CROP YIELD AND WATER USE IN SMALLHOLDER IRRIGATED AGRICULTURE: A CASE STUDY OF NYANYADZI (ZIMBABWE) AND MATANYA (KENYA) IRRIGATION SCHEMES

BY

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DECLARATION

I hereby declare that this is my original work and has not been submitted in any university for examination. All sources of information have been duly acknowledged.

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DEDICATION

This thesis is dedicated to my late brother **Spencer**, whom I loved and miss so much.

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ABSTRACT

The performance of most smallholder irrigation schemes has been disappointingly low. This study aims at establishing the causes of low crop yield in Nyanyadzi and Matanya irrigation schemes and to identify possible interventions. Nyanyadzi irrigation scheme was developed in 1938. Maize crop yields are between 0.86-2.5 t/ha compared to a potential of 4-5 tons/ha. Matanya irrigation scheme was developed in 1940 and its crop yields for maize are between 0.5-1 t/ha compared with a potential of 5-6 t/ha.

Causes of low crop yields at Nyanyadzi irrigation scheme were established using literature review, questionnaire study and field observations. The questionnaire survey was also used to assess farmer perceptions on the on -farm water supply situation and their management practices (among other issues). The main factors limiting crop production were identified in order of their importance as water shortage, low input use (fertilizer and manure), poor irrigation scheduling, low pesticides use, and inadequate technical advice to farmers. The level of input was found to be related to the water availability and to the position in the scheme.

As a follow-up to the findings at Nyanyadzi irrigation scheme, maize yield response to water scenario studies were carried out using the DSSAT model under Matanya conditions (also a small-scale irrigation scheme with similar water problems as Nyanyadzi). In this study, 5 levels of irrigation (0, 33, 66, 100 and 133 % irrigation requirement) were used and 3 nitrogen levels (0, 50 and 100 kgN/ha) were used to form a 5*3 factorial experiment with 15 treatment combinations. The model was calibrated using data collected by Ragwa in 1995. Maize crop water requirements and irrigation requirements were determined at. 0, 33, 66, 100 and 133% of the irrigation requirement applied depending on the treatment. Nitrogen was split applied during the vegetative stage, as this is the period when maize growth is most sensitive to nitrogen stress.

The results indicated that:

1. Higher yields are attainable with proper water and nutrient management
2. At low levels of nitrogen the yield response to water is very low, that is 1087 kg/ha for rainfed conditions compared to 1387 kg/ha when crop water requirements are fully met.

3. At high levels of water and nitrogen significant yield increases can be attained, from 1087 kg/ha for rainfed conditions and no fertilizer added to 8117 kg for 273 mm of irrigation water and 100 kg of nitrogen.

4. There are benefits in applying less than 100% irrigation requirements if the soil fertility status is improved as evidenced by the 33% and 66% irrigation requirements when 2382 and 5567 kg were obtained at 91 and 181mm of water respectively under 50 kg of nitrogen

From this study, it can be observed that investment in water improvement without a corresponding investment in improving soil fertility does no significantly increase yield. There is thus a high yield potential that has not been tapped in most small -scale irrigation schemes.

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LIST OF ABBREVIATIONS

AGRITEX.... Agricultural Technical and Extension Services

APSIM Agricultural Production Systems Simulator

DSSAT........Decision Support System in Agrotechnology Transfer

NRM^3 .... Natural Resource Monitoring, Modeling and Management

ODA.......... Overseas Development Agency

1.0 INTRODUCTION

1.1 BACKGROUND

The importance of irrigation in semi-arid and arid lands cannot be over -emphasized. Irrigation contributes to food security, increased farmer's income, and foreign exchange to the country as well as employment creation. Thus, man has utilized irrigation from earliest times to grow his food in the arid lands and has helped to foster large and prosperous civilizations over the centuries (Zimmerman, 1966). Irrigation plays a very important role in the timely provision of water at the root zone for plant growth. Water for plant growth can be made available through two basic ways, either natural rainfall or irrigation.

Hillel (1987) defined irrigation as the supply of water to agricultural crops by artificial means, designed to permit farming in arid regions and to offset drought in semi-arid or semi-humid regions. It is rare for the seasonal pattern of precipitation to coincide with crop water requirements during the growing season and often, in humid areas, short-term deficiencies in soil moisture can occur which check crop growth and reduce financial returns (Carruthers and Clark, 1981). Sometimes the rains come late when much of the growing season is already lost or they just do not meet crop water requirements.

Irrigation minimizes some of the vagaries of weather by providing the farmer with water in a reliable, controllable and predictable manner (Gichuki, 1988). Gichuki further cautions that it is only when farmers are confident of their water supply will they be willing to provide the complementary inputs for agricultural production. Thus, as the demand for food and fiber increases as a result of the continued increase in world population, men and women with knowledge of irrigation will be called upon to find the solutions to world food and fibre problems. It is important to note that irrigated agricultural development, however, greatly lags behind the potential.

Expansion of irrigated agriculture in most areas is limited by water availability, and yet most irrigation schemes operate at very low levels of efficiency. It therefore goes without saying that there is need for efficient and economic use of irrigation water if the potential of irrigation is to be realized. Potentially higher profits resulting from more efficient water use will ultimately result in lower prices for consumers, with lower prices resulting in more consumption of food and fiber, greater availability of food and fibre results in higher standards of living for the peoples of the earth (Israelsen, 1932).

1.2 RATIONALE FOR THE STUDY

Hillel (1987) posed a question: " Why is it that irrigated farming in so many areas fails so woefully to achieve its potential? He went on to state that the problem is not inherent in the principle of irrigation per se, but in its frequently careless practice. It is no doubt that what is at fault is the unmeasured and generally excessive application of water to land, with little regard either for the real cost of the water (in contrast with its often arbitrarily set price) or for the potentially insidious processes set in motion. Indeed the general and universal fallacy of man is to assume that if little of something is good, then more must be better.

Realistically in irrigation (as indeed in many other activities), just enough is best, and by that we mean a controlled quantity of water just sufficient to meet the crop water requirements and to prevent the accumulation of salts. The application of too little water on the other hand is an obvious waste, as it might fail to produce the desired benefit (Hillel, 1987). On the other hand, over-irrigation brings in such problems as poor soil aeration, disease infestations, salinity build up, leaching of nutrients and subsequent yield reduction or sometimes complete crop failure. The practice brings unjustifiable costs to the farmers. Thus, it is important that only optimal amount of water should be used to attain maximum yields, which are cost effective.

The performance of irrigated agriculture, particularly smallholder irrigation in eastern and southern Africa has remained rather low and disappointing. In Kenya and indeed in Zimbabwe the solution to the problems of irrigated agriculture lies in the improvement of water use efficiency at the farm level. Unfortunately there is inadequate data and information upon which to select the best strategy for improving the performance of irrigated agriculture. It is important to assess water use efficiencies being attained by farmers under limited water conditions and establish their perceptions as regards the strategies in place for increasing water use efficiency at the farm level. As of now, the following are some of the questions begging for answers in smallholder irrigation schemes:

1. What additional yield would one get if they applied an additional x mm of water?
2. If one had limited water which crops should they irrigate preferably?
3. For the irrigation water volume allocated to a farmer what application volume would give him the highest yield, for example is it less than optimal application rate for a large irrigated area?

Identifying solutions to these problems and questions is not only a step forward in finding a permanent solution to the poor performance of many smallholder irrigation schemes, but will also provide adequate data and information upon which decision makers can plan for performance improvement. This would help ensure that potential gains of the community from irrigation are realized and also improve the social aspect of the community through a reduction in conflicts among water users.

1.3 OBJECTIVES

The main objective of this study was to document constraints and opportunities for increasing irrigation efficiency in smallholder irrigation schemes in Kenya and Zimbabwe. The specific objectives were:

1. To determine the causes of low crop yields at Nyanyadzi irrigation scheme
2. To assess maize yield response to water and nitrogen at Matanya irrigation scheme
3. To identify and recommend strategies for coping with water and fertility constraints in smallholder irrigation schemes.

2.0 LITERATURE REVIEW

2.1 SMALL HOLDER IRRIGATION IN ZIMBABWE AND KENYA

2.1.1 Nature and extent

Underhill (1983) quoted in Carter and Kay (1988) defines smallholder irrigation as "*those schemes, which are under local responsibility, controlled and operated by the local people in response to their felt needs*".

Smallholder irrigation systems have been designed and operated in Zimbabwe for the last half century, reports Pazvakavambwa (1989). Generally small holder irrigation in Zimbabwe is practiced in communal lands, which extend over some 40% of the area of Zimbabwe and support 4.3 million people. Mostly for reasons related to the political history of the country, the communal lands are mainly situated in natural regions IV (fairly low total rainfall area, subject to periodic seasonal droughts and severe dry spells during the rainy season) and V (very low and erratic rainfall, with mean rainfall below 600mm), Vincent and Thomas (1960) quoted in Hungwe (1988).

In Kenya approximately 80% of the country may be described as semi-arid or arid (Achola, 1992). The main determinant of availability of water resources is rainfall which is in turn influenced by the twice-yearly movement of the Inter-Tropical Convergence Zone (ITCZ) and this leads to two rainy seasons in March-June and October-November. The precipitation pattern is also influenced by altitude as well as proximity to large bodies of water such as lakes. Total annual rainfall therefore ranges from less than 250 mm in Northern Kenya to 2000 mm on the slopes of Mt. Kenya (Achola, 1992). Only 17% of the 585 000 km^2 of the land area in Kenya is suitable for rainfed agriculture (Kimani, 1989). Kimani went on to conclude that given the current population growth rate and consequent pressure on the high potential land resources, irrigation is expected to play an important role in the future expansion of agricultural production into the arid and semi-arid lands and in crop intensification in the high potential areas. Most of the smallholder irrigation schemes in Kenya are mainly government promoted with a main objective of fostering irrigation development.

This type of irrigation development is of recent origin and represents an appreciable shift in the conception of future irrigation development in Kenya. It is envisaged that in formulating such schemes, water from a common source will be shared by a group of farmers (100-300) without the need for change in either farm boundaries or land tenure. Investment in supporting infrastructure (roads, schools and health facilities) is expected to be low.

2.1.2 Productivity and profitability

2.1.2.1 Agroeconomic performance indicators

The welfare of plotholders in an irrigation scheme is determined mainly by:

1. irrigated holding size
2. cropping pattern in those holdings and
3. gross income they receive from crop production

Meinzen-Dick *et al* (1994) state that although gross margins per holding size are used to provide an assessment of irrigation systems performance in terms of increasing gross crop incomes per family, very little is said about the efficiency of land and water resources use in creating those incomes.

Thus, it has been argued that total crop income may be higher on some schemes not because the holdings are being used productively, but simply because the farmers have been allocated larger holdings. As a result of these drawbacks and to account for differential resource (land and water) endowments, the gross margin per unit area and per unit of water supplied to the irrigation system were recommended for use.

2.1.2.2 Productivity per unit of water

Meinzen-Dick *et al* (1994) used the gross margin per unit of water as an indication of the efficiency of water use in terms of financial returns to the input. It is cautioned however that this measure has got some loopholes as it is based on the assumption that the same amount of water is delivered to the entire cultivated area, which in practice is never the case. It is also reported that the gross margin per unit water also does not explicitly account for the timing and volume of each application. Makadho (1994) demonstrated that normally water supplies are in excess of crop demand during some periods and inadequate in some other periods although total water availability may be high. Thus it has been noted that poor spatial or temporal distribution of water is likely to reduce average gross returns per unit of water over the scheme.

2.1.2.3 Productivity per unit of land

Meinzen-Dick *et al* (1994) presented two alternative measures of gross margins per unit area as indicators of irrigation performance. These are:

1. Performance per hectare actually cropped.
2. Performance per hectare of total holdings (or command area).

The measure of gross margins per actually cropped area gives an indicator of plot level performance, and it shows farmer performance on the cultivated land given the amount of irrigation water that was available to them. The gross returns per unit area take into account the production over the entire potential command area and is thus reported to be a better measure of the performance of the scheme as a whole. It is further reported that gross margins on the area cropped are likely to be higher if cultivation is restricted to only part of the potential command, and provide a high relative water supply to that area. Gross margins per unit cultivated area are likely to be high if water is concentrated on some of the area and the other land is left fallow. In Zimbabwe this effect is more distinct in winter than in summer since during winter more schemes leave land fallow and in summer most of the command area is under cultivation (Meinzen-Dick *et al*, 1994).

2.1.3 Constraints

The main drawback in irrigated smallholder agriculture in Zimbabwe and Kenya and indeed elsewhere, is the shortage of irrigation water. For example in Zimbabwe, the situation with regard to water supply in smallholder-irrigated areas tends to be critical with most rivers flowing for only six to eight months of the year (Hungwe, 1988). Those rivers that are perennial tend to have significantly low flows during periods of peak demand for irrigation water in winter. The situation in Zimbabwe is worsened by the fact that prospects for underground water supply in the communal areas are poor, not to mention the exorbitant and prohibitive costs of pumping out underground water for small-holder irrigation.

More often than not, the decline in the popularity of many smallholder irrigation schemes has been attributed mainly to social factors. While it is not proper to overlook social issues, the continued deterioration of soil fertility and subsequent yield decline could be another cause of concern worth investigating. Another constraint was noted in Kenya and that is the competition between irrigation and subsistence crops and coffee for labour (Kimani, 1989). In Zimbabwe, poor supply of inputs is a major issue. Although the farmers have attempted to increase their purchasing power by acting as a group, however the pre-payment system works against the poorer farmers (Chancellor and Hide, 1996). Inequity in the use of irrigation water among farmers on the head, middle and tail end positions of the scheme is also a major setback on performance of small holder irrigation schemes. Sometimes farmers at the tail end of the scheme, in an attempt to get themselves more water, have been known to break or vandalize control structures, which are often difficult to replace at times (Pazvakavambwa, 1989). This "inevitable" situation comes about as a result of the tendency by head-end farmers to over -water at the head end since water would be "plentiful".

2.2 YIELD RESPONSE TO WATER

2.2.1 Irrigation water use

Water used for irrigation is obtained either from surface water supplies, such as reservoirs or rivers, or from ground water. In Kenya, irrigation is practiced for growing rice, cotton, fruits, coffee and vegetables. Keoro and Mecheo (1992) commented that, compared to other users, irrigation makes the highest demand on water resources. The use of water for irrigation is largely consumptive with limited return flow which is estimated to range from 0 to 30% depending on the method and management practices used.

Thus, being a major water user, irrigation can create water conflicts especially in arid and semi-arid regions, where water supplies are limited. It is logical therefore that good management practices are needed to prevent water being wasted (or polluted), so that the needs of all other water users can be met (Keoro and Mecheo, 1992).

2.2.2 Crop water requirements

Crop water requirements are based normally on the rate of evapotranspiration (ET) in mm/day or mm/period (FAO, 1986). The evaporative demand can be expressed as the reference evapotranspiration (ETo). ET_0 represents the rate of evapotranspiration of an extended surface of an 8 to 15 cm tall green grass cover, actively transpiring, completely shading the ground and not short of water. Methods to calculate ETo are given in texts. Owing to the difficulty in obtaining accurate direct measurements of pan evaporation under field conditions evapotranspiration is often predicted on the basis of climatological data (Michael, 1986). The approaches followed are to relate the magnitude and variation of evapotranspiration to one or more climatic factors (temperature day length, humidity, wind and sunshine). The influence of crop type on crop water needs is given by:

$$ETc = Kc * ETo$$

Where ET_C = crop evapotranspiration (crop water needs) mm/day, Kc = crop factor and varies with the crop growth stage, type of crop and the climate, ETo = reference crop evapotranspiration in mm/day.

2.2.3 Crop Water Stress

2.2.3.1 Water Deficit Stress

Stress, technically, occurs when there is a loss of water from a plant, or a part of a plant, creating negative water potential. Generally plants grow best when they are not under moisture stress. When the water potential, measured in units of pressure (bars) falls below 0.5 to -1.0 bars, stress is said to exist (Carruthers and Clark, 1981). It is reported that most physiological processes continue normally until the water potential falls below -10 bars.

The internal water balance or degree of turgidity of a plant depends on the reactive rates of water absorption and water loss, and is affected by the complex of atmospheric, soil and plant factors that modify the rates of absorption and transpiration (Michael, 1986). Conditions are often such that the rate of water loss exceeds the rate of water absorption, causing an internal water deficit to develop in the plant. Michael (1986) comments that it is this internal water deficit, through its influence on many of the physiological processes in the plant, that is directly responsible for the growth and yield of a crop under the prevailing conditions.

The yield of a crop is the integrated result of a number of physiological processes. Reduction in leaf area, cell size and inter-cellular volume is common under water stress. It is however, important to note that water stress at certain critical stages of plant growth causes more injury than at other stages. For example, in maize, stress at setting results in a greater reduction in yield than stress at other stages in the crop growth (Carruthers and Donaldson, 1971).

Although the yield of useful product will be reduced by stress, it will not be economic to minimize stress because this could involve very large quantities of water very frequently applied. From an economic point of view, Carruthers and Clark (1981) came up with four categories of stress:

1. Stress which does not affect physiological processes;
2. Stress that has a temporary effect which can be overcome by subsequent compensatory growth;
3. Stress that reduces useful crop products;
4. Stress that results in crop growth failure.

