EVALUATION OF CENTRE PIVOT SPRINKLER IRRIGATION SYSTEM PERFORMANCE AND ITS EFFECT ON SUGAR CANE YIELD AT KAGERA SUGAR ESTATE

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BY

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (IRRIGATION ENGINEERING AND MANAGEMENT) OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

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ABSTRACT

Centre pivot irrigation is a medium to low pressure sprinkler system capable of irrigating large circular areas. It consists of a galvanised steel lateral supported by "A" - shaped frame mounted on powered wheels. It rotates about a fixed point at the centre of the irrigated field. The study evaluated the performance of a centre pivot spray nozzle irrigation system and its effects on sugarcane yield at Kagera Sugar Estate, Tanzania. The specific objectives were to assess: (i) the performance of the centre pivot spray nozzle sprinkler system (ii) soil parameters that influence cane yields and (iii) irrigation water quality. High and low yielding areas were represented by centre pivot GP7 and BP5. The results showed that low yields were contributed by poor performance of centre pivots and soil parameters. Centre pivot GP7 had average coefficient of uniformity (CU) of 96.91% while it was 86.28% for BP5; average distribution uniformity (DU) of 95.1% and 78.23%; average potential application efficiency (PELQ) of 86.83% and 79.14%; average application efficiency (AELQ) of 64.97% and 59.36%, respectively. The minimum recommended values for CU, DU, PELQ, and AELQ were 85%, 75%, 90%, and 85%. The performance parameters for GP7 were within the recommended values except AELQ and PELQ which was lower than the recommended value. The PELQ and ALQ for BP5 were lower than the recommended value. In general, the performance parameter estimated for GP7 were higher than for BP5 as the result of differences in sugarcane yield. For instance, fields under GP7 and BP5 had average yields of 123 and 74 tonnes per hectare respectively. Soil parameters that contributed to low yield were low water holding capacity, low cation exchange capacity; high acidity; poor structure and compaction by farm machinery. Irrigation water quality was high that could not contribute to low yield.

DECLARATION

I Paul Reuben, do hereby declare to Senate of Sokoine University of Agriculture that the work presented here is my original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

16/11/2010

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15/11/2010

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This work is dedicated to my wife E. Ernest whose love before and after starting my research work was uniform.

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ABBREVIATIONS AND SYMBOLS

*	-	Multiplication
Σ	-	Summation
AELQ	-	Application Efficiency of Low Quarter
BP5	-	Centre Pivot Number 5 in the field located in Area B
C	-	Carbon
CEC	-	Cation Exchange Capacity
CP	-	Centre Pivot
CU	-	Coefficient of Uniformity
D	-	Application rate (mm/day)
DU	-	Distribution Uniformity
ECe	-	Electric Conductivity of the soil
ECw	-	Electrical Conductivity of water
ER	-	Efficiency Reduction
ESP	-	Exchangeable Sodium Percentages
ET	-	Evapotranspiration
GP7	-	Centre Pivot Number 7 in the field located in Area G
KSL	-	Kagera Sugar Limited
LAC	-	Low Activity Clay
MAD	-	Management Allowable Deficit
ml	-	millilitre
PELQ	-	Potential Application Efficiency of Low Quarter
SAR	-	Sodium Adsorption Ratio
SMD	-	Soil Moisture Deficit
SOC	-	Soil Organic Carbon
LEPA	-	Low Energy Precision Application
SOM	-	Soil Organic Matter

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Irrigation systems can be very simple and also very complex like the mechanized sprinkler ones. The introduction of automation in irrigation systems has increased the application efficiencies and drastically reduced labour requirements. Nowadays, the most commonly used systems around the world are the centre pivot sprinkler system. In a survey carried out in 1997 by Kincaid (1997), it was found that nearly one - third of the irrigated land in the United States was irrigated by centre pivots.

In Sub Saharan African countries, the use of centre pivot irrigation systems has increased over the years particularly in South Africa and Zimbabwe (Kincaid *et al.*, 2000; DeBoer *et al.*, 2000). Surface irrigated areas are gradually being converted to sprinkler irrigation, primarily centre pivots, due to labour and water quality concerns (Heermann, 1990).

