied to the field, but never utilized by the crop (e.g., losses due to evaporation and drainage).

In Zimbabwe, with the ever-increasing demand for wheat products and scarce water resources for irrigated wheat, it is imperative to maximize water-use efficiency. At the research level, there is the need to better understand the relationship between water consumption and crop yield. At

³Water-use efficiency is defined as wheat yield per unit of net water applied kg/mm.

the farm level, knowledge of the influence of soil water management on plant growth is necessary to maximize output from a given water input.

Research must address several important issues to understand and enhance farm level water-use efficiency. Research directed at increasing wheat production with limited water resources would allow farmers to save water, thus enabling them to irrigate additional wheat area. Finally, research should focus on saving energy (e.g., electricity for pumping water) through improved irrigation management.

Irrigation scheduling

Irrigation scheduling is the technique or process by which the timing and amounts of irrigation water applications are determined. Irrigation scheduling provides a set of guidelines to farmer which indicate when to irrigate, how much water to apply, and how to apply it. At the farm level, proper scheduling can increase the productivity of water and result in considerable savings of water, energy, and labour.

It is of paramount importance that farmers view irrigation scheduling as a flexible management tool to increase their profits, not merely as an exercise. Interviews with farmers suggested that irrigation scheduling, as practiced in Zimbabwe, falls far short of being a management tool. Since scheduling is viewed by many farmers as a routine task to be carried out at regular intervals, many farmers make little effort to schedule in response to crop needs, resulting in low water-use efficiency.

Improper scheduling persists for several possible reasons, including:

- o Water is too inexpensive for farmers to worry about conserving it.
- o Pumping and energy costs are low.
- o Farmers lack the know-how to implement scientific scheduling.
- o Farmers do not want to be bothered with a management practice that appears academic.
- o There has been inadequate research carried out in Zimbabwe to show farmers the benefits of improved water management.
- o The marginal benefits from improved scheduling appear minimal and are not obvious, compared to the extra effort required.

If water-use efficiency is to be improved through scheduling, all, or at least some of the above items, have to be corrected through well-designed research and extension. On the research side, there is a need for adaptive research that replicates work done elsewhere, to produce results relevant to local conditions (e.g., critical growth stage scheduling and deficit irrigation). Results from the proposed adaptive research will enable farmers to fine tune their irrigations and increase water-use efficiency. No matter how well an irrigation system is designed, if water management is poor, the system's performance is lowered with subsequent reduction in water-use efficiency.

Yield response to water

Research carried out in the United States on wheat yield response to water applied (Stewart and Hagan, 1973) suggests a curvilinear relationships where yields first increases linearly with increasing amounts of water. After a certain level of water applied, the yield response to increasing amounts of water decreases, until finally there is no response to additional water. If excessive water is applied, yields decrease due to soil saturation.

Unfortunately, it is difficult to predict yield response to water because water application rates are a poor measure of water-use rates by the crop--water application rates are subject to many uncontrollable variables. Consequently, empirical results tend to be site specific and nontransferable. A more dependable parameter to estimate water use is evapotranspiration (ET). Unfortunately, since ET is very difficult to quantify, farmers are unlikely to use it in irrigation management. Research is needed to determine the optimum amount of water required to carry a crop to maturity under varying climatic and soils conditions, as well as under different irrigation regimes.

Water production functions.

At the regional level, resource planners need a clear understanding of how overall crop production patterns vary as a function of water availability, if they are to properly manage regional water supplies. When water becomes scarce and/or the cost of irrigation water rises, planners and farmers need to know how to best adjust cropping patterns such as by decreasing area under crops that use too much water, or by applying less water to more drought-resistant crops.

Water production functions, which relate water availability to output, may be applicable on a regional basis to determine optimal utilization and allocation. They are most useful as a planning guide in the following three cases:

- o land is limited, but water is available (at a price).
- o irrigation water is limited, but land is available.
- o both water and land are limited.

Research by Longmire *et al.*, (1986) reports that the second case applies to Zimbabwe. When water is scarce, the management objective should shift from maximizing net returns per unit of land to maximizing net returns per unit of water (Stewart *et al.*, 1973).

Additional research is needed to estimate production functions with reliable predictive capacity (i.e., valid over a wide range of conditions). Farm level data is of limited use for estimating these functions because it is impossible to control factors such as soils, crop variety, sowing dates, and management.