When the full crop water requirements are not met, water deficit in the plant can thus develop to a point where crop growth and yield are affected. The manner in which water deficit affects crop growth and yield varies with the crop species and crop growth period. FAO (1986) came up with a methodology, which makes it feasible to quantify the effect of water stress on crop yield. FAO argues that it is necessary to derive the relationship between relative yield decrease and relative evapotranspiration deficit given by the empirically - derived yield response factor Ky., or

$$\left(1-\frac{Ya}{Ym}\right)=Ky\left(1-\frac{ETa}{ETm}\right)$$

Where Ya = actual harvested yield Ym = maximum harvested yield, Ky = yield response factor, ETa = actual evapotranspiration and ETm = maximum evapotranspiration

Since the relationship is affected by some other factors other than water, it refers to high producing varieties, well adapted to the growing environment, optimum agronomic and irrigation practices including adequate input supply, except for water. The yield response to water deficit in different individual growth periods is of major importance in the scheduling of available but limited water supply in order to obtain highest yield. In general, crops are more sensitive to water deficit during emergence, flowering and early yield formation than they are during early (vegetative, after establishment) and late growth periods (ripening) (FAO, 1986). Timing of water supply is as crucial as the supply level over the total growing period. Maize is relatively tolerant to water deficits during both the vegetative stage and ripening stage. The greatest decrease in grain yields is caused by water deficits during the flowering period, including tussling, silking and pollination, due mainly to a reduction in grain numbers per cob. Normally, severe water deficits during the flowering period, particularly at the time of silking and pollination, may result in little or no grain yield due to silk drying (FAO, 1986). Water deficit during the yield formation period may lead to reduced yield due to a reduction in grain size. On the other hand, water deficit during the ripening period has little effect on grain yield.

2.2.3.2 Water stress induced by waterlogging

Inefficient use of irrigation water may lead to waterlogging, and just like water deficit, this causes a stress on the plant. It is important to understand that excess water affects plant growth by reducing aeration (Schwab *et al*, 1981). Plants are not adversely affected even in total water culture if air is provided. Another adverse effect of waterlogging is denitrification, leading to the depletion of nitrogen (an essential nutrient for plant growth) in the soil. Thus, over-irrigation does not only result in wasteful use of water (an important and costly input in the production process) but also is detrimental to the plant. In some instances, over application of irrigation water results in the rise of the water table and salinity build up, often leading to the eventual abandonment of the irrigation scheme. Salinity control is important not only to the farmer who is concerned with crop production on his farm, but also irrigation project planners and to organizations that are concerned with development, storage, diversion and distribution of irrigation water within a drainage basin or valley area.

2.2.4 Optimal water level

FAO/UNESCO (1973) defined optimum water requirement as the amount of water required during the growing season to produce maximum yields of different crops. Although this definition may be interpreted as water sufficient to produce maximum yield per hectare, Carruthers and Clarks (1981) cautioned that such an interpretation is likely to be wrong because it is maximum return per unit of scarce input that matters and which in most instances is water. Crop response to water supply is a complex of physical, biological and biochemical processes. A measure of the marginal response of a crop to irrigation water can provide the basis for a useful first check on the economic returns to irrigation. Normally, the first step in establishing crop response is the simple analysis of the effects of changes in the total water supply during the growing season. The effects of the timing of water inputs and the design of an optimum watering strategy constitute much more complex problems.

Crop production and optimum use of water are determined by the total environment, and consequently are location specific (FAO, 1986). The method presented for analyzing the relationship between crop yield and water use allows an integration through a yield response factor (ky) of a large number of complex processes into a simple quantitative relationship between relative yield decrease (1 - Ya/Ym) and relative water deficit (1 - Eta/Etm). For the method to have wide application, FAO (1986) concluded that the relationship for the different crops be (I) derived from experimental data of high producing varieties obtained under conditions where production inputs other than water are adequate and (ii) presented on a relative scale.

2.3 YIELD RESPONSE TO FERTILIZER

2.3.1 Importance of Fertilizers

In most of Africa, Asia and Latin America, only small quantities of fertilizers are as yet being utilized. Almost wherever efforts are made to raise agricultural efficiency and production for expanding populations, more fertilizers are needed (Ignatieff and Page, 1958). It has been demonstrated in many countries that great potentials for sustained crop production increases can be realized through the greater and more efficient use of fertilizers. Fertilizers enable farmers to increase production and get higher returns for their expenditure of work and materials.

Perhaps even more important on many soils, they make possible good yields of valuable crops that would not grow at all without them or would grow very poorly. Through the judicious use of fertilizers the quality of the crop may also be improved. Although it is common knowledge to often regard chemical fertilizers as substitutes for animal manure, that is not a correct interpretation of their purpose. Animal manure improve soil conditions and supply nutrients, but they are essentially the by -products of any particular farm. Thus, the use of commercial fertilizers makes it possible to introduce extra supplies of nutrients into the cycle of growth and decay and so improve fertility. Even though every essential nutrient is added, singly or included in a fertilizer mixture, in practical farming in many parts of the world, only a few are used widely on many soils, and the most generally needed are the three primary nutrients, nitrogen, potassium and phosphorus.

Ignnatieff and Page (1958) reported that it is unfortunate there is not enough manure available on most farms to permit an adequate application to each field each year. In a rotation, emphasis should be given to the use of manure on the more valuable crops that respond well to applications of plant nutrients and to improved soil structure. For example, maize and oilseeds respond particularly well to manure although this is not the case with most legumes. The plant nutrient content of manure naturally depends on the kind and amount of feeding stuffs and litter, and on the way manure is made and used. It is important to note that manure often improves the structure of soils, and they do this directly through their action as bulky diluents in compacted soils or indirectly when the waste products of animals or micro-organisms cement soil aggregates together. The structural improvements increase the amounts of water useful to crops that soils can hold, improve soil aeration and drainage, and encourage good root growth by providing enough pores of the right sizes and preventing the soil becoming too rigid when dry or completely waterlogged and devoid of air when wet (Cook, 1972).

2.3.2 Nitrogen uptake by crops

In order to determine nitrogen stress on crop growth, an estimate of the nitrogen uptake is required. Woodruff (1984), quoted in Littleboy *et al, (1989)* described the uptake functions as:

$NU_i = T_i NA_i f_i$

NU_i = total nitrogen uptake for layer i (g/ m^2)

T_i = transpiration from layer in layer *i* (mm)

NA_i = available nitrogen concentration *i* (kg/ m^3)

f_i = depth weighting factor

The total nitrogen used never exceeds the optimal daily nitrogen requirements.

2.3.3 Nitrogen Stress

Nitrogen stress in crops is reported to occur when the total nitrogen used is less than the minimum nitrogen requirement (Littleboy *et al,* 1989). The optimum and minimum nitrogen requirements are calculated by:

Y =P (0.091-0.045X, 0.014)(V+S)-T

Z = P (0.041-0.017X 0.009) V +0.015S -T

Y = optimum nitrogen requirement (g/ m^2)

Z = minimum nitrogen requirement (g/ m^2)

X = phenological stage of crop

V = above ground total dry matter (g/ m^2)

S = total dry matter (g/ m^2)

T = total nitrogen used by crop (g/ m^2)

P = Maximum nitrogen requirement

Nitrogen stress on crop growth is estimated from:

nsi = 1.0- A / Z

nsi = nitrogen stress index ($0.0 < nsi < 1.0$)

A = total nitrogen uptake (g/ m^2)

Z = minimum nitrogen requirement (g/ m^2)

It is important to note that nitrogen stress on crop growth cannot occur after anthesis

2.4 STRATEGIES FOR INCREASING WATER USE EFFICIENCY

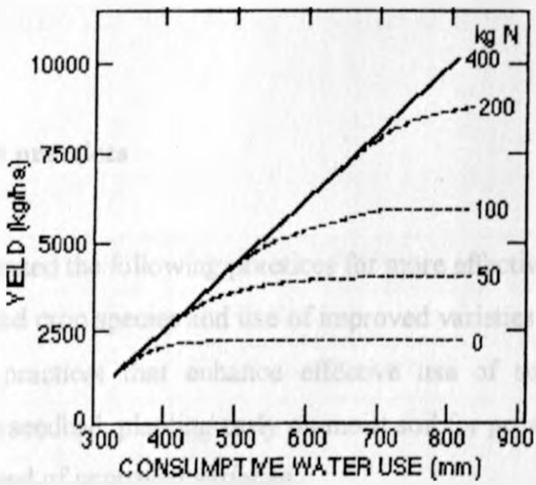
2.4.1 Judicious use of Irrigation Water

Water constitutes a major constraint to increasing crop production in our hungry world. In order to grow successfully, each crop must achieve a water economy such that the demand made upon it by the climate is balanced by the supply available to it (Hillel, 1987). There is therefore need for efficiency in the way farmers administer and manage their water if they are to make productive and profitable use of the limited water resources. There are indeed strategies in place for increasing water use efficiency.

Manzungu (1996) reports that as of now, most irrigation scheduling in Zimbabwe is premised on maximization of yield per unit land area rather than maximization of yield per unit of water. He went on to state that in smallholder irrigation, where water is in short supply, this can be considered a contradiction. It is also reported that in circumstances of scarce water supplies, a maximization of the water resource, which can be achieved through deficit irrigation and irrigation at critical crop growth stages, is most appropriate (Tembo and Senzanje, 1988). One hypothesized way of achieving the efficient use of irrigation water is to subject the crop to some degree of water stress particularly during those growth stages, which are not so critical. Michael (1986) suggested that where irrigation water supply is limited, it is important to take into account the critical stages of crop growth with respect to moisture and be more biased to such stages in terms of water allocation.

2.4.2 Use of Nitrogen Fertilizers

Water use efficiency can also be achieved through increase in the fertility status of the soil .The relationships between crop yield, water supply and soil fertility were reviewed by Viets (1962) and Black (1965). It has been reported that the effects of frequency of irrigation and amount of water applied are affected by the fertility of soils. Yaron (1973) reported that the most desirable frequency of irrigation could have maximum benefit on the crop only if a supply of readily available nitrogen is present in the soil. There is therefore need for correction of any deficiencies in soil fertility through fertilizers and soil amendments in order to foster deeper rooting and greater yields. Shimshi (1967) quoted in Yaron (1973) demonstrated a relation between consumptive water use and maize yield at different nitrogen levels.



Source: Yaron (1973)

Figure 1: Consumptive water use and maize yield at different nitrogen levels.

From Fig.1, it can be observed that use of nitrogen increases the efficient use of water by maize as demonstrated by the increase in consumptive water use with increase in nitrogen level.

2.4.3 Proper mix of water and nitrogen fertilizers

Experimental evidence indicate that the mineralization of nitrogen increases as the water content of the soil increases from permanent wilting point to field capacity (Michael, 1986). It is important to note that as the fertilizer nitrogen is applied to the soil surface, its uptake is inhibited when the soil dries. Results of studies on fertilizer- irrigation relationships led to the following conclusions (Michael, 1986):

1. Water -use efficiency is raised by fertilizer which increases dry matter production
2. The response to fertilizer is generally of a higher order under irrigated conditions than under dry land conditions
3. Response to frequent irrigation is generally enhanced by increase in the level of fertilizer applications.

Thus, through proper use of water and nitrogen fertilizers, yields of irrigated crops can be increased significantly.

2.4.4 Viable Agronomic practices

Litzenberger (1974) proposed the following practices for more effective use of soil water:

1. selection of adapted crop species and use of improved varieties of each crop
2. Use of cultural practices that enhance effective use of soil water, that is early preparation of the seedbed, planting early on moist soil for prompt germination.
3. use clean viable seed of improved varieties
4. control weeds
5. combat pests as needed and harvest promptly to avoid crop losses and deterioration

2.4.5 Use of questionnaire survey data

Use of questionnaire survey data forms an important tool in seeking constraints and opportunities for increasing irrigation efficiency in smallholder irrigation. Unless the irrigation planners and policy makers get to know the problems affecting farmers, their perceptions about the water delivery system (among other things), very little can be done to increase the welfare of farmers as they may feel things are being imposed upon them.

The data collected should be representative of the farmers under study and where possible stratification should be done. In Zimbabwe, guidelines by Meinzen-Dick *et al* (1994) on sampling procedure are often used (Table 1). The tenants' register that is maintained at all formal irrigation systems is used as the sampling frame for selecting sample farmers in each block in the scheme. Under the sampling procedure if a scheme or block has up to 20 farmers, all should be included in the surveys. For blocks with 21 to 80 farmers copying all names from the tenant's register (eliminating all duplicate names of those farmers with more than one plot), and drawing out slips of paper select a simple random sample of 20 farmers. For blocks with over 80 tenants the names are first stratified by sex then listed in alphabetical order. A random number between one and five is then drawn for the first name and every fifth name selected. Farmers in the tenants' register stratified by sex then arranged alphabetically.

Table 1: Farmer sampling criteria

Total No of Farmers	Sampling Criteria
0-20	Select all
21-80	20 (selected randomly)
81-120*	every fourth
121-200*	every fifth
>200*	every seventh

* **Source:** Meinzen-Dick *et al* (1994)

2.4.6 Use of Computer Models in Planning

2.4.6.1 Crop growth models

Crop growth and water use can be modeled at different complexity levels (Littleboy *et al*, 1989). The range of crop models vary from a simple evapotranspiration to pan evaporation ratio (ET_{pan}) driven water use model to a fully dynamic crop growth and yield prediction model.

Crop growth and yield predictions are estimated using dynamic crop growth models. Such models generally describe the development, growth and yield of a crop grown on a homogeneous area of soil exposed to certain weather conditions. They predict crop phenology, leaf area and dry matter using functions of transpiration, transpiration efficiency, potential evapotranspiration, daily temperature and photoperiod. Crop growth is often reduced due to water or nitrogen stress.

For over twenty years scientists and engineers have been developing process-oriented simulation models of various crops. Many models have been published for most of the world's major food crops. These include the Apsim model, which can be used to assess crop response to pre-sowing water and nitrogen stress, drought and frost risk prediction in wheat production, among other things. Complex dynamic crop models include the CERES family of models (Littleboy *et al*, 1989). The DSSAT model is one such model and has been developed from versions one to three over the past few years (Tsuji *et al*, 1994).

The Decision Support System for Agrotechnology Transfer (DSSAT) software and reference documents are products of the International Benchmark Sites Network for Agrotechnology Transfer (IBSAT) Project (Tsuji *et al*. 1994).. The DSSAT v 3 is a collection of computer programs integrated into a single software package in order to facilitate the application of crop simulation models in research and decision making. Although the overall goal of this system is similar to its predecessor, DSSAT v 2.1 (IBSAT, 1989), the DSSAT v 3 databases, models, application programs and their linkages have undergone major revisions.

Sustainable agriculture requires tools that enable decision-makers to explore the future. It is important that a decision support system must help users make choices today that result in desired outcomes, not only next year, but also 10, 25 and 50 years or more into the future. But what confidences can one place in such predictions? A decision support system, which purpose to predict the future, should be able to do the same for events in the past. Predicting outcomes of historical events enables users to validate the system management operations.

In agriculture, production outcomes are determined by weather, soil conditions, genetic make up of the crop, pests and diseases and crop management. Predicting genotype by environment and management interactions clearly requires an interdisciplinary approach (Tsuji *et al*, 1994).

The employment of computer models to plan for irrigation should be done carefully. The selected model should undergo several steps of testing before establishing its authenticity in predicting sought parameters. The objectives of crop modelers have varied from understanding mechanisms of plant growth processes to assisting in management and decision making. Most models are deterministic, operate on daily time steps and require similar input data for soil, weather and management.

Crop models that predict crop performance in differing environments are appealing to users from diverse disciplines. In crop production planning a major objective is the increase of production efficiency.

In order to achieve this, decision-makers from state legislators to individual agriculturists have to consider the following questions (Schulze, 1985):

1. Which crops grow optimally at a given location?
2. What yield of a given crop might be expected, on average, at a given location?
3. Are the average yields of this crop above the break-even level of profitability?
4. What is the variability of crop yield from year to year?
5. What is the probability of crop failure in the short and long terms?
6. What factors are causing yield reduction?
7. To what extent would irrigation assure yields close to the environmental optimum?
8. Would alternative crops be less prone to drought-induced failure under dryland conditions?

After establishing the answers to these questions the individual farmer may go on and plan confidently for effective cultivation of a crop, be it in terms either of maximum yield or maximum profit per unit of land area. Only the climate remains "uncontrollable" and the answers to many of the questions posed above effectively lead to the determination of the question of climatic suitability for specific crops. Although the ultimate goal of applying crop yield models varies with users, the models are important tools in the determination of optimum planting dates, risk analyses of yield, irrigation water requirements and overall crop production planning, also in regard to food security.