In Tanzania, centre pivot irrigation systems have recently been introduced. However, only three sugar estates have been able to install this system; these are Kagera, Mtibwa and Kilombero Sugar Estates. One of the reasons of less popularity of centre pivots in Tanzania is due to high investment costs.

In centre pivot irrigation as other types of pressurized irrigation, one has to ensure that an adequate water depth over the field with a minimum runoff is applied. To avoid runoff problems, it is necessary to have a good understanding of soil infiltration characteristics when designing and managing centre pivot irrigation systems. Runoff problems also tend to increase when irrigation systems with high-water application rates are used (Silva, 2007).

Centre pivots are useful not only for irrigation but also for applying nutrients and chemicals to the crop via fertigation and chemigation. Advances in sprinkler technology for mechanized irrigation have answered many of the previous challenges. Today a farmer can apply water and chemicals with precise uniformity and high irrigation efficiency (Nelson Irrigation Corporation, 2004). The improvements in irrigation efficiency, uniformity, and the control of runoff illustrate major technological advancements with centre pivots.

Climate change in the world has caused water resources to be scarce thus, it has to be utilised in such a manner as to protect and conserve the available water reserves. In agriculture, water conservation will have to be obtained through the effective management of water application (Pereira, 1999; Turral *et al.*, 2010). Therefore, irrigation systems will have to apply water in the most efficient way possible to prevent unnecessary losses and water wastage. In order to achieve this, the uniformity and other design parameters with which the irrigation system applies water, will have to be appropriate. The distribution uniformity of a system has an effect on the system's application efficiency and on the crop yield (Letey *et al.*, 1984; Solomon, 1984; Letey, 1985; Solomon, 1990; cited by Ascough and Kiker, 2002). Irrigation systems with poor distribution uniformity experience reduced yields due to water stress and/or water logging. Poor distribution uniformity also has increased financial and environmental costs. Nutrients can be leached out of the soil due to excess water being applied to overcome poor irrigation uniformity. This will increase fertiliser costs and pumping costs, and may have environmental impacts if the excess runoff and deep percolation are contaminated with nutrients (Solomon, 1990).

The distribution uniformity of different types of irrigation is influenced by different factors that are characteristic of the particular system. Surface irrigation is influenced primarily by soil intake characteristics. Overhead irrigation is influenced by the condition of sprinkler packages, strength and direction of the wind (Burt *et al.*, 1997) and the pressure variation within the system. These factors need to be correctly managed to ensure that the distribution uniformity is at an acceptable level. This will ensure optimal use of water resources.

1.2 Problem Statement and Justification

Kagera Sugar Estate uses a modern centre pivot spray nozzle sprinkler irrigation system which applies water to meet the crop evapotranspiration rate of 6 mm/day as well as uniform agronomic practices. However, yield of sugarcane has varied from one area to another. For example some areas of this estate have produced an average yield of 120 tonnes of sugarcane per hectare while others have given low yield of less than 80 tonnes per hectare. This shows that there are some problems in the production of sugarcane at Kagera Sugar Estate. By evaluating the performance of Kagera Sugar Estate, the reasons of low yield of sugarcane in the field were established. Also anomalies in water distribution due to poor maintenance of regulating valves (that cause poor operating pressure and water application) and wind drift were identified.

1.3 Objectives

1.3.1 Overall Objective

This study was therefore initiated and the main objective was to evaluate the centre pivot spray nozzle sprinkler irrigation system at Kagera Sugar Estate and its effects on sugar cane yield.

1.3.1 Specific Objectives

The specific objectives of the study were to:

i) Assess the performance of centre pivot spray nozzle sprinkler system;

ii) Assess soil parameters that influence cane yield; and

iii) Assess irrigation water quality

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Centre Pivot System Description

The centre pivot system is classified as a medium to low pressure sprinkler system capable of irrigating large circular areas. It consists of a single galvanised steel lateral which rotates about a fixed point (Plate 1) in the centre of the irrigated field (Kranz *et al.*, 1992). The lateral, equipped with spray or impact sprinklers, consists of 40 to 50 m long spans, each supported above the crop with as much as 3 m clearance by A-shaped steel frames (towers) mounted on powered wheels (Plate 2). Steel cables or trusses between the towers provide the strengthening support to the system. Starting from the pivot point, each additional span irrigates a larger area than the previous one (Lalouette *et al.*, 1998). Therefore, for economic design centre pivots are reasonably long.