Research done in the United States has shown that water production functions are polynomial in nature (Stewart *et al.*, 1973; Yaron, 1971). Yaron obtained a quadratic function of the form:

$$Y = a + bW - cW^2 \quad [1]$$

where:

Y = yield (mt/unit area)

W = water applied

a,b,c = constants

This function is particularly appropriate because it takes into account the detrimental effects of excess water application.

A second function which can be fitted is the Mitscherlich-Spillman function:

$$Y = a\{1 - e^{-cW}\} \quad [2]$$

where:

Y = yield

a = maximum yield when W is used to the limit

W = water applied

c = constant

A shortcoming of this function is that it does not take into account the injurious effects of excess water application. It assumes that as W is increased successively, Y becomes asymptotic to a.

To compensate for this deficiency, the Spillman function may be improved by adding "injury" factors (k), so that it becomes:

$$Y = a\{1 - e^{-cW}\} * e^{-kW} \quad [3]$$

Water production functions are of limited value unless they are estimated from properly designed experiments. On-station trials are needed in Zimbabwe to allow researchers to test a wider range of water application levels than could be analyzed by relying exclusively on farm survey data. If developed from properly designed experiments, water production functions are very powerful tools which, for example, would enable extension agencies to develop more effective irrigation-scheduling recommendations. With the availability of computers and simulation models, it is now possible to estimate these production functions with considerable accuracy and incorporate a variety of critical variables.

Additional irrigation research needs

Several complementary studies should be carried out in Zimbabwe to fill gaps in irrigation systems research.

Critical growth stage irrigation

Under this strategy, water is applied only at crop growth stages during which a water shortage reduces yield. The method is applicable in deep soils where the soil is filled to field capacity at planting. For wheat, this implies that the crop is first irrigated at planting, followed by irrigations at booting, flowering, and finally at grain filling (Salter *et al.*, 1967). Critical growth stage irrigation stretches the limited water supply without overly compromising yield. Research to evaluate this water application method would not require additional capital investment. Research institutions, such as the Agricultural Research Trust (ART) farm (just outside Harare in the highveld) and the Chiredzi Research Station (in the lowveld) are currently conducting research on some aspects of critical growth stage irrigation. These important initiatives need to be continued and expanded.

Evapotranspiration deficit irrigation

Under this scheduling procedure, the soil profile is filled to field capacity at planting. Low soil moisture deficits are maintained in the early season, when the pumping capacity of the irrigation system can satisfy ET requirements. Then, in the peak stress period, the crop is irrigated more frequently to maintain high soil water potential in the top of the root zone. During grain filling, the soil is irrigated to field capacity. This method is applicable to Zimbabwe, especially in deep soils with moderate-to-high water-holding capacity. Also, farmers can use this method in irrigation systems where it is possible to apply frequent irrigations in controlled amounts (Fonken *et al.*, 1974). To effectively implement this method, research is necessary to develop computer simulation models to determine the probable yield loss risks for the various combinations of pumping capacity, soil types, and crops.

Stress day index method

Under this semiquantitative irrigation strategy, irrigations are initiated when a calculated stress day index (SDI) approaches a defined critical level in specified growth stages (Hiller and Clark, 1971). The SDI is determined as:

$$SDI = \sum_{i=1}^n (SD_i * CS_i) \quad [4]$$

where: n = number of growth stages considered

SD_i = degree and duration of plant water deficit in growth stage i

CS_i = crop yield susceptibility in crop growth stage i at that water deficit level

The SDI can be calculated daily, at each growth stage, or for an entire season. Research done in the United States showed that higher water-use efficiencies are obtained using this scheduling strategy, compared to other methods.

OVERHEAD SPRINKLER IRRIGATION DESIGN IN ZIMBABWE

Most old sprinkler irrigation system designs, and even many of those currently being installed, are based on a "peak water requirements" design philosophy which assumes cheap water. The decreasing availability of water will require a design revolution, if Zimbabwe is to realize the government's stated wheat self-sufficiency objective.