2.4.6.2 Model validation

Most models require adjustments to the process control parameters in order to "tune" them to reproduce the response of the system under study, and the procedure of adjusting parameters is called calibration (Fleming, 1979). Calibration of the model is one of the most important steps in model application since the accuracy of the whole process will depend on the level of calibration achieved. The process of model calibration depends on both input and output information in order to adjust the parameter values controlling the model to levels where the response matches the prototype (Fleming, 1979). Comparison between model output and prototype measured output must take data errors into account before calibration can be achieved to the required level of accuracy. Viessman (Jr.) *et al* (1989) reports that there is no rule that specifies when adequate matching is achieved. He goes on to report that this determination must be made by the modeler based on his or her understanding of the problem and the use to which the model's results are to be put. Calibration procedures vary from model to model. However there exist general alternatives which apply to all models, namely:

1. Trial and error calibration
2. Automatic calibration
3. Combination of the two above.

In the trial and error calibration, the user inputs all the parameters that can be based on physical observations and provides estimates of the unknown. Thus, in this method the model is run and the output compared to observed output from the observed prototype. Adjustments are henceforth made to one or more of the trial parameters to improve the fit between observed and simulated output. The comparison may be by means of visual pattern recognition of the simulated and observed output or it may be based on some mathematical criterion of "goodness of fit". Repeated trial runs of the model are made until the required accuracy is achieved.

In automatic calibration, the model is designed in such a way that it contains internal programming that adjusts the trial parameters in a step by step manner until the predefined goodness of fit criterion is satisfied. By so doing the model automatically calibrates itself and carry out the necessary number of trial runs until the best set of parameters is achieved.

The third method involves the trial and error manual adjustments of parameters until the model is almost calibrated, then automatic search is introduced to refine the goodness of fit.

Once calibration is completed and it is determined that the model can be expected to yield dependable results, the model can be directed towards analyzing many different types of management and development options so that the outcomes of different courses of action that might be followed in the future can be assessed (Viessman Jr. *et al* 1989).

2.4.6.3 Verifying Simulation Accuracy

Results from model simulations are used by decision-makers to plan the future use of land and water resources. Thus, it is important at some point either before or during the use of models to ask questions on the validity of a particular model to the problem being studied and the predictions being made (Fleming, 1979). It is of paramount importance for the model developer, model user and the decision-maker to take a collective responsibility in ensuring that model validity is tested. Normally it is not possible to completely validate a predictive "decision-aiding" model, as the events being predicted are not represented by real data. However with a prolonged period of use, a model can be "well proven" in assessing future events and hence be validated to the point where the decision-maker has confidence in the results obtained from the model. Emsshoff and Sisson (1970), quoted in Fleming (1979) gave the sequence of testing model validity. The analyst assures himself that the model performs the way he intends it to, using test data, and this is referred to as debugging. Reasonableness is checked by:

1. showing that key subsystem models predict their part of the world well (through use of historical data)
2. showing, where parameter identification is required , that parameters can be fit (that the search terminates with a close match to historical data)
3. That the parameters have reasonable values.

The decision-maker has an opportunity to explore the use of the model to become familiar with its predictions and to examine the interactions it implies. At this point the analyst and decision-maker may be able to agree as to what is a close enough fit between simulator output and actual data.

The model is used for decision aiding. Careful records are kept of its predictions and of actual results (this may involve a time span of years, so that the evaluation procedure has to be set up carefully).

If validation is not satisfactory, then recalibration of the model must be carried out. After the primary validation is checked, the model can be used for predictive purposes. With time, use of the model will highlight areas where model validity is suspect and will result in changes to the model structure, or the data requirements of the model to improve the validity of future predictions.

2.4.6.4 Sensitivity analysis

Sensitivity analysis entails the study of the sensitivity of model outputs to changes in input data parameters (Littleboy *et al*, 1989). This information is required when obtaining parameter values by calibration, estimation or measurement.

It is important that great care must be taken in selecting parameter values if a small change in the parameter produces a large change in model output. On the other hand, if the model output is not sensitive to an input parameter then the estimation of that parameter may not be critical (Littleboy *et al*, 1989). It is also reported that it is important to note that a parameter may cause changes in only one section of model output, for example, slope and slope length will only affect soil erosion predictions. Thus, degree of care taken in selecting parameters will depend on both the output of interest as well as the sensitivity of a parameter. There are three categories under which parameter sensitivity has been subjectively grouped. These are low, medium and high. Low sensitivity implies that the model output will not change significantly with changes to the input parameter and high sensitivity refers to large changes in model output with changes to the parameter.

2.5 NATURE AND IMPORTANCE OF THE TEST CROP,

Maize (also referred to as corn) is widely used as a food crop in the tropics and subtropics. Maize originates in the Andean region of Central America and is one of the most important cereals both for human and animal consumption (FAO, 1986). Maize is a food crop that is rich in starch or carbohydrates, averaging about 71% on a worldwide basis, but comparatively low in protein (9.5 %) (Litzenberger, 1974). Thus, being largely starch, maize grain is an energy food and should be supplemented with protein foods, such as animal products and grain legumes or oilseed meals, and with other foodstuffs to supply vitamins and minerals to produce a balanced human diet.

Maize thrives in warm sunny climates where moisture supply is adequate during the growing season. Maize is an efficient user of water in terms of dry matter production (FAO, 1986), and among cereals it is potentially the highest yielding grain crop. A medium maturity grain crop requires between 500 and 800 mm of water (depending on the climate) for maximum production. The crop factor (Kc) relating water requirements (ETm) to reference evapotranspiration (ETo) for different crop growth stages of grain maize is for the initial stage 0.3-0.5 (15 to 30 days), the development stage 0.7-0.85 (30 to 45 days), the mid-season stage 1.05-1.2 (30 to 45 days), during the late season stage 0.8-0.9 (10 to 30 days), and at harvest 0.55-0.6 (FAO, 1986). In most cases, the occurrence of dry periods during the growing season may adversely affect crop yield if soil moisture supplies are exhausted before rains recur.

The fertility demands for grain maize are relatively high and amount, for high producing varieties, up to 200 kg/ha N (FAO, 1986). The actual N required depends on the yield potential. In the dryland Laikipia district (Matanya) farmers are normally advised to apply nitrogen fertilizer at around 40 to 60 kg/ha (under rainfed conditions). Thus, the lower the yield potential the lower the N to be applied. Maize yield potential is also dependent on the cultivar and different maize cultivars have been developed over the years and it is important to ensure that the correct cultivars are used in a given ecological environment.

The following are some of the parameters used to define a maize cultivar:
Length of growing season and water requirements
Genetic coefficients which include:

1. P1 - Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of $8^{\circ}C$) during which the plant is not responsive to changes in photoperiod
2. P2 - Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (considered to be 12.5 hrs)
3. Ps - Thermal time from silking to physiological maturity (expressed in degree days above a base temp of $8^{0}c$)

4. G2 - Maximum possible number of kernels per plant
5. G3 - Kernel filling rate during the linear grain filling optimum conditions (mg/day)
6. G3 - Kernel filling rate during the linear grain filling optimum conditions (mg/day)
7. PHINT - Phylochron intervals, the interval in thermal time (degree days) between successive leaf tip appearances (Tsuji *et al*, 1984).

3.0 MATERIALS AND METHODS

3.1 INTRODUCTION

The methodology was divided into two major parts namely: (1) Problem analysis and (2) Model validation and application. Assessment of the causes of low crop yields was done at Nyanyadzi irrigation scheme using a questionnaire survey during the 1996 summer season, and the DSSAT V3 model was used to answer 'what if' questions for maize water –nitrogen scenario studies at Matanya irrigation scheme.

3.2 DESCRIPTION OF THE STUDY AREAS

3.2.1 Nyanyadzi irrigation scheme

3.2.1 .1 General

Nyanyadzi irrigation scheme lies at the 100 kilometer peg along the Mutare-Birchnough road, south of Mutare in the Manicaland Province of Zimbabwe (Fig. 2). The surrounding countryside is semi-arid and produces rainfed crops (Chancellor and Hide, 1996).

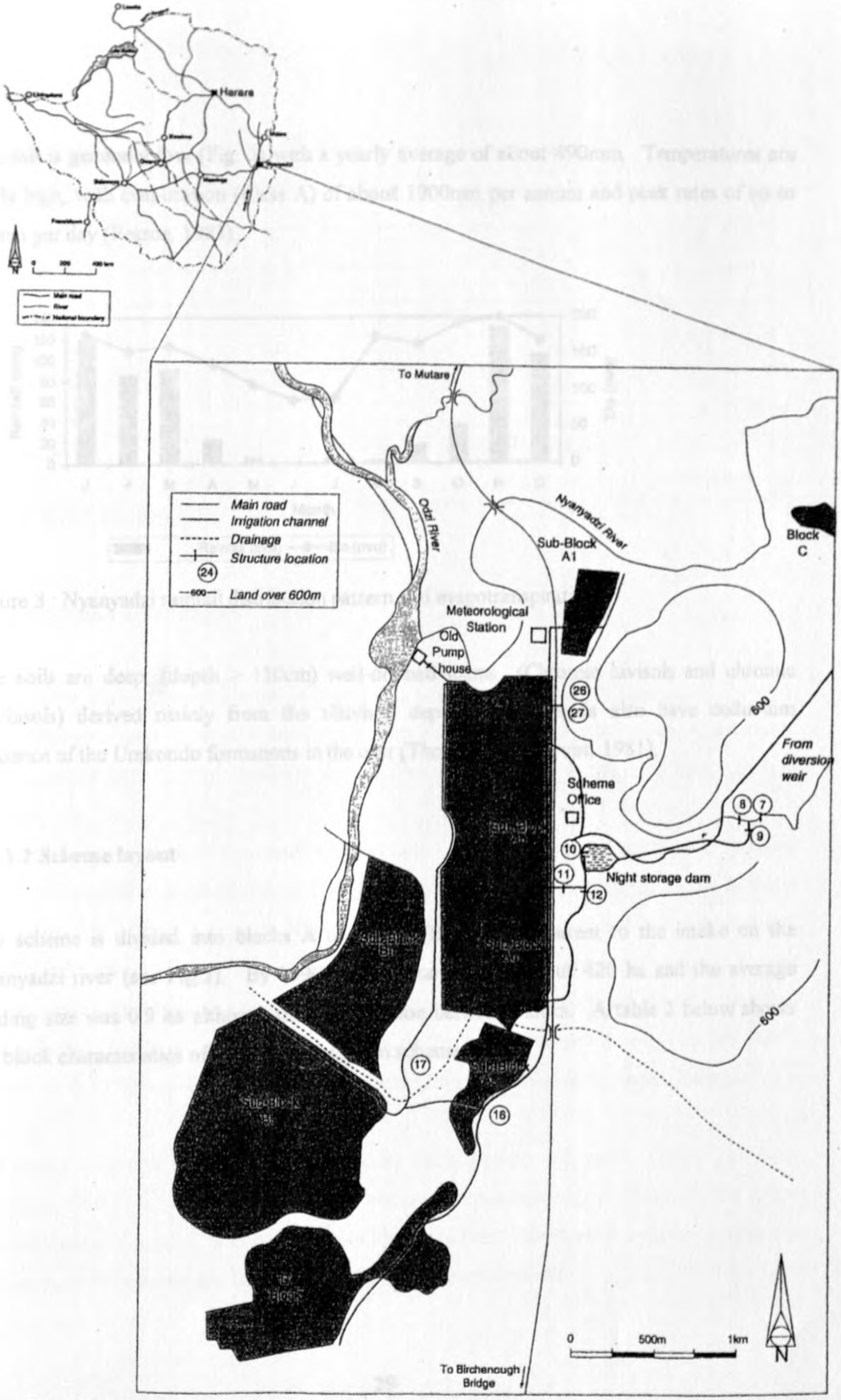


Fig. 2 Location map of Nyanyadzi and scheme layout

Rainfall is generally low (Fig. 3) with a yearly average of about 490mm. Temperatures are fairly high, with evaporation (Class A) of about 1900mm per annum and peak rates of up to 11mm per day (Pearce, 1983).

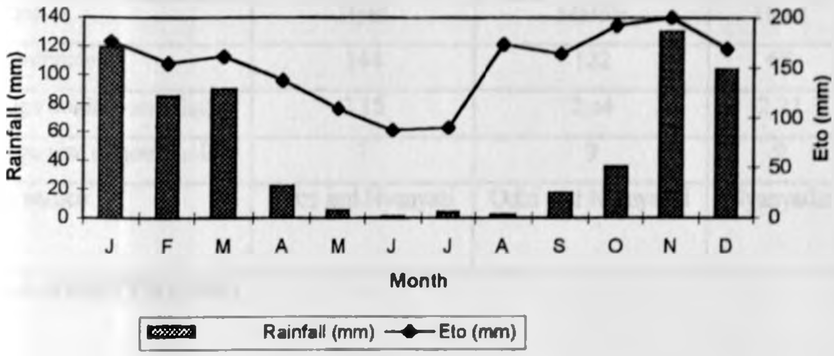


Figure 3 : Nyanyadzi rainfall distribution pattern and evapotranspiration

The soils are deep; (depth > 150cm) well-drained loams (Chromic luvisols and chromic cambisols) derived mainly from the alluvium deposits. The soils also have colluvium influence of the Umkondo formations in the east (Thomson and Purves, 1981).

3.2.1.2 Scheme layout

The scheme is divided into blocks A up to D. Block C is nearest to the intake on the Nyanyadzi river (see Fig.2). By 1990, the scheme covered about 420 ha and the average holding size was 0.9 ha although there is variation between blocks. A table 2 below shows the block characteristics of Nyanyadzi irrigation scheme.

Table 2 : Block characteristics of Nyanyadzi irrigation scheme

Parameter	Block			
	A	B	C	D
Area (ha)	136.44	143.57	65.02	69
Location	Head	Middle	Head	Tail
No. Plotholders	144	122	68	75
Average holding size (ha)	2.15	2.04	2.21	2.10
Average size of household	7	9	9	8
Water source	Odzi and Nyanyazi	Odzi and Nyanyadzi	Nyanyadzi	Odzi and Nyanyadzi

Source: AGRITEX (1996)

3.2.1.3 Scheme water supply

The scheme lies at the confluence of Nyanyadzi and Odzi rivers in the Manicaland Province of Zimbabwe. Gravity flow is used to convey water from Nyanyadzi river. A battery of pumps, which have proved unreliable due to frequent breakdowns, supports this. A night storage dam was built so that the continuos flow from the canal could be stored for use the following day. Although the distribution system is partly lined, the main canal bringing water to the night storage dam from Nyanyadzi river is not, and is a major source of water loss within the scheme. Water is delivered on a rotational basis between and within blocks. Control of flow has been hampered seriously by lack of management information for the system. Inequity of water supply between blocks is so pronounced and dramatic in a bad year affecting income of farmers in the tail end to the extend of getting as low as less than a quarter of that obtained elsewhere. Blocks A and C are least affected by water shortages.

Nyanyadzi irrigation scheme is characterized by a number of water related problems (Bolding, 1995). It has been reported that the main and everlasting problem of the scheme has been water shortage. The water supply has never been able to cope with the continuous expansion of the scheme and the resulting increase in water demand.

3.2.1.4 Cropping systems

Crops commonly grown in summer include maize, cotton, summer vegetables and groundnuts, whilst in winter, beans, wheat, tomatoes and vegetables are grown. Cropping pattern varies from block to block, to make the best of the water supply. Until recently, tomatoes were mainly grown on block C as the water supply was relatively good. Input supply and marketing are normally channeled through contractors and the scheme co-operative which unfortunately has a limited function.

3.2.1 Matanya irrigation scheme

3.2.2.1 General

The research site is located in Matanya sub-location, Tigithi location, Lamuria Division in Laikipia District of Kenya (Fig.4). Matanya area lies in Upper-Lower Midland zone which is characteristic of livestock and agricultural food production. The research site is situated in middle of a moderately sloping stretch of land covering the area running from Matanya Shopping Centre to the drainage valley on the lower side.

Matanya irrigation scheme has got a bimodal rainfall pattern (Fig.5) divided into short rains (Oct-Dec) and long rains (March-July).