Plate 1: Pivot point of a centre pivot

Plate 2: A-shaped steel frames (towers) mounted on powered wheels

Modern centre pivot systems are driven by hydraulic system. The system uses hydraulic oil which is pumped by electric motor installed at the pivot point. Hydraulic tubes for oil transmission run from the centre of the pivot connecting each wheel set to the last span wheel set. The rotary speed of a pivot can be adjusted to meet the crop water requirements. The slower the lateral moves, the more water is applied. The movement of the system and the depth of irrigation applied are controlled by regulating the speed of the outer most towers (Lalouette *et al.*, 1998).

The advance of the last tower sets the other towers into motion one after the other by a system of sensors located on each tower and which is activated when the angle between the spans exceeds a pre-set limit.

The sensor at each tower switches off again once a pre-set angle in front is reached. These sensors acts as safety devices which stop the machine automatically whenever there is any malfunctioning (Evans, 2001).

2.1.1 Centre pivots equipped with spray nozzles

Spray nozzles are water distribution devices equipped with a stationary, rotating or oscillating deflection pad (Plate 3) used to distribute water in 180 to 360 degree circles (Kranz and Martin, 2005).They are low pressure spray nozzle sprinklers having a fixed-head and a full circle application pattern.

A deflection plate creates spray by deflecting the water jet exiting the nozzle. Water leaves the smooth plates as a mist-like spray and leaves grooved plates as tiny streamlets. The sprinklers are mounted upside-down on drop tubes that extend below the lateral; they have a smaller wetted area than impact sprinklers and require closer sprinkler spacing. The smaller wetted area greatly increases application rates along the centre pivot system (King and Kinkaid, 1997).

2.1.2 Centre pivots equipped with impact sprinklers

Impact sprinklers are water application devices equipped with one or two nozzles and an impact arm to cause sprinkler rotation (Plate 4) and water stream breakup (Kranz and Martin, 2005). This is one of the most popular irrigation systems. Sprinkler outlets are installed on the top of a pipe supported by steel trusses between adjacent tower structures (Evans, 2001). Centre pivot irrigation systems with impact sprinklers operate in the range of pressures. These sprinkler sets provide good application uniformity when the system nozzles are properly sized and pressure variation along the lateral is within recommended limits though there is a high water loss from wind drift and evaporation (King and Kinkaid, 1997).

Plate 3: Centre pivot equipped with spray nozzles.