To effect this revolution, additional agronomic research is required to investigate the yield response of wheat to water. This research is needed to identify how much water must be applied and at what critical crop growth stage; and in some cases, how that water must be applied. For example, engineers need to know whether well-watered wheat plants use more water per unit of dry matter than plants subjected to stress at various stages. Most Zimbabwe wheat farmers believe that the wheat crop should never be stressed during its growth. Yet, considerable research evidence from United States indicates that moisture stress at certain growth stages does not appreciably reduce yields (Neghassi, *et al.*, 1975). In a detailed study of wheat irrigation with limited water, Schneider *et al.*, (1969) showed that water stress before booting had a negligible impact on yield. On the other hand, water stress during heading-to-grain formation reduced yield. A related study (Hurd, 1968) showed that slight crop stress promoted root development; which allowed the crop to use a larger soil reservoir, thus enhancing greater water-use efficiency.

These studies provide design engineers with the information required to design flexible irrigation schemes that accommodate the crop's varying water requirements at the different growth stages. With such information, engineers can design schemes for deficit irrigation--the practice of deliberately

stressing a crop. This practice is particularly attractive for Zimbabwe in light of limited water supplies and rising irrigation costs. Deficit irrigation allows farmers to greatly reduce water and energy use without reducing net income. Viewed in another way, it will increase their incomes without significantly increasing water and energy use.

The latter is particularly applicable to farmers with fixed water allocations from free-flowing rivers or public dams. Deficit irrigation implies accepting some level of crop stress, imposed through long irrigation intervals and reduced soil-moisture uniformity. Engineers control both of these phenomena through the design of the irrigation system.

Irrigation frequency directly affects the capital (fixed) and running (variable) costs of irrigation schemes. In hand-moved overhead sprinkler systems (as are predominantly found in Zimbabwe) that employ high irrigation frequencies, more laterals may be required to cover the command area--implying higher capital and maintenance costs. In this case, reductions in capital, running, maintenance, and labour costs could be realized by designing systems for low frequency irrigations. With the proposed low frequency deficit irrigation, moisture levels would be allowed to fluctuate over a wide range. A heavy irrigation at a critical growth stage would be followed by a long moisture extraction period, during which the crop would be stressed at some less yield injurious stage. A subsequent irrigation would refill the profile to field capacity. This process would be repeated over the crop growth range. This proposed approach differs from current practices in Zimbabwe in that it recognizes the different crop water requirements at different stages of growth, seeks to reduce net water applied, and conserves energy.

The efficiency with which irrigation systems store water in the root zone (water storage efficiency) depends on two design parameters; namely the uniformity coefficient and the irrigation adequacy. The uniformity coefficient measures the uniformity pattern of irrigation water applied. Irrigation adequacy measures the percentage of the command area refilled to field capacity during an irrigation. Standard irrigation designs seek to optimize both factors. However, a study by English *et al.*, (1982) showed that water storage efficiency was increased from approximately 77%-92% even though adequacy was reduced from 82-50%. In other words, higher storage efficiency is possible at lower adequacy levels. This suggests that improved systems designs can save both water and energy.

IRRIGATION ENERGY COSTS IN ZIMBABWE.

As noted earlier, standard irrigation design and scheduling methods used in Zimbabwe waste water and require high capital and running costs. Farmers surveyed by Longmire *et al.*, (1986) reported that electricity costs are a

major cost component in their wheat production systems. Electricity is sold to farmers through a tariff that is characterized by a declining block rate, which encourages consumption. Against this background, this section highlights energy-saving practices that would produce benefits to farmers.

Farmers tend to over-irrigate to prevent crop yield reduction. However, several irrigation-scheduling trials have demonstrated that a reduction in water applied may, in some cases, actually improve wheat yields in Zimbabwe (MacRobert and Mutemeri, 1987). It is obvious that any reduction in water pumped will reduce energy consumption, even if no other changes are made in the irrigation system.

Energy use in irrigation is a function of numerous parameters, including design flow rate, pumping lift, net irrigation, irrigation system efficiency, management practices, and the type of irrigation system. Pumping energy (PE) requirement is given by (Batty *et al.*, 1975):

$$PE = c \cdot A \cdot D \cdot H / E \cdot Ep \quad [5]$$

Where:

- PE = pumping energy (kW hr)
- A = area irrigated (ha)
- D = net depth irrigation (mm)
- H = total dynamic pumping head (m)
- E = irrigation efficiency
- Ep = pumping efficiency
- c = conversion factor for units (0.0271 for SI units)

This relationship shows that the PE can be reduced by :

- o reducing net depth of irrigation through proper scheduling and management practices;
- o increasing irrigation efficiency through proper system management;
- o reducing total dynamic head through proper design and pipe selection; and
- o increasing pump efficiency through proper design and pump selection.