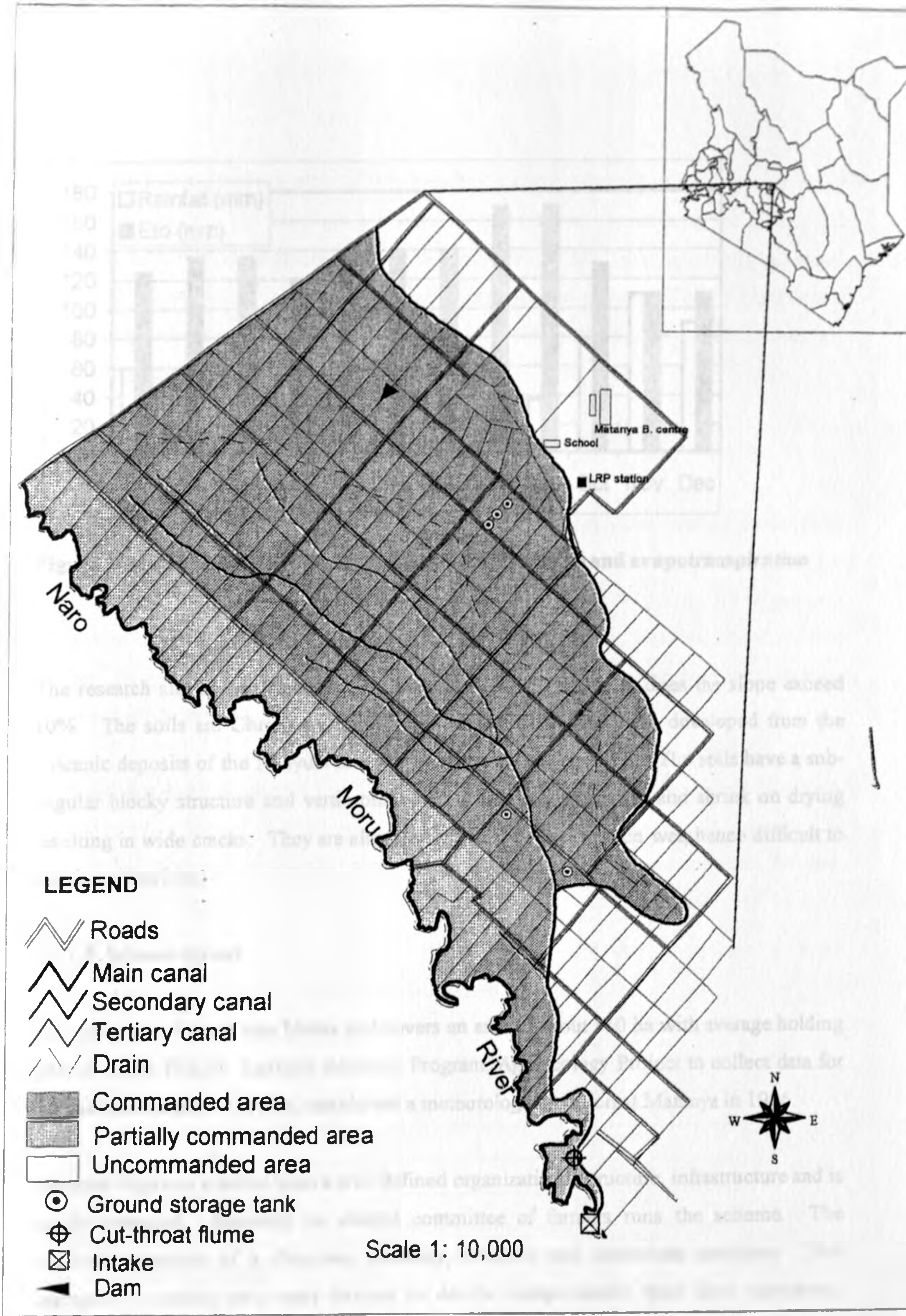


Figure 4: Location map of Matanya and scheme layout, Kenya

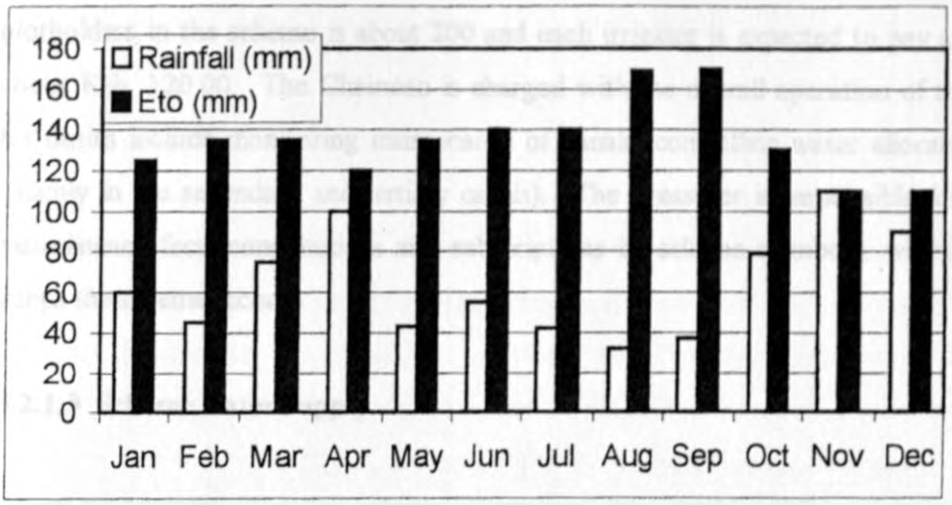


Figure 5: Matanya rainfall distribution pattern (1986-1995) and evapotranspiration

The research site has moderately low slopes of 2-5%. Very rarely does the slope exceed 10%. The soils are Chromic vertisol/Typic chromusterns and were developed from the volcanic deposits of the Nanyuki formation (Ann and Geiger, 1987). The soils have a sub-angular blocky structure and vertic properties, they swell when wet and shrink on drying resulting in wide cracks. They are also plastic and very sticky when wet, hence difficult to traffic and work on.

3.2.1.2 Scheme layout

The scheme is divided into blocks and covers an area of about 310 ha with average holding size of 1.2 ha (Fig.6). Laikipia Research Program, Agroecology Project to collect data for the various research activities, established a meteorological station at Matanya in 1986.

Matanya irrigation scheme lacks a well-defined organizational structure, infrastructure and is poorly managed. Basically an elected committee of farmers runs the scheme. The committee consists of a chairman, secretary, treasurer and committee members. This segregated structure empowers farmers to decide independently their farm operations, including such aspects as cropping patterns and cropping calendar. The total number of plotholders in the scheme is about 200 and each irrigator is expected to pay a joining fee of about Ksh. 120.00. The Chairman is charged with the overall operation of the scheme and his duties include monitoring maintenance of canals, controlling water allocation to farmers (mainly in the secondary and tertiary canals). The Treasurer is responsible for collection of maintenance fees, contributions and subscriptions by scheme members, whilst the secretary keeps the scheme records.

3.2.1.3 Scheme water supply

Water for Matanya irrigation scheme is conveyed from the Naro Moru river by gravity flow, using a perennial canal. Distribution canals from the main canal are not lined and seepage losses are high. There are no storage facilities on the scheme and the priority for irrigation is rather low. The scheme lacks a well-defined infrastructure for water distribution and rotation system. In most cases, there is over-abstraction of water at the intake with low irrigation water use efficiency.

3.2.1.4 Cropping calendar

Table 3: below shows the irrigated crop in the scheme, and average planting dates for each crop.

Table 3: Cropping calendar at Matanya irrigation scheme

Crop	Growing season	
	Summer	**Winter**
Maize	Oct to Nov	March to July
Beans	Oct to Jan	April to July
Cabbage	Oct to Jan	April to July
Potatoes	Oct to Feb	March to July
Tomatoes	Oct to Feb	April to Aug

Source: NRM[3] database (1996).

3.3 NYANYADZI STUDY

The Nyanyadzi study was conducted from early November 1996 to early February 1997. Prior to the commencement of research, a reconnaissance trip was undertaken in October to establish the facts on the ground, get a general feel of the field conditions, arrange for field technicians and to get clearance from the AGRITEX officials in Manicaland. The rain season in 1996 started rather late and there were critical water shortages throughout the scheme since the water levels in Nyanyadzi and Odzi rivers were very low. This situation delayed data collection as not much activity was taking place in the scheme since farmers were engaging themselves in off-farm activities elsewhere. Surprisingly when the rains finally came (around early December), they were so heavy and much higher than the normal trends. At some periods it would rain for more than two weeks continuously, making it difficult for farmers to carry out such operations as weeding and fertilizer application.

3.3.1 Data Collection

3.3.1.1 Background information

Background information on the following aspects was obtained through informal interviews and discussions held with Mr. Marwa (AGRITEX staff):

- Recommended maize seed rates
- Recommended fertilizer rates, both Ammonium and Compound D (for maize crop)
- Recommended manure levels
- Water rotation system
- Recommended maize planting dates

3.3.1.2 Questionnaire survey

The following information was sought from farmers in order to determine the causes of low crop yields in the scheme

- Level of education of plotholders
- Availability of labour (hired or family)
- Crops grown and average acreage
- Type of seeds used
- Planting dates
- Fertilizer inputs
- Average crop yields
- Water supply situation, including the rotations
- Tillage implements used
- Degree of pesticide and insecticide use
- Use of early maturing varieties
- Timeliness of operations (among other things).

Some field observations were also made during the study period as a follow-up to some of the issues raised by the farmers. The questionnaire details are given in Appendix 2.

Guidelines used to get the farmer sample size are summarized in section 2. The sample size used in this study is summarized in table 4.

Table 4: Sample farmer selection

Block	No. of farmers interviewed
A	30
B	25
C	20
D	20

The procedure was readily acceptable by farmers and the scheme staff. A register containing the official plotholders numbered sequentially according to their positions within blocks and the corresponding plotholder names attached to the plots was used. Randomization was done by selecting every fourth farmer in the tenants register in each block to ensure that the sample was representative of the population under study and hence draw meaningful conclusions from the results, since the error component would be low (Torrie and Steel, 1980). The names of the prospective respondents were then forwarded to the Irrigation Workers Committee, which then assisted in making available farmers for interviews (see Appendix 3). Mr. Marwa suggested that it was easier to interview farmers from their plots rather than from their homes since it was difficult to trace them by virtue of the settlement pattern. Interviewing farmers from their plots also had the advantage that one could make some field observations as a follow up to some of the farmer responses. The survey results were used to assess the farmer practices, the extent to which farmers are aware of water saving strategies and also their willingness to adopt new technologies.

Conclusions drawn from the study at Nyanyadzi formed the basis upon which scenario studies were made. The information was also part of the basis upon which recommendations on copying with water and fertility constraints were made to irrigation planners, policy makers and managers of small-scale irrigation schemes.

3.4 MODELING STUDY

3.4.1 Introduction

The study involved the use of the computer simulation model (DSSAT V_3) to assess maize yield response to water and nitrogen, using Matanya scheme for simulation input data. Based on the findings at Nyanyadzi, it was found necessary to assess the yield response of maize to nitrogen and water, and hence determine how yield changes with change in fertilizer application with a view to establishing the optimal yield levels at which farmers can operate without incurring high water and nitrogen input costs. Although nutrient nitrogen plays an important role in improving maize yields, most of the farmers in small-scale irrigation schemes do not afford the high costs involved with application of recommended rates.

Although nearly all farmers, agriculturists and irrigation planners appreciate the importance of water in crop production, not much has been done to establish the yield response to water of agricultural crops. Without such knowledge a lot of water shall continue to be used inefficiently and this is not a healthy situation especially in such schemes were irrigation water shortage is increasingly becoming a big problem.

Thus, use of computer modeling in assessing yield response to water and nitrogen forms a powerful tool for decision making and planning. Different water levels were used in the scenario studies to accommodate the possible water supply situations existing within the scheme and elsewhere.

Maize was used as the test crop for simulation studies since most of the farmers at Nyanyadzi irrigation scheme are giving high priority to its production. The crop plays an important role in their lives for food security and there already exist some data on maize yield response to water at Matanya irrigation scheme.

Five water levels and three nitrogen levels were used in the model to form a 5*3 factorial experiment with 15 treatment levels. The five water level treatments were:

- W_1- 0% irrigation water. This represents rainfed agriculture
- W_2-33% irrigation (This implies 33% of the maize crop water requirements, plus rainfall received during the growing period). This represents a low level of application adopted by farmers with limited water and willing to spread it thinly to maximize their irrigated acreage.
- W_3-66% irrigation water.
- W_4-100% irrigation water. This represents the situation when full irrigation is being achieved.

- W_5- 133% irrigation. This represents farmers or sections where over-irrigation takes place. This could be a section of a farm for head enders who believe that the more water one applies, the better the yield.

The 3 nitrogen levels used where:

- N_1-0kgN/ha. This represents those farmers who do not use fertilizers
- N_2-50kgN/ha. This represents those farmers applying the recommended rates
- N_3-100kgN/ha. Since conditions are under irrigation, it was argued (for the purposes of this study) that higher levels of N were justified for higher levels of production.

Thus the 15 treatment combinations were therefore (1) W_1N_1 (2) W_2N_1 (3) W_3N_1 (4) W_4N_1 (5)W_5N_1 (6)W_1N_2 (7) W_2N_2 (8) W_3N_2 (9) W_4N_2 (10) W_5N_2 (11) W_1N_3 (12) W_2N_3 (13) W_3N_3 (14) W_4N_3 (15) W_5N_3

3.4.2 Model selection and validation

The DSSAT V_3 model was selected for this study because of the following reasons:

- It is user friendly as it contains (a) a Data Base Management System (DBMS) to enter, store and retrieve the "minimum data set" needed to validate, list and use the crop models for solving problems (b) a set of validated crop models for simulating processes and outcomes of genotype by environment interactions and (c) an applications program for analyzing and displaying outcomes of long-term simulated agronomic experiments. Thus, the resulting system is much more flexible and has functionality for data base manipulation and model applications.
- The decision support system is designed to answer "what if" questions frequently asked by policy makers and farmers concerned with sustaining an economically sound and environmentally safe agriculture.
- DSSAT enables its users to match the biological requirements of crops to the physical characteristics of land so that objectives specified by the user can be obtained.

The model was validated using observed field results on maize yield response to water (Ragwa, 1995). The weather input data (daily rainfall, daily maximum and minimum temperature, and daily solar radiation for Matanya 1995 was used (see Appendix 10). The same soil profile analytical input data as for the scenario studies was used for model validation. The irrigation treatments used are summarized in table 5

The treatments represent the percentage of the crop water requirements that were added to the crop (including any rainfall received during the growing period). A Julian date is a date in which only the year and day of the year are depicted. For example, the first two numbers indicate the year (in this case, 95 for 1995) and the last three numbers, day of the year up to 365 total annual days. Thus Julian date 95002 is actually 2nd of January 1995.

The crop was planted in early January and harvested beginning of May. This growing season was the one used for scenario studies also. Irrigation was applied taking into consideration the critical growth stages of maize

Table 5: Model validation irrigation applications

Application date (JD)	Applied irrigation water (mm)		
	33% IR	**66% IR**	**100% IR**
95002	3.3	6.6	10
95006	2.3	4.6	6.9
95010	1.8	3.7	5.6
95014	1.6	3.2	4.9
95018	1.9	3.7	5.6
95022	2.0	4.0	6.1
95026	1.2	2.3	3.5
95030	2.3	4.6	7.0
95034	2.1	4.2	6.4
95038	5.1	10.2	15.5
95054	3.2	6.4	9.7

Source: Ragwa (1995) Unpublished.

3.4.3 Model data and simulation runs

3.4.3.1 Baseline data

The soil and climatic data needed to run the model was obtained from Matanya irrigation scheme (NRM[3]). The soil parameters entered into the soil file are summarized in tables 6 and 7 respectively.

Table 6: Soil mechanical parameters (Matanya)

Depth (cm)	Horizon	% clay	% silt	% sand	Bulk density g/cm
0-10	A11	48	24	28	1.20
10-45	A12	58	18	24	1.20
45-90	B2	62	14	24	1.28
90-140	B3	52	20	28	1.28

Source: NRM[3] database (1996).

Table 7: Soil fertility status

Depth (cm)	% C	% N	pH (water)	CEC meq/100gm)
0-10	0.79	0.23	6.90	36.40
10-45	0.69	0.18	7.20	48.00
45-90	0.64	0.11	7.50	43.20
90-140	0.31	0.08	7.60	51.20

Source: NRM[3] database (1996).

The weather-input parameters needed to run the model are daily rainfall data, daily minimum and maximum temperature and solar radiation data. These are summarizes in table 8.

This is the weather data required to run the model. The –99 value indicates that the value(s) in question was/were not available and the model can run by substituting with –99, otherwise it computes automatically.

Table 8: Monthly means and rainfall

Month	SRAD MJ/m 2	T Max ^o_c	T Min ^o_c	Total rain (mm)	No. of wet days	Min sunH	Angstrom (Y-int)	Coeff B Slope
1	22.4	26.0	8.4	25.1	6.0	-99.0	0.25	0.50
2	23.9	28.3	8.0	11.4	5.0	-99.0	0.25	0.50
3	23.4	28.8	9.3	30.6	11.0	-99.0	0.25	0.50
4	22.4	26.6	10.6	95.3	20.0	-99.0	0.25	0.50
5	22.0	23.6	13.7	53.8	10.0	-99.0	0.25	0.50
6	20.4	23.4	11.8	133.1	11.0	-99.0	0.25	0.50
7	20.3	24.4	10.4	24.3	1.0	-99.0	0.25	0.50
8	22.4	24.2	11.5	10.8	4.0	-99.	0.25	0.50
9	23.0	27.1	11.0	18.1	10.0	-99.0	0.25	0.50
10	22.6	27.0	12.3	53.0	11.0	-99.0	0.25	0.50
11	22.6	24.4	12.9	215.3	18.0	-99.0	0.25	0.50
12	22.6	24.9	8.9	90.5	7.0	-99.0	0.25	0.50

Source: NRM[3] database (1996).

3.4.3.2 Treatment data

The model requires treatment data on:

- Maize cultivar used
- Initial field conditions
- Planting details
- Irrigation and water management
- Fertilizers used
- Residues and organic materials
- Chemical applications
- Tillage and rotations

(See Appendix 1 and 6 for details)

The treatment details used in the simulation runs are given in Appendix 7. Irrigation scheduling was based on FAO (1986) recommendations which state that where rainfall is low and irrigation water supply is restricted, irrigation scheduling should be based on avoiding water deficits during the flowering period, followed by yield formation period.

Crop water requirements were calculated using the Pan method. The monthly crop water requirements were computed by relating the corresponding K_C value with the ET_O value (Appendix 5). Application losses were assumed to be zero, hence depth of irrigation for each treatment was equal to the crop water requirement. The average plot size was taken to be a hectare such that the total volume of water applied would be the total irrigated area multiplied by depth of irrigation.

Nitrogen levels of 0, 50 and 100kg N/ were split applied according to the crop nitrogen sensitive stages of growth and applied on the reported Julian dates (see Appendix 7).