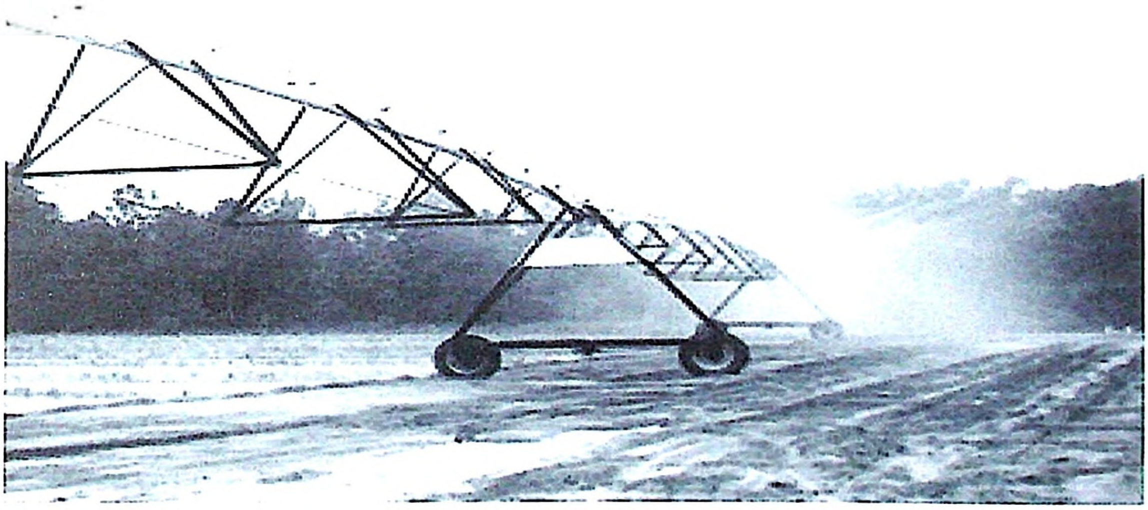

Plate 4: Centre pivot equipped with impact sprinklers.

2.1.3 Comparison between spray and impact sprinklers

Spray nozzle sprinklers are mounted upside-down on drop tubes (Plate 3) that extend below the lateral (King and Kinkaid, 1997) while in case of impact sprinkler (Plate 4) outlets are installed on the top of the lateral (Evans, 2001). Spray nozzle sprinklers operate in low pressures whereas impact sprinklers can be operated over a wider range of pressures (Kranz and Martin, 2005). Water leaves the spray nozzle sprinkler in smooth plates as a mist-like spray (Plate 3) whereas in impact sprinklers, water leaves the nozzle in large water droplets (Plate 4). Spray nozzle sprinklers have a smaller wetted area than impact sprinklers and require closer sprinkler spacing. This increases application rates in spray nozzle sprinkler along the centre pivot system than in impact sprinklers centre pivot (King and Kinkaid, 1997).

2.0 Factors Influencing Sprinkler Performance

Sprinkler performance is influenced by several factors, such as application rate, nozzle size and operating pressure, sprinkler spacing, evaporation and wind. These are briefly discussed in the following sections.

2.2.1 Application rate

The amount of water received by soils at a particular point during irrigation in one revolution of the centre pivot is the net application rate. It is an important parameter that is used in design and evaluation of sprinkler irrigation system to properly match sprinklers to the soil, crop, and terrain on which they operate (Melvyn, 1988 cited by Magongo, 1995). For centre pivot irrigation, the application rate is the amount of water discharged at a point in one revolution, for example, if the amount discharged is 6 mm, and the centre pivot completes one revolution per day, then the application rate will be 6 mm/day. According to Ross (1997), the net application rate can be determined as follows:

$$d_n = \frac{d_g \times t \times E_q}{h} \quad (1)$$

Where

d_n = net application rate (mm);

d_g = gross application (mm);

t = time of centre pivot operation per day (hours);

E_q = Application efficiency of low quarter; and

h = time taken to complete one revolution (hours).

The optimum application rate of centre pivot spray sprinkler irrigation system depends on the design. For instance, if the irrigation interval is one day, then the minimum net application should be equal to crop evapotranspiration in order to meet the minimum crop water requirements.

2.2.2 Nozzle size and operating pressure

Pressure and nozzle size control the drop size distribution from a spray nozzle sprinkler and drop size influences the application rate pattern. Changing the operating pressure can affect the design application rate. The operating pressure can be determined by pressure gage installed within the system (Keller and Martin, 2000).

Generally, nozzle sizes are small near the pivot base and gradually increase in size and discharge as the radius increases. On very long systems, the largest nozzles may not have enough flow capacity and two or more sprinklers must be installed or the system flow requirements reduced and system pressure increased (Evans, 2001). The design sizes of nozzles for spray sprinklers depends on sprinkler set employed (Nelson Irrigation Corporation, 2009).

2.2.3 Sprinkler set and spacing

Modern centre pivots use spray sprinklers which have a smaller wetted area than impact sprinklers and require closer spacing. The smaller wetted area greatly increases application rates along the centre pivot system (Nelson Irrigation Corporation, 2009). Centre pivot sprinkler size increases from the pivot point outwards due to the increase of speed of the centre pivot; thus the centre pivot moves faster in the outer spans than in the inner spans. There are a number of sprinkler set such as Nelson's 3000 series pivot products, these are R3000, S3000, N3000, D3000, A3000, T3000 (Nelson Irrigation Corporation, 2009). The advantage of 3000 series is that it is easy to change the sprinkler set, thus it gives the best configuration. Table 1 shows different nozzle sets with their characteristics. The table helps in selection of proper sprinkler type depending on system pressure, application rate and the relative throw diameter requirements.