The combined effects of changes in D, H, Ep, and E is evaluated by the following relationship, developed by Gilley and Watts (1976):

$$\begin{aligned} \text{PES} &= \{(PE_1 - PE_2) * 100\} / PE_1 & [6] \\ &= [1 - (D_2/D_1) * (H_2/H_1) * (Ep_1/Ep_2) * (E_1/E_2)] * 100 \end{aligned}$$

Where:

PES = the potential energy savings (% relative to before and after changes in each parameter)⁴

Gilley and Watts (1976) argue that realistic potential coefficients for variables in this model are: $D_2/D_1 = 0.8$, $H_2/H_1 = 0.85$, $Ep_1/Ep_2 = 0.87$, and $E_1/E_2 = 1.0$. At these values, energy is reduced by 41%. Without a pressure reduction or change in total dynamic head (i.e., $H_2=H_1$), an energy saving of 32% is possible.

Most of the energy used in irrigation is consumed by the pumping unit. Although no pump tests were carried out during the 1986 wheat survey, we believe that many of the pumping units in Zimbabwe are operating well below their design-pumping efficiencies, due to very poor service and maintenance.⁵ In many cases, pump efficiencies are may be below 50%, which is highly wasteful of energy.

Reduced pumping heads decrease energy requirements by reducing the energy required to push the water to the required elevation. In most cases, nothing can be done to change the elevation factor, as it is a function of land and terrain. Yet, it is possible to reduce the pumping head and energy requirements through proper pipe size selection.

IRRIGATION TECHNOLOGY

Hand-moved equipment is labour intensive. A high level of labour intensity influences irrigation set time and introduces rigidity in field level irrigation management. Set time is the irrigation time required to refill the root zone to the design moisture level, usually to field capacity. Most hand-moved systems are designed for a set time of 11 hours. This allows the farmer to

⁴Subscripts 1 and 2 denote before and after values of the other parameters, respectively.

⁵ Pump operational design life is normally 10 years. However, a leading irrigation design firm in Harare estimates the operational life on typical farms as low as 5 years (50% lower), due to the general lack of spares (bearings in particular) and poor maintenance.

change the lateral positions twice a day, generally at 6:00 am and again at 6:00 pm. This saves labour for the farmer, as he does not need to employ an overnight crew to move the laterals. However, even though many farmers follow this practice to save labour and for convenience, in most cases it is introduced at the expense of agronomic factors that might increase yield and, in some cases, save water.

Centre pivot irrigation systems that operate at low pressure offer reduced pumping costs (as much as 30%), facilitate precise water application, and--more importantly--allow flexibility in irrigation set time. The major disadvantage of centre pivot systems is their high initial cost, substantially greater than line irrigation systems. However, these automated systems make it possible to more accurately schedule irrigation water to meet actual plant requirements. Consequently, in the long-run, they save both water and labour. The four farmers experimenting with centre pivots systems claimed greater management flexibility, as well as savings in water applied and energy costs, compared to their hand-moved systems.

We believe that the adoption of computer based water scheduling for winter wheat would yield significant water and energy savings, even on hand-moved systems. A precedent has been set by the Zimbabwe Fertilizer Company which has introduced a computer based package for irrigation water scheduling. Initially launched to increase fertilizer sales, the wheat survey (1986) reported wide adoption of this package. Farmers regard it as a cost-reducing technological innovation with great potential for increasing water-use efficiency.

Centralized computer based scheduling, as proposed by Corey and Franzoy (1974), would provide farmers daily data to assist in making irrigation management decisions. This service could be located at the Agronomy Institute, Department of Research and Specialist Services, or at the ART farm. Farmers would phone in every morning giving agronomic (i.e., soil type, crop growth) and climatic data (i.e., location, rainfall, evapotranspiration) from the previous day. The data would be fed directly into the computer through a dedicated telephone line. Then, the computer would calculate when to irrigate next, how much water to apply, etc. This is a low-cost option to the farmer, since he would pay only for the computer service. The capital and ownership cost of the computer could be borne by the state or by a farmers' organization. In addition, the farmer would not have to be computer literate and would be freed from making mathematical calculations.