3.4.3.3 Long –term simulation data

Long-term simulations were made for a period of ten years (1986 to 1995). This was done to assess the behaviour of the model and also changes in yield with change in climate. Daily rainfall, solar radiation, maximum and minimum temperature data for each year was obtained from the NRM[3] database (see Appendix 10). The same soil input file used for the scenario studies was used in the long-term simulation. All other treatments were maintained at the same level, so that change in yield from one year to the next could only be a result of changes in climatic conditions.

4.0 RESULTS AND DISCUSSION

4.1 PROBLEM ANALYSIS

A problem analysis of the causes of sub-optimal yields was carried out for Nyanyadzi irrigation scheme.

4.1.1 Crop Management

The recommended crop management practices are given in table 9. Farmers are encouraged to adhere to these recommendations in order to realize meaningful yields, unfortunately most of them cannot afford to, due to high inputs cost.

Table 9: Some recommended input rates and expected yields at Nyanyadzi

Crop type	Inputs			Expected Yield (t/ha)
	Fertilizer (kg/ha)		Seed rate (kg/ha)	
	Type	Amount		
Maize	Compound D NH_4NO_3	300 100	25	4-5
Cotton	Compound L NH_4NO_3	300 100	25	1.5
Winter Beans	Compound D NH_4NO_3	300 100	100	1.5

Source: Manzungu, 1995.

4.1.1.1 Crop type and variety

At Nyanyadzi irrigation scheme, there was no data on the most suitable crop type and variety farmers could grow. The recommended crops for the summer season are maize, cotton and groundnuts. The main winter crops are wheat, beans and tomatoes. Whilst cotton does not require a lot of water, more and more emphasis is put on maize during this season. As a result of the limited land (average plot size of 0.5 ha), farmers give preference to maize production since maize is the staple food crop in Zimbabwe. Thus, growth of cotton is highly marginalised and this often creates critical water shortages, as maize requires more irrigation water.

Farmers argued that if they had enough land, they could be allocating land to different crops for each season. During winter, most of the farmers prefer growing maize for sale as green cobs and during this season water supply is normally very critical as flows would be very low in the Odzi and Nyanyadzi rivers. This often results in low crop yields, as water supply cannot copy with the demand.

Most of the farmers do not have much choice on the type of maize seed they grow as they receive seed handouts. Since the general belief by policy makers is that water is not limiting in irrigation schemes, they advocate for high yielding cultivars without an up to date understanding of the water supply situation in the scheme.

There was use of high yielding, water demanding varieties even in parts of the scheme with low water availability. Farmers in block D and B, where water problems are most prevalent, continued to grow high yielding maize varieties which apparently require a lot of water. Only 23.9 and 36% of the farmers (table 10) in these blocks respectively, were growing the maize seed variety R201 which is early maturing and hence requires less water. In all the blocks, growth of other drought resistant crops was very low. Less than 10% of the plotholders in all the blocks were growing drought resistant crops like sorghum and millet. It is important for farmers to note that selection of high yielding varieties often creates a high demand on the available irrigation water supplies, requires high levels of inputs and takes a relatively long time to mature.

Table 10: Farmer survey results: Nyanyadzi

Parameter	Block			
Crop Inputs	**A**	**B**	**C**	**D**
% of farmers using recommended seed rates (maize)	90	88	85	90
% of farmers applying ammonium nitrate (NH_4NO_3)	83.3	28.0	20.0	trace
% of farmers using recommended NH_4NO_3	50	20	25	0
% of farmers using compound D fertilizer	70	44	35	trace
% of farmers using recommended compound D	0	0	0	0
% of farmers not using fertilizer at all	6.7	24	20	45
% of farmers applying pesticides	63.3	28	25	15
Input averages: Over 5 years				
Seeding rate (kg/ha	23.05	24.30	24.40	24.90
NH_4NO_3 kg/ha	70.50	20.43	63.80	trace
Compound D (kg/ha	125.60	90.61	77.20	78.31
Manure (t/ha)	12.1	11.4	11.9	10.7
Maize yield (5 year average) t/ha	2.50	1.68	1.95	0.86
Water saving strategies				
% of farmers using early maturing varieties	33.0	24.0	23.3	36.0
% of farmers using late maturing varieties	63.3	76	45	64
% of farmers practicing weed control	100	100	100	100
% of farmers growing other drought resistant crops	6.7	8.0	8.0	8.0
% of farmers reducing the size of irrigated area	0	0	0	0
% of farmers changing cropping calendar to supplement irrigation with rainfall	43.3	24.0	75.0	80.0

4.1.1.2 Crop rotation and calendar

The recommended cropping patterns and cropping calendar are shown in table 11 below. The crop rotation system at Nyanyadzi is maize, cotton (during summer) followed by winter beans, wheat and tomatoes. Farmers reported that shortage of land was offsetting their efforts in adhering to the recommended rotation system with the result that there was mono cropping of maize in most of the seasons.

Table 11: Recommended cropping calendar and cropping patterns at Nyanyadzi

Crop	Season	
	Summer	Winter
Maize	Nov to March	
Cotton	Oct to March	
Tomatoes		Feb to June
Beans		April to July
Wheat		March to Oct
Groundnuts	Oct to Feb	

On the other hand, if adopted quite well, crop rotation can improve soil aggregation and organic matter content, avoids nutrient mining and results in more efficient use of irrigation water as there would be a match between crop type and the available irrigation water.

Farmers were planting on wrong periods of the year leading to poor crop growth and low yields. For example, farmers are not encouraged to grow crops during the period (August-Sept) as irrigation water would be most critical and incidences of pests would be high. Surprisingly most of the farmers were not adhering to this. Consequently they have adopted a cropping calendar which is not in synchrony with the water supply situation and some of the water shortages experienced during the growing season(s) are purely a result of poor planning. The cropping calendar followed by farmers in the irrigation scheme determines (i) how much rainwater they can use to supplement their irrigation water supplies (ii) whether the growing season is favourable to other climatic conditions (iii) the degree of pest and disease control required.

4.1.1.3 Pests and diseases

Control of pests and diseases was not being coordinated as per block (as recommended by AGRITEX). It was observed that whereas one farmer could spray his crop for a certain pest, the neighbouring plotholder(s) would not. The absence of an integrated pest management practice at the scheme thus resulted in marked yield reduction. The presence of different crops in a block was making it difficult to make effective pest and disease control. Spraying could not be done easily on a block basis, as there was no sole cropping which would otherwise make spraying easy. Sole cropping enhances the chances of synchronized spraying which prevents the possibility of re-infection of crops from the other crops that may not have been sprayed. Thus, pests and disease vectors could easily hide away in the crops that had not been sprayed.

It was difficult for all farmers to act responsibly and spray at the right time due to the high degree of autonomy enjoyed by the farmers in the scheme. For example, planting could not be done at the same time making it difficult to co-ordinate spraying activities since different types of pests and diseases attack crops at different stages of growth. The highest number of farmers using pesticides was reported in block A with63.3%. Blocks B, C and D reported 28, 25 and 15% respectively. Farmers not using pesticides sited the following reasons:

- disillusionment with the water supply situation
- financial constraints

Nearly all the farmers interviewed were not aware that some crops are more susceptible to some pests and diseases than others. This is useful information to farmers as growth of crops more suitable and resistant to pests and diseases found in a given area reduces the incidence of pest attack, results in less money being used on crop protection, thus ensuring better yields and higher profit margins. Some improved varieties of the irrigated crops are less susceptible to pests and disease attack and use of such crops can be increased to avoid yield losses. Most farmers at the scheme could not afford the high cost of chemicals for pest and disease control, and as a result there was marginal use of pesticides.

4.1.1.4 Plant population

Although most of the farmers in the blocks were applying the recommended 25kg/ha maize seed, it was observed that there was a lot of inter-cropping with such crops as tomatoes. Tomatoes apparently need a lot of water with the overall result that it leads to increased competition for soil moisture with the maize crop. The resulting plant population per hectare therefore becomes much higher than what the soil nutrient reserve and moisture regime can sustain. Due to data inadequacy on the optimal plant population for different levels of irrigation water availability, the situation in most acres was such that the plant population per hectare was either too high for the available irrigation water or too low. A high plant population may lead to competition for limited water supply and nutrients resulting in poor growth and low crop yields. On the other hand, a low plant population may result in low yield even if there is enough water and nutrients.

4.1.2 Water Related Causes

4.1.2.1 Mismatch between rainfall and irrigation

At Nyanyadzi scheme, in some good seasons rainfall supplies enough water during the months of November, December and February such that there is need for only supplemental irrigation. In most cases, this is not done and irrigation continues on as usual, as was observed during the study period. The result from such a practice is over-watering. This is not only wasteful of irrigation water, but could also create such problems as waterlogging, leaching of essential plant nutrients leading to reduced plant growth and eventual yield reduction.

Sometimes members of the Irrigation water management committee at the scheme tended to over-estimate the contribution of rainfall to soil moisture recharge (during the rainy season) and ended up cutting back on irrigation, with the result that an inadequate amount was available in the crop root zone, creating a water deficit on the crop. During the study period, many farmers were complaining that their maize crop was wilting as no more irrigation water was being allocated to them. Over-estimating the effective rainfall from rainfall event results in less water being applied through irrigation than the actual crop water requirements, with an eventual negative effect on crop growth and yield. There is there for need for better irrigation scheduling.

4.1.2.2 Inadequate knowledge on irrigation scheduling

In order to accurately determine irrigation water requirements in the scheme, the following assumptions were made during the scheme design:

- all farmers who share the same irrigation turn plant their crops on the same day or close to that
- water is not limited in the scheme to such an extend that crop productivity per unit area is the ideal parameter (Manzungu, 1995).

What is actually happening on the ground has rendered these assumptions inaccurate leading to serious problems in ensuring that water is available when most needed. Firstly, farmers were planting their crops at different dates and much worse, the assumption that water is not limited in the scheme was a great fallacy as now water is the most limiting resource in the scheme. In most instances water was being applied evenly throughout the growing period of any particular crop. Farmers did not know how much to apply at which particular stage or which stage tolerates water stress. This may result in yield reduction as the crop runs a risk of being subjected to water stress at the critical growth stages. Since water application in the scheme was not done according to crop type nor crop growth stage there was a tendency of applying irrigation water far much more than the crop water requirements, often by head-enders, creating artificial shortages for tail-enders. Over-irrigation does not benefit the head –enders as the excess water is not converted into useful crop product. On the contrary over-irrigation often leads to waterlogging, loss of soil nitrogen through denitrification, leaching of nutrients, poor root aeration and subsequently poor crop growth and yield (Michael, 1986).

The irrigation rotations often caused excess water in some parts of the scheme. The irrigation cycles were not fixed and did not take into account the crop water requirements leading to over-irrigation during stages of low crop water demand. There was no mechanism to monitor how much water an individual farmer uses during irrigation cycles. Thus farmers could not tell how much water they had used to produce a specific crop during the season and this often led to over-application of water by head enders and critical water shortages for the tail enders. Once a plotholder failed to get water during an irrigation cycle (which could last for up to 21 days) they had to wait till the rotational cycle was complete and this indeed was a very unhealthy situation as the crop(s) started wilting.

Since the amount of irrigation water was being applied independent of crop type and crop growth stage, the bulk of the maize crop showed severe signs of water stress during flowering and tussling stages (the growth stages which cause a high yield reduction if subjected to moisture stress). A lot of water was being wasted in sustaining the vegetative stage, which apparently can cope with some degree of water stress without much effect on yield. The farmers reported that they were willing to cooperate with the extension workers for improvement of the scheduling system. Such poor scheduling may be partly responsible for the low yields experienced in the scheme. There was no match between the irrigated area and the available irrigation water. Most farmers continued to irrigate all their acres even when the available irrigation water could not sustain them. All the farmers interviewed "laughed" at the idea of reducing the size of the irrigated area in order to cope with water shortage as they argued that the irrigated land area was already too small (average of 0.5 ha per household).

4.1.2.3 Unreliable and inadequate water supply system

Water supply within the scheme was not reliable due to the easily manipulatable irrigation cycle. Sometimes some members of the irrigation management committee charged with supplying farmers with irrigation water, for one reason or the other, manipulated the irrigation rotation system so that it favoured certain individuals. These farmers ended up over-irrigating disadvantaging other plotholders.

The canal supplying water to block C, from Nyanyadzi river is not lined and was observed to be silted, overgrown with grass, thus increasing the chances of deep percolation losses. The canal was increasingly becoming so inefficient so much so that farmers in block C, though head enders, were facing acute water shortages. There is a general belief among the farmers that the more water one applies, the higher the yields. Thus since head-end farmers have better access to irrigation water, they tended to over-irrigate resulting in wasteful use of water by the head-enders leading to increased leaching of nutrients and subsequent low yields.

Since the scheme is rather old, most of the lined canals in the distribution network have now developed some cracks leading to conveyance losses. This situation was contributing to the problem of irrigation water shortage and it was mostly felt at the tail ends since conveyance losses increase with distance. The shortage of irrigation water is finally translated into poor crop growth and sub-optimal yields.

The supply of irrigation water at Nyanyadzi irrigation scheme is becoming increasingly unreliable, especially when low flows are experienced at the intake. Both the Odzi and Nyanyadzi intakes were experiencing siltation problems due to poor land use planning in the catchment. This implied that not enough water could be abstracted for irrigation use, hence inadequate water in the whole scheme in general, to such an extent that the available irrigation water could not meet total water demand.

The unreliable water delivery has created a bad attitude by farmers towards irrigation. Some of the plotholders were now diverting their time and skills elsewhere, in search of alternative income sources. Irrigation water delivery was so unreliable to the extent that irrigation intervals of more than 30 days were reported in some sections of the scheme.

Inequitable delivery of irrigation water was common among farmers occupying a common conveyance canal. The tail-end farmers were often disadvantaged as head-end farmers tended to abstract more than their intended allocation. Illegal abstractions were also prevalent along the conveyance canals. This inequitable delivery in irrigation water leads to low yields in tail-end positions and creates problems associated with over-application of water amongst head-enders.

4.1.2.4 Inefficient irrigation method

Farmers at Nyanyadzi scheme use border strips as the irrigation method. The water is siphoned onto the plots from the distribution canals. Some of the border strips in the plots were no longer well graded resulting in lack of uniformity in irrigation water distribution during water applications. Since there was no uniform contact time, there was resultant under-irrigation on the upper end of the plot and over-irrigation at the lower end.

As a result of the lack of uniformity in water opportunity time plants at the upper end of the plot ended up being water stressed whilst those at the lower parts ended up being waterlogged, with the soil losing essential nutrients through leaching. Water application was basically "wild" and there was no clear mechanism governing water application time. Basically plotholders stopped irrigating after the advance front had reached the tail end of the border strip and the degree of ponding greatly varied from one farmer to the next.

There were no restrictions on how much water one should apply and head enders within a distribution canal took advantage of this to over-irrigate their plots. The arrangement was such that water was released to lower end plotholders after the upper end farmers were through with their irrigation. With no regard for water application time, lower end farmers were always disadvantaged.

4.1.2.2 Inappropriate cropping calendar

The absence of an appropriate cropping calendar was also contributing to the inadequacy of irrigation water. Although there exists a recommended cropping calendar by AGRITEX, farmers were not adhering to it. Each farmer decided on his or her own planting dates without any consideration of the rainfall pattern. Although it is important for farmers to enjoy some degree of autonomy in their operations, there is danger that farmers may plant their crops at such a period when the available irrigation water is not enough to sustain the acreage under irrigation, and without the contribution of natural rainfall, very low yields would be realized. Good cropping calendar releases pressures on the available irrigation water making maximum use of rainfall.

4.1.3 Fertility related constraints

4.1.3.1 Inadequate amounts of fertilizer

The soils at Nyanyadzi irrigation scheme are mainly alluvium (being on the banks of Odzi and Nyanyadzi rivers. As such one would expect them to be of high inherent fertility, unfortunately they have been subjected to intense nutrient mining over the years. Although there is no recent data on the soil fertility status at the scheme, it is evident that soil fertility has deteriorated considerably (especially soil nitrogen) as evidenced by the yellowing maize leaves and poor crop stand in such blocks as D where nitrogen use was very minimal. Without use of fertilizers, these soils now have low potential to sustain a crop plant. Although most of the farmers appreciated the importance of fertilizers, very few were applying the recommended levels. Most of the farmers were poor and therefore could not afford the high cost of inorganic fertilizers; hence inadequate quantities were often applied.

There was a distinct difference in the maize crop stand as one moved from the head end blocks to the tail end blocks. Crop stand in block D in particular showed a high degree of wilting and appeared yellow due to nitrogen deficiency. An interesting relationship between irrigation water availability and fertilizer application existed in the scheme. It was noticed that use of chemical fertilizers tended to fall from the head end to the tail end block, following the general pattern of water availability. The highest number of farmers applying chemical fertilizer was found in block A with 83.3 % applying ammonium nitrate and 70% applying compound D fertilizer. Only 28% of the farmers in block D were applying ammonium nitrate fertilizer and 44% applying compound D. For block C, 20% of the farmers were applying ammonium nitrate and very few farmers reported applying ammonium nitrate in block D. Of those farmers applying ammonium nitrate fertilizer 50% were applying the recommended rate in block A, only 25% in block C, 20% in block B and 0% in block D. In all the blocks no farmer was applying the recommended 300kg/ha compound D (6% total N) fertilizer due to financial constraints.

Farmers most hit by water shortage (C, B south and D) were not investing much in such inputs as fertilizers. They reported that by so doing they would be putting their money to waste, as they believe the available irrigation water did not warranty such an investment. Most of the farmers in these blocks reported that as a result of their perennial water problems, most of their time was now being spend doing alternative jobs like craft instead of managing their plots. Thus water inadequacy has now affected the attitude of farmers towards irrigation and they do not want to commit themselves and their scarce resources in the required management aspects.

However, through the judicious use of fertilizers, the quality of the crop can be improved. A few of the farmers were of the notion that manure can be used to substitute inorganic nitrogen fertilizers. Although it is common knowledge to often regard fertilizers as substitutes for animal manure, that is not a correct interpretation of their purpose. Although animal manure improves soils conditions and supply nutrients, they are essentially the by-products of any particular farm (Ignatieff and Page, 1958).

Thus use of commercial fertilizers makes it possible to introduce extra supplies of nutrients into the cycle of growth and decay and improve fertility, ensuring the availability of nutrients for increased crop yields.

4.1.3.2 Low manure levels

Use of manure in all the blocks was very low. Average manure application rate in the scheme was about 11.5 t/ha, although AGRITEX recommends about 30t/ha. Due to the high temperatures in Nyanyadzi, soil organic matter levels are likely to be low owing to increased oxidation. Increase in manure application does not only result in an increase in soil nutrient reserves but also increases the soil moisture holding capacity, hence ensures increased water uptake by crops. Manure inputs are low mainly as a result of cattle shortage and where the manure is available; it is likely to be of low quality. Thus, these soils are generally of low marginal fertility and their fertility status is likely to offset yields unless artificial fertilizers and manure are added.

4.1.4 Management related constraints

4.1.4.1 Delays in land preparations, planting and weeding

As a result of draught power shortage and other priorities like craft, some of the farmers were not doing their land preparations in time and as such late planting was reported in some sections of the scheme. Planting late may mean loosing part of the growing season and may also mean failure to take advantage of the natural rainfall. By planting late the farmer may already have lost part of the growing season during which conditions were favourable for growth of that particular crop. Since proper management and co-ordination of farm activities is crucial in the realization of potential yields, delays in farm operations can significantly offset yields.

Timeliness of operations is as crucial as the operations themselves. It was noted that some farmers (especially in tail-end blocks) were committing their time and efforts on alternative sources of income leading to delays in such operations as planting and weeding. Although all the farmers interviewed reported that they did weed their plots, it was observed that quite a number of the plots, especially in tail end blocks, were overgrown with weeds. The concerned farmers argued that the crop would eventually die anyway, due to water shortage and they did not see a reason why they should waste their labour. Weeds are undesirable since they compete with crop plants for moisture and nutrients, thus reducing crop yields. Timely weeding reduces wasteful use of water and nutrients and increases the amount of water and nutrients available for uptake by crop plants.

4.1.4.2 Delays in fertilizer application, pest and disease control

As a result of poverty and to some extent, poor planning, some farmers in the scheme acquired their fertilizers when the crops were already showing signs of nutrient deficiency. In some cases, the fertilizer was applied when the crop had already been affected by nutrient deficiency and the applied fertilizers failed to redress the situation. As a result of their low level of education, some of the farmers did not for see the implications of such practices. This did not only result in low yields but was also a waste of money. Such operations as fertilizer applications, pest and disease control should be done at the ideal time to avoid any negative effect on crop yields.

Most farmers were not knowledgeable on when to apply pesticides and when to effect disease control and in most cases these were done when the crop was already under attack. Pests and disease control should be done in time as it increases crop viability. Pests physically damage crop plants and that reduces crop growth, increases risk of disease outbreaks, reduce water and nutrient uptake by crop plants and may altogether lead to death of the plant.

4.1.4.3 Low quality operations

Some farmers lacked technical advice on the best way to manage their operations. For example, some in the scheme could not tell the tillage depth suitable for a particular crop. Since there is no use of mechanized technology in the scheme and farmers use draught power for tillage operations, it is important that the depth of till is deep enough to reduce crop root impediment. Poor tillage operations may lead to shallow soil depth for some crops and reduce the volume of soil from which the roots can effectively exploit soil nutrients and moisture reserves. Management operations should be carried out according to set standards. Poor operations often fail to achieve the intended objectives, and compromise on yields.

4.2 YIELD RESPONSE TO WATER AND NITROGEN

The maize yields and treatment results from the simulation runs for Matanya irrigation scheme) are summarized in table 12. The simulation period was January to May of 1987.

Table 12: Maize yields under different treatments (scenario studies)

Treatment	Yield (kg/ha)	ET_C (mm)	Total rain (mm)	Initial soil water	Final soil H_2O at maturity	Total irrig (mm)
1. Rainfed no N	1087	322	163	161.9	0	0
2. 33% irrig no N	1137	360	163	161.9	20	91
3. 66% irrig no N	1362	379	163	161.9	64	181
4. 100% irr no N	1387	387	163	161.9	91	273
5. 133% irrig no N	1520	394	163	161.9	132	365
6. rainfed 50kg/ha N	2126	322	163	161.9	0	0
7. 33% irrig 50kg/ha N	2382	368	163	161.9	12	91
8. 66% irrig 50kg/ha N	5567	405	163	161.9	53	181
9. 100%irr 50kg/ha N	6218	417	163	161.9	61	273
10. 133%irr 50kg/ha N	6584	417	163	161.9	115	365
11. rainfed 100kg/ha N	2961	322	163	161.9	0	0
12. 33% irrig 100kg/ha N	3380	370	163	161.9	10	91
13. 66% irrig 100kg/ha N	7890	408	163	161.9	50	181
14. 100%irr 100kg/ha N	8117	425	163	161.9	55	273
15. 133% irrig 100kg/ha N	8024	427	163	161.9	111	365

4.2.1 Model validation

Fig 6 shows the relationship between the observed maize yield versus the predicted yield. The plots show the predicted versus observed yields are grouped around the 1:1 line indicating a good fit. The model tends to over-predict maize yields, and this may be due to disease and other production factors which were not considered in the model or assumed to be non-limiting. However, the model can be used as a useful predictive tool in irrigation planning with a reliable degree of certainty.

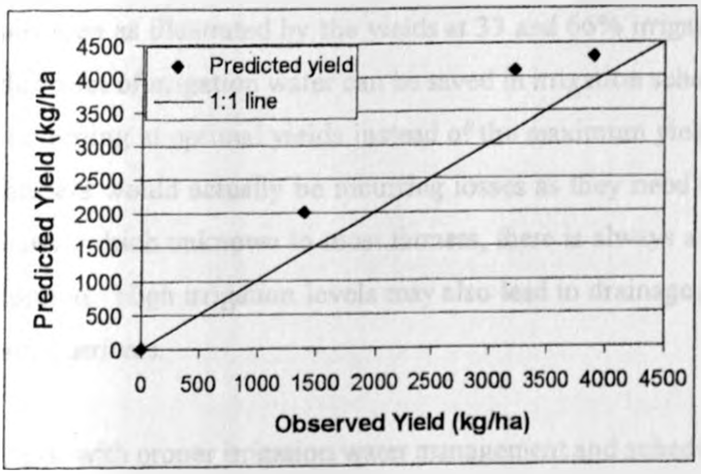


Figure 6: Comparison between predicted maize yield and observed yields

4.2.2 Yield response to water

4.2.2.1 Effect of increasing water levels on maize yield

The model illustrates that increasing irrigation water level increases yields up to an optimal point.

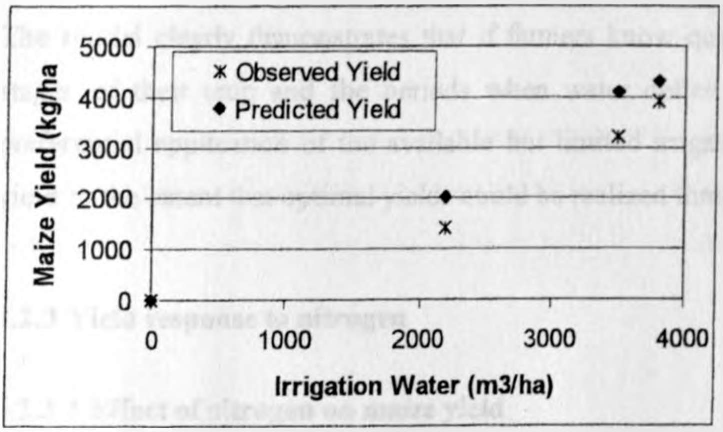


Figure 7: Yield response to water at different levels of nitrogen

This trend was observed at all nitrogen levels. In all cases, optimal yields were observed at around 60-70% irrigation levels. One hundred percent irrigation could not effect much different yields from the 66% level. By allowing some degree of water stress during the grain filling stage, substantial and optimal yields were still realized with proper mix of nitrogen as illustrated by the yields at 33 and 66% irrigation at 50kg/ha N. This may imply that a lot of irrigation water can be saved in irrigation schemes if farmers understand the need for aiming at optimal yields instead of the maximum yields. By going for maximum yields, farmers would actually be incurring losses as they need to apply higher levels of irrigation water, which unknown to most farmers, there is always a cost attached to each unit of water applied. High irrigation levels may also lead to drainage problems and leaching of essential soil nutrients.

Thus, with proper irrigation water management and scheduling, one could see that it does not necessarily mean that meeting full crop water requirements is the only viable option. On the contrary, sustainable yields could be attained through subjecting the crop to some degree of water stress.

This information can be gainfully employed to demonstrate to farmers, especially head-enders in irrigation schemes that contrary to common belief, significant yields are attainable without use of high irrigation water levels. This would ensure that more irrigation water reaches the tail-enders, leading to equitable distribution of water within the scheme.

The model clearly demonstrates that if farmers know quite well the phenological growth stages of their crop and the periods when water deficit significantly affects yield, then preferential application of the available but limited irrigation water significantly increases yield to the extent that optimal yields could be realized through judicious water applications.

4.2.3 Yield response to nitrogen

4.2.3.1 Effect of nitrogen on maize yield

From the results, it can be shown that nutrient nitrogen (N) has a direct effect on the yield of maize. In all cases, an increase in N level resulted in increased maize yield (Fig.8).

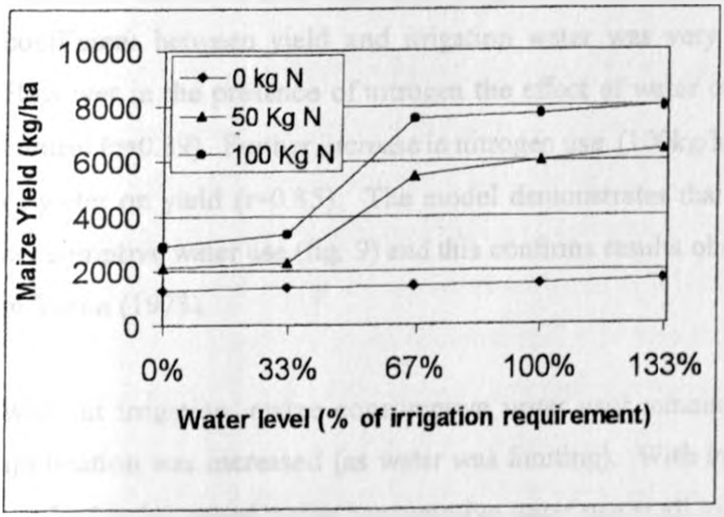


Figure 8: Yield response to N at different irrigation levels

For the rainfed treatments, maize yield under zero N application was 1087kg/ha, when the level was raised to 50kgN/ha; yield was 2126kg/ha and 2961kg/ha at 100kg/ha. The model clearly demonstrates that where irrigation water is scarce and farmers depend so much on rainfed agriculture, yields can be increased significantly by investing in nitrogen fertilizers. The extra yield from an additional 50kg increase in N is not justified and farmers could do better by applying moderate levels like 50kg/ha. Thus farmers do not need to apply high levels of nitrogen as demonstrated by the rather insignificant difference in yield between 50kg and 100kgN/ha levels. Nitrogen increases the efficiency with which the crop utilizes the limited available water and ensures that there is an increase in biomas product per unit of water used by the plant.

It is also important to note that as more and more levels of nitrogen are applied, the effect on yield becomes less pronounced. These results may go a long way in saving farmers' incomes since they would necessarily need not to apply high nitrogen levels in order to attain optimal yields.

4.2.3.2 Effect of Nitrogen on Maize yield response to water

The model illustrates that a proper mix of water and nitrogen can significantly increase crop yields, at the same time saving on irrigation water. Without nitrogen use, the correlation coefficient between yield and irrigation water was very high (r=0.98), see Appendix 8. However in the presence of nitrogen the effect of water on maize yield is compared to the control (r=0.89). Further increase in nitrogen use (100kg/ha) resulted in an even lesser effect of water on yield (r=0.85). The model demonstrates that use of nitrogen increases maize consumptive water use (fig. 9) and this confirms results obtained by Shimshi (1967), quoted in Yaron (1973).

Without irrigation, maize consumptive water user remained constant even when nitrogen application was increased (as water was limiting). With irrigation, increase in nitrogen use resulted in increased maize consumptive water use at all irrigation levels, indicating that use of nitrogen results in the efficient use of irrigation water by the crop plant. Without use of nitrogen, crop yields were low (yield less than 2.0t/ha) despite increased application of irrigation water.

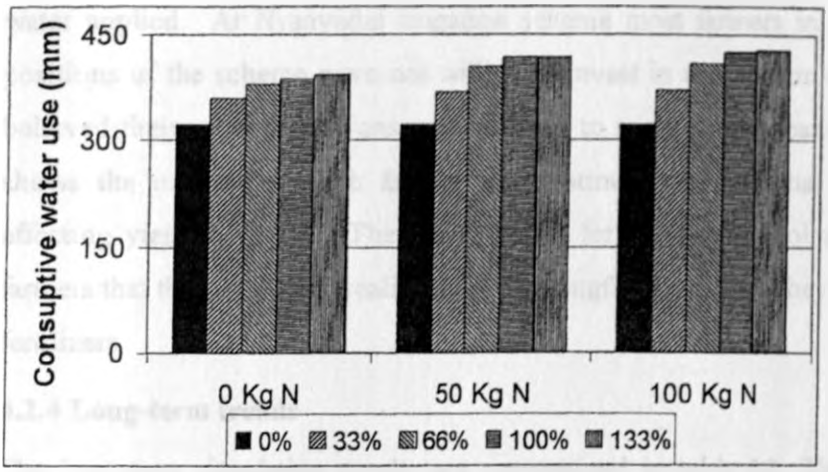


Figure 9: Effect of nitrogen on maize consumptive water use

When nitrogen application was increased to 50kgN/ha, there was a marked increase in yield for the same irrigation water levels. Nitrogen application rate of 100kgN/ha did not produce remarkable differences in yield. High nitrogen and water levels should not be recommended since the high costs incurred are not justified by the yield increases and therefore farmers are better off using moderate rates. For example, the yield from the 66% water level and 50kg/ha N would be quite appropriate for most farmers as it produces optimal yields at lower production input costs.

Whilst irrigation water is of primary importance to the growth and yield of irrigated maize, an appropriate mix of water and nitrogen could result in irrigation schemes realizing better yields at high water use efficiency. Thus, it can be seen that lack of water, which lowers yield, may be mitigated by the application of chemical N fertilizers and the widely held view that the effects of drought are accentuated by such additions may be erroneous. Another similar study on fertilized grass demonstrated that fertilizer, far from increasing the plant's demand for water, can in effect serve as a "substitute" for it (Low and Armitage, 1959).

Farmers often think that use of fertilizer requires a parallel increase in applied water. Unless the application of fertilizer results in dense foliage which provides a much more complete coverage of the soil surface (hence allowing a higher degree of evapotranspiration per unit area) no significant increase in water use could be expected with increased fertilizer use. Carruthers and Clark (1983) reported that in many cases, vegetation cover is already sufficient and fertilizers provide an important means of increasing crop production per unit of water applied. At Nyanyadzi irrigation scheme most farmers in the middle and tail-end positions of the scheme were not willing to invest in ammonium nitrate fertilizers as they believed their water allocations were too low to sustain any meaningful crop yields. This shows the extend to which farmers underestimate the potential of nutrient nitrogen in effecting yield increases. The results could form a useful tool with which to convince farmers that they could still realize more meaningful yields than they perceive by investing in fertilizers.

4.2.4 Long-term trends

The long-term simulation results are summarized in table 12. The long-term simulation trends for the ten-year period are given in Fig.10. The yields are in synchrony with the rainfall pattern and where the seasonal rainfall was high, yields were also found to be relatively higher. However in some instances, the predicted yields were not so conspicuously conforming to the rainfall pattern and this might have been due to waterlogging as the increase in water may have interfered with root aeration and nutrient uptake. The model can however be relied upon to predict future trends in crop yields and it can thus be used to make long-term predictions and assess the impact of change in climate on crop yields and this forms an important component in crop production.