Yet, centralized computer scheduling requires:

- o a good data base on soil-crop-water relationships;
- o reliable climatic data;
- o computer expertise to implement the system; and
- o a reliable telecommunications system.

Most of the above conditions are either lacking or are at an infant stage in Zimbabwe; and would require further development before these technological benefits can be realized.

CONCLUSION

Increasing water-use efficiency would enable Zimbabwe to become more self-sufficient in wheat production. To achieve this objective, several constraints must be overcome.

Expanding the research data base

Most of the cost-saving methods outlined in this paper could be adopted and implemented in Zimbabwe if not for the lack of one critical factor--a research data base. Irrigation research in general, and irrigation research on wheat in particular, has only begun in Zimbabwe. Ongoing varietal improvement research trials at both the ART farm and the government research stations are commendable, but may have reached the point of diminishing returns. Wheat yields in Zimbabwe already are among the highest in the world. A recently released local variety, Sengwa, yielded 10 mt/ha under station conditions at Harare Research Station. Researchers must now focus their efforts on improving water-use efficiency by, for example, providing guidelines to farmers on how to increase wheat production through more efficient utilization of the two limiting resources, water and energy. We must not ask the farmers simply to produce more wheat; rather, we must ask them to "efficiently" produce more wheat. Before farmers will adopt new technologies, convincing evidence of the benefits under Zimbabwean conditions is needed. Irrigation research is needed that investigates the agronomic, technical, and economic aspects of new wheat technologies. Therefore, it requires the collaboration of breeders, agronomists, and engineers; and provides an excellent opportunity for stronger cooperation between public and private sector institutions.

Cost of electricity.

As previously indicated, the cost of electricity is directly related to the type of irrigation system. Centre pivot systems, which operate at lower operational pressures, offer significant electrical energy savings over conventional high pressure systems. Although farmers cite electricity as one of their major cost, they still find it uneconomic to invest in automated, low pressure systems--especially since labour is still cheap.

In Zimbabwe, electricity is priced using a declining block rate that encourages consumption. On the one hand, this is justifiable for expanding power supply systems where the long-run marginal cost of generating elec-

tricity is declining (when each new plant brought on or an extension of a line lowers costs because fixed investment is spread over more units of output). On the other hand, time-of-use pricing (offering discounts during off-peak hours when overall demand is lowest) would encourage farmers to conserve energy. Introducing time-of-use pricing would require no extra capital cost to the electricity suppliers and would encourage farmers to avoid power usage during peak industrial use when it is expensive. This is feasible in automated irrigation systems, where time of day puts no operational constraints in the system.

Costing of water

Irrigation water in Zimbabwe is priced too low to encourage farmers to adopt practices that improve water management. Longmire *et al.*, (1986) showed that the pattern of water application reflected source and cost of water, which was often determined by institutional factors. Farmers who did not pay, or paid relatively less than others for water, were more wasteful; they applied a lot more water than is required to grow a wheat crop to maturity.

The current blend price of public water (Z\$10-18/1,000 m³) is subsidized and tends to encourage waste. Agronomic research is required to establish the optimal amount of water required to grow a wheat crop (mm/ha or m³/ha), and a new water tariff must be established that penalizes farmers who apply more than the optimal water level. The system should credit those who save water and at the same time, maintain optimal yields. This could be effected by transferring whatever water volume a farmer has saved into the next season.

To enforce this system for all public water, the Regional Water Authorities would have to install user flow meters and additional manpower to enforce compliance. Water savings from this institutional restructuring could be used to help pay for the capital invested and the management required to maintain the system. In the long-run, farmers may find it attractive to allocate the saved water to increase their wheat area.

Irrigation management.

Currently, irrigation management in Zimbabwe is more of a tradition than a science. Farmers have not had to modify management practices in response to growing scarcity because the scarcity is not reflected in water and energy pricing. In the main, farmers continue to accept "rule of thumb" irrigation-design recommendations based on peak water requirements; and they continue to move the laterals twice a day because it is convenient. Their behavior is understandable; they have been exposed to little empirical evidence showing the benefits of alternative strategies, and they are subject to few economic

disincentives to alter these established practices. Additional research would help to generate such evidence. Finally, pricing policies oriented toward water and energy savings would encourage irrigation designers to be innovative in developing water efficient systems and, at the same time, would force farmers to more efficiently manage Zimbabwe's scarce water resources.

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