Table 12: Long term simulation yields for Matanya irrigation scheme

Year	Yield (kg/ha)														
	Treatment														
	1	2	3	4	5	6	7	8	9		11	12	[illegible]	[illegible]	
1986	1241	1345	1485	1538	1701	1829	2142	4658	5310	[illegible]	2328	2987	6542	7144	
1987	1087	1137	1362	1387	1520	2126	2382	5567	6218	6584	2961	3380	7890	8117	8024
1988	1368	1452	1523	1613	1769	2214	2390	5671	6342	6710	3028	3410	7925	8216	8132
1989	1264	1353	1461	1531	1725	1996	2214	4986	5431	5918	2751	3286	7769	7982	8010
1990	1451	1642	1215	1360	1509	2038	2143	5346	6089	6337	2931	3315	7821	8069	7989
1991	1121	1241	1438	1451	1625	2350	2486	6158	6329	6794	3059	3529	8063	8329	8338
1992	1042	1146	1301	1339	1494	2019	2096	5288	5978	6295	2851	3185	7642	7882	7796
1993	1395	1486	1610	1720	1805	2381	2562	6289	6541	6851	3125	3490	8125	8467	8395
1994	1289	1438	1572	1605	1750	2014	2070	5196	5823	6139	2836	3189	7658	7824	8158
1995	1356	1422	1510	1598	1680	2123	2331	5497	6184	6475	2959	3478	7961	5142	8271

Treatment legend:

1: Rainfed no N	4: 100% irr no N	7:33% irrig 50kg/ha N	10:33%irr 50kg/ha N	13:66% irrig 100kg/ha N
2: 33% irrig no N	5: 133% irrig no N	8: 66% irrig 50kg/ha N	11:rainfed 100kg/ha N	14:100%irr 100kg/ha N
3: 66% irrig no N	6:rainfed 50kg/ha N	9: 100%irr 50kg/ha N	12:33% irrig 100kg/ha N	15:133% irrig100kg/ha

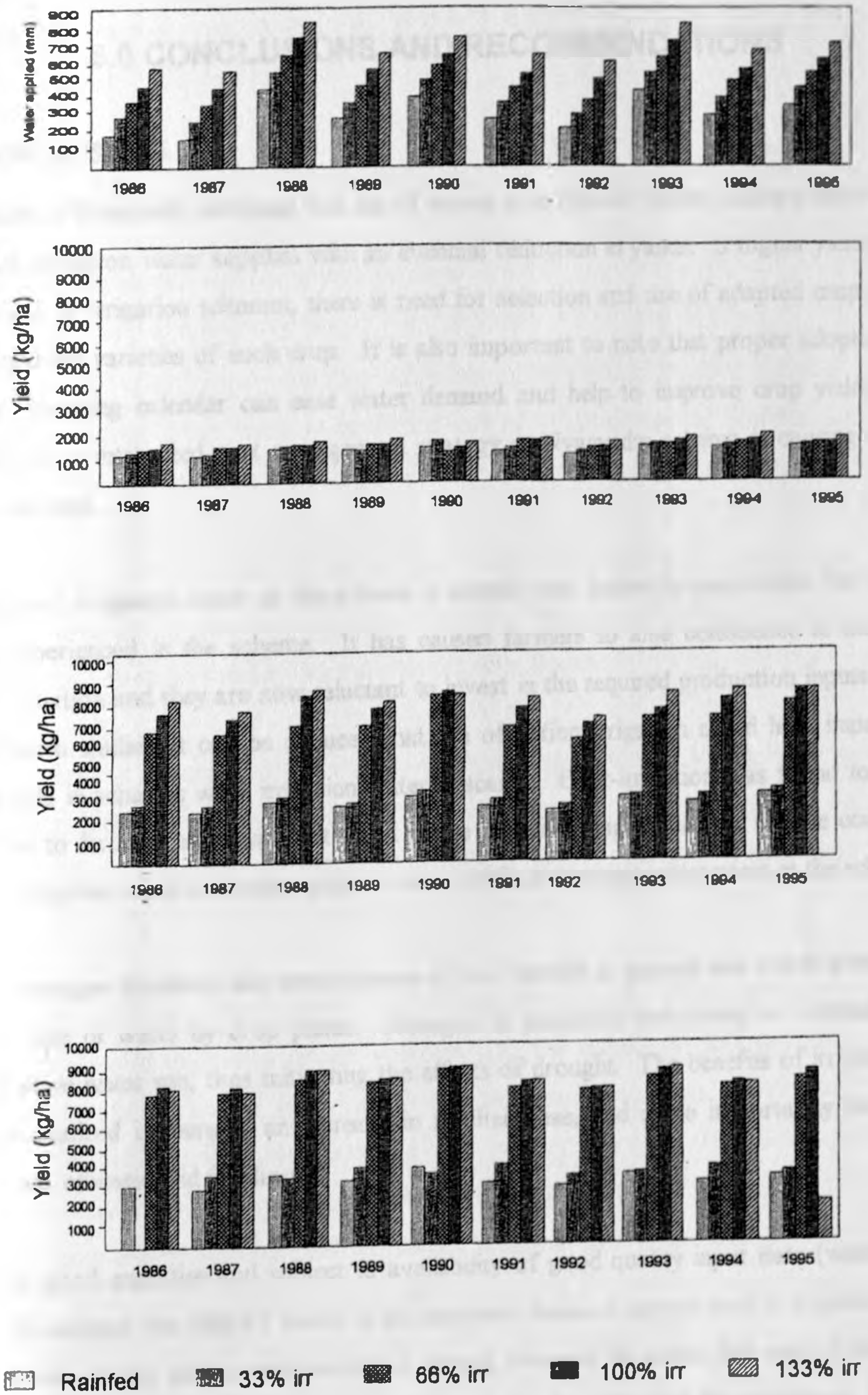


Figure 10: Long-term simulation yield trends at (a) 0 kgN/ha, (b) 50 kgN /ha and 100 kgN/ha

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The study at Nyanyadzi indicated that use of wrong crop type or variety causes a strain on the available irrigation water supplies with an eventual reduction in yields. If higher yields are to be realized in irrigation schemes, there is need for selection and use of adapted crop species and improved varieties of each crop. It is also important to note that proper adoption of a suitable cropping calendar can ease water demand and help to improve crop yields. The absence of an integrated pest management strategy at Nyanyadzi scheme is causing marked yield reduction.

Shortage of irrigation water in the scheme is directly and indirectly responsible for the low yields experienced in the scheme. It has caused farmers to lose confidence in the water supply situation and they are now reluctant to invest in the required production inputs. From the scenario studies, it can be deduced that use of deficit irrigation could help improve on crop yields in schemes were irrigation water is scarce. Over-irrigation was found to be not beneficial to farmers, as it does not result in the perceived higher yields. On the contrary it wastes irrigation water and only results in more conflicts amongst water users in the scheme.

Use of nitrogen fertilizers and improvement of soil fertility in general can result in increased efficient use of water by crop plants. Nitrogen in particular was found to increase maize consumptive water use, thus mitigating the effects of drought. The benefits of irrigation can be fully realized if there is an increase in fertilizer use, and more importantly through a proper mix of water and fertilizer.

Through good expertise and subject to availability of good quality input data (weather and soils information), the DSSAT model is an important decision support tool in irrigation water management during primary production. It should, however be noted that models have their own weaknesses. They tend to be costly and need good quality data for validation. Some of the software involve solving complicated equations, thus need for well-trained personnel who can use and interpret model outcomes. Models can not be used as substitute for fieldwork, but they are only decision aiding tools.

5.2 RECOMMENDATIONS

5.2.1 Matching water allocation with demand

The selection of crops to be grown any irrigation scheme should be done carefully. Growth of unsuitable crops often leads to inefficient use of irrigation water. Farmers need to be advised on the type of crops, the improved variety of each crop most suited to the agro-climatic environment of the scheme. In cases where farmers receive crop seeds, the irrigation planners responsible for the scheme should make sure that suitable seed varieties are made available to farmers. Tail- end farmers should be encouraged to grow drought resistant crops since they reduce pressure on irrigation water.

There is need to ensure that there are no illegal abstractions of water by farmers along conveyance and distribution canals. This can be achieved through (a) stiffer penalties to offenders (2) establishment of security committees in each block (3) increased extension work to sensitize farmers on the dangers of over-irrigating.

Minimization of losses during delivery and application can be done through (1) desiltation of canals (2) uprooting grass and any vegetation in the canals (3) having relatively large irrigation streams for border strip method (4) Gentle topography and careful land leveling. Careful land grading and gentleness of the slope are important factors that ensure increased water application efficiency. In order to enjoy the benefits of deficit irrigation, there should be coordinated teamwork within blocks and the whole scheme in general. During periods of low water flows in the Odzi and Nyanyadzi rivers farmers may be encouraged to stagger maize planting as per block so that the maize crop reaches the tussling and grain filling stages at different periods, thereby reducing the strain on the limited water supplies. For example, blocks B and D may plant their maize crop first such that their crop reaches critical growth stages before the crop in other blocks and this reduces pressure on the irrigation water. By so doing substantial yields could be realized in all the blocks and the problems of inequitable water delivery would therefore be minimized.

The assumption used in irrigation scheduling, that water is not limiting is now highly erroneous. With continued scheme expansion and increase in the plotholders water is now the limiting factor in primary production and there is need for rescheduling since the rotation cycles being used within and between blocks have left many farmers disillusioned.

A long-term solution to the water problems at Nyanyadzi scheme would be construction of a dam on one of the rivers. Dam construction should be accompanied by sustainable land use practices in the catchment area to avoid reservoir siltation.

5.2.2 Proper use of fertilizers

Timing of fertilizer applications has to be assured that it satisfies three needs:

- Ensures an adequate supply for crop growth and dry matter production
- Stimulates growth at particular stages of crop development
- Enables fertilizer to be used as efficiently as possible

Split application of nitrate fertilizers should be encouraged to reduce leaching losses. Periodic soil fertility tests should be encouraged on the scheme. The initial soil fertility is important since it establishes a baseline for the quantity of nutrients and fertilizers supplied from manure and fertilizers to meet crop water requirements.

5.2.3 Pests and disease control

Unless all farmers in the scheme take a collective responsibility in the fight against pests and diseases, the efforts of those few embarking on pest control shall continue to be in vain. AGRITEX extension staff should give advice to farmers on when to spray their crop.

5.2.4 Enhancing efficient use of irrigation water

- The scenario studies indicate that farmers can realize optimal yields if they practice deficit irrigation. This would not only save on irrigation water but may also reduce drainage problems associated with over-irrigation
- Use of nitrogen fertilizers can reduce the effects of irrigation water shortage during primary production
- Farmers should make use of a proper mix of water and fertilizers if they are to realize the full benefits of irrigation
- There should be increased use of crop growth simulation models in primary production as a decision making tool in irrigation water management.

Successful transfer and adoption of these recommendations will depend on the cooperation between the extension staff and the farmers. It would be much easier if this could be done through liaison with the Irrigation management committees.

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7.0 LIST OF APPENDICES

Appendix 1: List of symbols and experimental codes

MinsunH	Minimum Sunshine Hours
NH4N03	Ammonium Nitrate
N	Nitrogen
SRAD	Solar Radiation
Tmax	Maximum Temperature

Factor levels

CU	Cultivar level
FL	Field level
SA	Soil analysis level
IC	Initial conditions level
MP	Planting level
MI	Irrigation level
MF	Fertilizer applications level
MR	Residue level
MC	Chemical applications level
MT	Tillage level
ME	Environment modifications level
MH	Harvest level
SM	Simulation level

Cultivars

@C	Crop component number
INGENO	Cultivar identifier
CNAME	Cultivar name

Fields

ID-FIELD	Field ID (Institute + Site +Field)
WSTA	Weather station code (Institute +site)
FLOB	Obstruction to sun (degrees)
FLDT	Drainage type code
FLDD	Drain depth (cm)
FLDS	Drainage spacing (cm)
FLST	Surface stones (abundance, % silt, S, M, L)
SLTX	Soil texture
SLDP	Soil depth (cm)
ID-SOIL	Soil ID (Institute, Site, Year +soil)

Initial conditions

PCR	Previous crop code
ICDAT	Initial conditions measurement, date, year + days
ICRT	Root weight from previous crop, kg/ha
ICND	Nodule weight from previous crop, kg/ha
ICRN	Rhizobia number, 0-1 scale
ICRE	Rhizobia effectiveness, 0-1 scale

Planting details

PDATE	Planting date, year + days from Jan. 1
EDATE	Emergence date, earliest treatment
PPOP	Plant population at seeding m^{-2}
PPOE	Plant population at emergence m^{-2}
PLME	Planting method, code
PLDS	Planting distribution, row R, broadcast B, hill H
PLRS	Row spacing, cm
PLRD	Row direction, degrees from N
PLDP	Planting depth, cm
PLWT	Planting material dry weight, kg/ha
PAGE	Transplant age, days
PENV	Transplant environment
PLPH	Plants per hill (if appropriate)

Irrigation Water Management

IEFF	Irrigation application efficiency, fraction
IDEP	Management depth for automatic application, cm
ITHR	Threshold for automatic appl., % of max. Available
IEPT	End point for automatic appl., % of max. Available
IOFF	End of automatic applications, code
IAMT	Amount per automatic irrigation if fixed, mm
IDATE	Irrigation date, year+day or days from planting
IROP	Irrigation operation code
(IR001	Furrow method)
IRVAL	Irrigation amount, depth of water (mm)

Fertilizers (inorganic)

FDATE	Fertilization date, year+day or days from planting
FMCD	Fertilizer material code
FE 001	Ammonium nitrate
FACD	Fertilizer application/placement code
FDEP	Fertilizer Incorporation/application code

FAMN	N in applied fertilizer, kg/ha
FAMP	P in applied fertilizer
FAMK	K in applied fertilizer
FAMC	Ca in applied fertilizer
FAMO	Other elements in applied fertilizer
FOCD	other elements code

Residues and other organic materials

RDATE	Incorporation date, year+days
RCOD	Residue material, code
RAMT	Residue amount, kg/ha
RESN	Residue nitrogen concentration, %
RESP	Residue phosphorus concentration, %
RESK	Residue potassium concentration
%RINP	Residue incorporation percent
RDEP	Residue incorporation depth, cm

Appendix 2: Questionnaire survey for the determination of causes of low crop yields at Nyanyadzi irrigation scheme

About the farmer (Informant)

1: Name of Informant...

2: Age group (years)
*<20, * 20-30, *31-40, *41-50, *>50 (put a tick)

3: Highest level of education attained (formal)
*Elementary school * High school *Certificate * Graduate degree *Other (Specify)

4: Marital status
* Married * Single

5: Sex * Male * Female

About the household

6. Size of household..

7. Sources of income
*Off-farm employment * Remittance * Dry land farming * Irrigation (Number in order of importance)

8. How much of irrigation produce is consumed on the farm?

About the farm

9. Location (reach) on the conveyance system
* Tail * Middle * Head

10. Farm size............................ (Acres/ha)

11. Technology available
* Mechanized *Animal power *Other (specify)

12. Soil type
* Sand (Light) * loamy *Clayey *Other (Specify)

13. Size of cropped area..................... (Acre/ha)

14. Size of irrigated area.....................(acre/ha)

15. Crops grown

Crop	Acreage/ Hectare	
	Irrigated	Rainfed
1		
2 (etc.)		

16. Inputs of irrigated agriculture

1. Labour

*Family * Hired * Both

2. Capital (Purchased inputs)

Input	Quantity per acre		
	Crop 1	Crop 2	Crop 3
Seeds (kg)			
Fertilizer (kg) State type			
Manure (t)			
Pesticides (l or kg)			
Water (m^3)			

17. Outputs from irrigated agriculture

Year	Crop	Yield (kg/acre)

Part 2. Water saving strategies

A Water saving at farm level

18. Method of Irrigation

* Drip * Furrow * Basin *Sprinkler * Bucket* Other (Specify)

19. Reasons for choice of method

* Labour availability * Cost *Slope *Technical-know how * Others (Specify)

20. Type of seeds used:

Variety	Irrigated fields	Rainfed fields
High yielding		
Early maturing		
Drought resistant		
Others (specify)		

21. **Cultural Practices**

(i) Fertilizer use
* None * Chemical (inorganic) * Organic (manure, crop residues) * Other (specify)
(ii) Crop protection
*Weed control * Pest control *Disease control

(iii) Crop rotation
* yes * no

(iii) Crop protection

(iv) Evaporation reduction
* Mulching * other (specify)

(v) Run-off reduction
* Retention ditches * Other (Specify)

Response to changes in irrigation water availability

22. Fluctuations in the area irrigated for the past years farmer has been irrigating
When did you start irrigating?
*< I (year) *1-2 *3-5 * 6-10 *>10

How much land have you been irrigating over those years?

Season	Year			
	Irrigated land (acres)			
	1	2	3	4
Summer				
Winter				

23. Which month of the year do you normally experience irrigation water shortage?

24. How is the water supply situation during irrigation water shortage periods?
* Rationing on (a) volume basis (b) Arial basis (specify acreage affected) * other

25. During periods of water shortage, when do you irrigate
* In the morning *afternoon * other (specify)

26. Do you experience yield reduction as a result of water shortage?
* Yes * No

27. What do you do to minimize yield loss during periods of irrigation water shortage?
* Change cropping calendar (planting time) to supplement irrigation with natural rainfall
* No crops grown *Grow crops which do not use a lot of water (specify
* Change the seeding rate * Change the cropping intensity * Irrigate more frequently high value crops (horticultural) *Increase manure levels or organic residues to increase soil water retention capacity * Other (specify)

Appendix 3: Farmer interviews schedule

Date	Block	Name of respondent
15/ 11/96	A	Baye M
		Masungise T
		Mujati E
		Munasireyi C
		Makuni E
17/1/96		Dziwande P
		Gamunorwa F
		Sinduna M
		Gororo W
		Takawira T.C
		Nhachi J
		Munyari T
		Bangwayo C
		Dziwandi B
22/11/96		Sithole S
		Mbengo E
		Gororo E
		Dirikwe P
		Masungise N
		Bingepinge T
23/11/96		Chipandwa T
		Marango M
		Muchadzinesa T
25/11/96		Chikotosa P
		Hodora C
		Mabika P
		Mugido J
		Mwashita E
		Katsaura F
		Gororo E

Date	Block	Name of respondent
02/12/96	C	Muzulu P.C
		Chinoda S
03/12/96		Chirombo M
		Muzama A
04/12/96		Nyanhanda A
		Shongwi T
		Mabika M
		Nyakakata M
		Nyanhanda E
		Muchira R
		Gonorenda B
		Joshua K
		Nenhawe M
		Chibvuma C
		Jena S
		Mungebe J.B
		Zvaagarwe M
		Gototo R
		Chibvuma T
		Dzitiro J

Date	Block	Name of respondent
02/01/97	B	Nechikwira D
		Muchirawatu M
		Emberai D
		Gudyanga P
05/01/97		Siyengi J
		Gonyamo M
		Mashingaidze M
		Duku M

14/01/97		Kutsiwa L
		Chiramwiwa P
		Mangwadza A
20/01/97		Chipise S
		Mafisheni K
		Chandakambata D
		Mwanyenyawepo C
		Kambeu S
		Pedzana W
		Makotano S
		Gudyanga M.M
		Rwizi M.L
		Hama A
		Maposa N.D
		Mangadza H
		Dzitiro T

Date	Block	Name of respondent
24/01/97	D	Mazirahu F
		Dirikwi K
		Shabati N
		Kugena M
		Muchirawatu M
		Mutama J
		Mwanyenyawepo N
		Mavha P
		Chipiro P
26/01/97		Pakari C
		Kwarire M
		Doro A
		Manyere N
		Kusena B
02/02/97		Ngaribvume G
		Mugomo S
		Katsaura F
		Masasi Z
		Chipiro G
		Gororo B

Appendix 4: Summary of model generated soil input parameters

Soil depth (cm)	Lower limit cm^3/cm^3	Upper limit cm^3/cm^3	SAT soil water cm^3/cm^3	Extr soil water	Initial soil water
0-15	0.246	0.365	0.380	0.119	0.365
5-15	0.268	0.386	0.400	0.118	0.386
15-30	0.290	0.406	0.421	0.116	0.406
30-45	0.290	0.421	0.421	0.116	0.406
45-60	0.308	0.421	0.436	0.113	0.421
60-90	0.308	0.421	0.436	0.113	0.421
90-120	0.264	0.381	0.396	0.117	0.381
120-140	0.264	0.381	0.396	0.117	0.381

Depth (cm)	Parameters		
	Soil water (mm)	Ammonium g/mg	Nitrate (g/kg)
0-10	0.365	0.50	3.60
10-45	0.406	0.50	3.10
45-90	0.421	0.50	2.70
90-140	0.381	0.50	1.30

Appendix 5: Calculation of crop water requirements based on the Pan method

The reference evapotranspiration (ETo) representing the mean value in mm/day over the period considered is given by:

$Eto = K_{pan} * E_{pan}$

Where: K_{pan} is the pan coefficient, calculated from tables using relative humidity data, wind speed data and the nature of vegetation cover on the site (FAO, 1986). E_{pan} is evaporation in mm/day form an unscreened class A evaporation pan. The pan coefficient values for the growing season are given below.

Month	E_{pan} (mm/day
Jan	4.2
Feb	5.1
March	4.7
April	3.9
May	4.4

The crop water requirement is then computed using the following relationship:

$ETc = Kc*ETo$

Where ET_C is the crop water requirement and K_C is the crop factor. Maize K_C values are given below.

Growth stage	Duration	K_C value
Initial	23	0.4
Development	38	0.78
Mid-season	38	1.125
Late season	20	0.85

The actual K_C values for each month were then computed to calculate the monthly crop water requirements

Appendix 6: DSSAT Model Input data file

Experimental Layout

EXP. DETAILS: NAMA0001 MZ NITROGEN* IRRIGATION EXPERIM*
GENERAL
@ PEOPLE
MAKUMIRE T.B & DR F.N. GICHUKI
@ADDRESS
UNIVERSITY OF NAIROBI BOX 30197 KENYA
@ SITE
MATANYA IRRIGATION SCHEME, NANYUKI
@ NOTES
EFFECT OF NITROGEN AND WATER ON MAIZE YIELD

*CULTIVARS
@C CR INGENO CNAME
1 MZ IB0001 CORNL281

* FIELDS
@L ID FIELD WSTA... FLSA FLOB FLDT FLDD FLDS FLST SLTX SLDP ID SOIL
1 NAMA0022 NAMA8701 -99 0 DR003 0 10 0 CLLO 140

* INITIAL CONDITIONS
@C PCR ICDAT ICDAT ICRT ICND ICRN ICRE
1 MZ 87001 100 -99 1.00 1.00

@C ICBL SH20 SNH4 SNO3

1 10 0.365 0.5 3.6
1 45 0.406 0.5 3.1
1 90 0.421 0.5 2.7
1 140 0.381 0.5 1.3

@ C PCR ICDAT ICRT ICND ICRN ICRE
2 MZ 87001 100 -99 1.00

@ ICBL SH20 SNH4 SN03
2 10 0.365 0.5 3.6
2 45 0.406 0.5 3.1
2 90 0.421 0.5 2.7
2 140 0.381 0.5 1.3

@C PCR ICDAT ICRT ICND ICRN ICRE
3 MZ 87001 100 -99 1.00

@C ICBL SH20 SNH4 SNO3

3 10 0.360 0.5 3.6
3 45 0.400 0.5 3.1
3 90 0.420 0.5 2.7
3 140 0.380 0.5 1.3

*PLANTING DETAILS
@P PDATE EDATE PPOP PPOE PLME PLDS PLRS PLRD PLDP PLWT PAGE PENV PLPH
.2 7.2 S R 61 O 7.0 -99 -99 -99

*IRRIGATION & WATER MANAGEMENT
@1 EFIR IDEP ITHR IEPT IOFF IAME IAMT
1 1.00 -99 -99 -99 -99 -99 -99
@I IDATE IROP IRVAL
1 87063 IR001 0
@ EFIR IDEP ITHR IEPT IOFF IAME IAMT
2 1.00 -99 -99 -99 -99 -99 -99
@1 IDATE IROP IRVAL
2 87010 IR001 33
2 87090 1R001 58
@1 EFIR IDEP ITHR IEPT IOFF IAME IAMT
3 1.00 -99 -99 -99 -99 -99 -99
@ 1 IDATE IROP IRVAL
3 87008 IR001 45
3 87055 IROO1 31
3 87089 IR001 105

@1 EFIR IDEP ITHR IEPT IOFF IAME IAMT
4 1.00 -99 -99 -99 -99 -99 -99
@1 IDATE IROP IRVAL
4 87008 IROO1 68
4 87015 IR001 10
4 87040 IR001 65
4 87065 IR001 35
4 87091 IR001 95

@1 EFIR IDEP ITHR IEPT IOFF IAME IAMT
5 1.00 -99 -99 -99 -99 -99 -99
@1 IDATE IROP IRVAL
5 87008 IR001 73
5 87020 IR001 21

5 87040 IR001 70
5 87070 IR001 86
5 87090 IR001 115

*FERTILIZERS (INORGANIC)
@ F FDATE FMCD FACD FDEP FAMN FAMP FAMK FAMC FAMO FOCD
1 87043 FE001 -99 0 -99 -99 -99 -99 -99 -99
2 87035 FE001 -99 10 25 -99 -99 -99 -99 -99 -99
2 87060 FE001 -99 10 25 -99 -99 -99 -99 -99 -99
3 87025 FE001 -99 10 20 -99 -99 -99 -99 -99 -99
3 87040 FE001 -99 10 40 -99 -99 -99 -99 -99 -99
3 87065 FE001 -99 10 40 -99 -99 -99 -99 -99 -99

* RESIDUES AND OTHER ORGANIC MATERIALS
@R RDATE RCOD RAMT RESN RESP RESK RINP RDEP
1 87085 RE001 0 -99 -99 -99 -99 -99

CHEMICAL APPLICATIONS
@C CDATE CHCOD CHAMT CHME CHDEP CHTI CHT2 CHT3
1 -99 -99 -99

* TILLAGE AND ROTATIONS
@T TDATE TIMPL TDEP
1 -99 TI021 15

*SIMULATION CONTROLS
@N GENERAL NYERS NREPS START SDATE RSEED SNAME
1 GE 1 S 87002N X IRRIGATION, MATANYA
@N OPTIONS WATER NITRO SYMBI PHOSP POTAS DISES
1 OP Y N

@ N METHODS WTHER INCON LIGHT EVAPO INFIL PHOTO
I ME M E R S C
@N MANAGEMENT PLANT IRRIG FERTI RESD HARVS
1 MA R M
@N OUTPUTS FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT
NI OUT MIOUT DIOUT LONG
1 OU N Y 3 Y N Y N Y

@ AUTOMATIC MANAGEMENT
@N PLANTING PFRST PLAST PH20 L PH20U PH$_2$OD PSTMX PSTMN
1 PL 155 200 40 100 30 40 10

@N IRRIGATION IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
1 IR 30 50 100 GS000 IR001 10 1.00

@N NITROGEN NMDEP NMTHR NAMNT NCODE NAOFF
1 NI 30 50 25 FE001 GS000

@N RESIDUES RIPCN RTIME RIDEP
1 RE 100 1 20

@N HARVEST HFRST HLAST HPCNP HPCNR
1 HA 0 365 100 0

NB The model assumes that all other factors affecting yields and related outputs are optimal and only the treatment effects would affect results

Appendix 7: Effect of nitrogen on Maize yield response to water (r-values)

0 kg/ha N treatment

Treatment (% IR)	0	33	66	100	133
Yield (kg/ha)	1087	1137	1362	1387	1520

Correlation coefficient (r): 0.98

50kg/ha N treatment

Treatment (% IR)	0	33	66	100	133
Yield (kg/ha)	2126	2382	5567	6218	6584

Correlation coefficient (r): 0.89

100 kg/ha treatment

Treatment (% IR)	0	33	66	100	133
Yield (kg/ha)	2961	3380	7890	8117	8024

Correlation coefficient (r): 0.85

Appendix 8: Nitrogen application and maize consumptive water use

Nitrogen level (kg/ha)	**Consumptive water use (mm) Water application levels (%)**				
	0%	**33%**	**66%**	**100%**	**133%**
0	322	360	379	387	394
50	322	368	405	417	417
100	322	370	408	425	427

Appendix 9: Long-term simulation data (1986-1995)

Monthly means (1986)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	16.8	25.8	8.6	0	0
2	15.1	26.1	9.1	0	0
3	15.8	26.4	8.8	69.6	9
4	16.4	23.6	12.9	124.2	18
5	15.6	22.9	13.3	38.2	12
6	13.7	22.5	11.9	130.8	14
7	14.5	20.8	10.3	69.1	7
8	16.7	24.2	9.8	8.4	3
9	16.9	24.9	10.8	66.5	8
10	11.2	25.2	9.8	91.2	15
11	12.3	23.8	10.7	189.3	20
12	13.5	23.8	10.5	77.0	14

Monthly means (1987)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	22.4	26.0	8.4	25.1	6.0
2	23.9	28.3	8.0	11.4	5.0
3	23.4	28.8	9.3	30.6	11.0
4	22.4	26.6	10.6	95.3	20.0
5	22.0	23.6	13.7	53.8	10.0
6	20.4	23.4	11.8	133.1	11.0
7	20.3	24.4	10.4	24.3	1.0
8	22.4	24.2	11.5	10.8	4.0
9	23.0	27.1	11.0	18.1	10.0
10	22.6	27.0	12.3	53.0	11.0
11	22.6	24.4	12.9	215.3	18.0
12	22.1	24.9	8.9	90.5	7.0

Monthly means (1988)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	15.4	26.3	8.5	41.3	5
2	17.1	27.4	9.2	73.1	8
3	15.4	26.3	10.3	174.1	12
4	14.1	24.1	13.2	156.1	21
5	16.4	23.4	13.3	21.6	8
6	16.4	23.2	12.6	105.8	0
7	15.4	22.2	11.9	122.7	12
8	16.7	23.0	12.5	45.3	8
9	16.9	24.6	13.1	47.9	10
10	15.3	25.3	11.1	80.9	18
11	11.8	22.2	10.9	59.5	22
12	13.6	23.5	9.6	155.8	11

Monthly means (1989)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	16.2	25.0	9.3	53.8	5
2	17.2	25.6	7.0	63	8
3	16.5	27.0	8.6	29	12
4	13.5	24.2	11.65	98.2	21
5	16.5	24.1	12.2	32.5	8
6	17.1	24.4	11.5	0	0
7	15.5	22.9	11.2	81.5	12
8	17.3	23.3	11.2	47.1	8
9	15.3	24.8	11.7	39.5	10
10	15.8	24.2	12.0	92.2	18
11	12.7	22.9	12.1	230.8	22
12	14.9	24.4	11.3	66.2	11

Monthly means (1990)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	17.6	24.7	7.9	74.5	12
2	15.8	26.4	9.7	46.1	13
3	15.0	24.9	11.2	127.3	21
4	16.1	24.4	12.0	114.6	20
5	18.3	24.7	12.4	41.6	10
6	18.8	24.2	11.2	6.5	2
7	17.6	24.1	10.2	24.3	7
8	17.3	23.3	11.3	9.4	3
9	18.4	25.9	11.4	7.3	3
10	15.3	24.9	11.6	80.6	14
11	14.2	23.4	10.4	96.2	18
12	16.6	23.8	9.8	74.5	11

Monthly means (1991)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	18.8	26.9	7.6	16.0	5
2	19.6	28.0	7.1	30.1	5
3	17.1	27.8	8.6	92.7	9
4	16.1	25.5	10.9	95.2	12
5	16.2	24.4	13.6	17.7	9
6	16.0	24.9	12.1	103.4	27
7	13.9	21.9	11.6	8	3
8	16.0	24.3	10.8	78.6	10
9	16.9	25.5	10.2	0	0
10	14.3	25.6	10.6	83.0	16
11	13.8	23.8	9.6	91.4	15
12	15.3	24.9	9.9	50.6	10

Monthly means (1992)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	16.4	26.8	8.1	35.7	9
2	18.1	28.6	8.0	17.8	3
3	16.3	28.5	9.7	49.0	6
4	15.1	26.7	12.4	99.7	12
5	15.6	24.7	12.7	19.3	5
6	15.8	24.9	11.8	5.2	1
7	16.1	23.5	11.5	8.9	2
8	16.7	23.1	11.1	10.7	8
9	17.4	24.8	11.6	66.7	11
10	15.1	25.2	11.8	75.6	21
11	14.1	24.3	10.3	148.8	18
12	14.6	24.2	11.1	146.8	21

Monthly means (1993)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	14.7	23.8	11.0	213.7	25
2	17.1	26.4	7.8	87.5	13
3	18.7	27.8	6.6	38.6	7
4	15.6	25.3	10.4	84.7	11
5	16.6	24.9	12.5	90.4	15
6	16.4	23.8	12.5	32.3	6
7	16.5	22.5	11.0	0	0
8	17.3	24.6	11.0	12.3	3
9	18.1	26.0	10.9	31.6	5
10	16.4	26.5	11.6	65.2	10
11	15.0	24.6	5.4	117.2	16
12	15.7	25.6	10.4	48.3	9

Monthly means (1994)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	18.9	28.3	6.9	3.1	1
2	19.5	28.9	7.0	38.2	4
3	16.5	28.7	9.4	26.1	5
4	16.1	26.2	13.2	206.8	16
5	16.2	23.7	13.0	60.8	7
6	17.6	25.2	11.9	47.5	8
7	15.7	23.4	11.3	24.2	4
8	16.8	23.6	11.0	57.2	10
9	18.8	25.9	12.6	8	3
10	15.0	26.2	10.0	99.4	12
11	14.1	24.6	9.6	155.2	21
12	16.3	25.1	10.1	60.3	14

Monthly means (1995)

Month	SRAD MJ/M2	Tmax Oc	Tmin Oc	Total rain (mm)	No of wet days
1	19.2	28.0	7.6	13.9	4
2	18.0	28.2	7.8	55.5	7
3	16.5	26.8	10.4	142.7	16
4	16.5	26.2	12.1	117.5	12
5	16.4	24.6	13.0	70.2	6
6	17.1	26.9	11.6	28.0	4
7	15.8	23.5	11.4	71.6	10
8	18.3	24.3	11.8	10.6	3
9	17.1	25.2	12.4	70.3	8
10	14.4	24.7	12.2	73.9	9
11	14.5	25.0	11.6	103.0	12
12	14.8	24.1	9.2	166.8	18