For a given wind condition, among others, sprinkler spacing is the primary factor affecting uniformity of water application. For a centre pivot system, there is one spacing dimension that is the distance between sprinklers on a lateral (Solomon, 1990). Due to this, centre pivots are required to operate as close as possible to the design parameters so as to attain the required uniformity and to cover the required wetted perimeter (Tarjuelo, *et al.*, 1999).

Table 1: Different nozzle sets with their characteristics

> 3000 series		Nozzle Type	Operating Pressure	Application Rate	Relative Throw Diameter
R3000	Rotator	3TN	1-3.4 bar	Low	15.2-22.6 m
S3000	Spinner	3TN	0.7-1.4 bar	Low -Medium	12.8-16.5 m
N3000	Nutator	3TN	0.7-1 bar	Low -Medium	13.4-15.9 m
D3000	Spray head	3TN	0.41-2.8 bar	High	4.9-12.2 m
A3000	Accelerator	3TN	0.7-1 bar	Medium	9.1-14.0 m
T3000	Trash buster	3TN or 3000 FC	Depends on sprinkler selection	Low -High	Depends on sprinkler selection

Source: Nelson Irrigation Corporation (2009).

Description of different spray sprinkler nozzle sets

The R3000 Rotator features the greatest throw distance available on drop tubes. The wide water pattern from rotating streams equates to lower average application rates, longer soak time and reduced runoff. More overlap from adjacent sprinklers improves uniformity.

The S3000 Spinner utilizes a free spinning action to produce a gentle, rain-like water pattern. It is designed for more sensitive crops and soils, low instantaneous application rates and reduced droplet kinetic energy help to maintain proper soil structure.

The N3000 Nutator combines a spinning action with a continuously offset plate axis for a highly uniform pattern even in the wind. Larger, wind penetrating droplets and low trajectory angles reduce wind exposure for maximum application efficiency.

The D3000 Spray head is a fixed spray designed with future needs in mind. As irrigation requirements change throughout the season, the D3000 features a flip-over cap to change spray patterns. The D3000 is easily convertible to LEPA or other 3000 Series sprinklers. The A3000 Accelerator maximizes performance of in-canopy water application. It is designed as a hybrid of Rotator and Spinner technology, the accelerator increases rotation speed through the nozzle range.

The T3000 Trash buster features an open-architecture body design to pass debris more easily. Available with the 3000 FC, a plug resistant, flow compensating sprinkler package can simplify maintenance (Nelson Irrigation Corporation, 2004).

2.2.4 Evaporation

Field comparisons indicate that there is 20 to 25 percent more water loss from sprinkler above- crop-canopy irrigation than from spray nozzle sprinklers within-crop-canopy centre pivot systems (New and Fipps, 1996). Techniques used to measure these losses are mass balance, electrical conductivity, and placement of catch devices (Thompson *et al.*, 1993). Wind speed is among the factors responsible for high evaporation rates, thus causing more non - uniform application of water, which in turn, affects application rates of the sprinklers as well as irrigation efficiencies.

2.2.5 Uniformity of application

The uniformity of application for centre pivot sprinkler irrigation system is affected mainly by pressure. It is also affected by wind (King *et al.*, 1997) and the speed of the centre pivot system at the end drive unit (Evans, 2001).

i) Pressure Effects

Each sprinkler is designed to operate within a range of water pressures. Typically, impact sprinklers can be operated over a wide range of pressures compared to low pressure spray nozzles (Kranz *et al.*, 2005) which are more limited to low pressure.

Changing the operating pressure can affect the design application rate. With low pressure, the application amount is reduced and vice versa. The application amount will remain the same if the flow rate and travel speed of the centre pivot are not changed. The desirable pressure head depends upon the cost of power, area to be covered, type of the sprinkler used, sprinkler spacing and the type of crops being irrigated (Hansen and Israelson, 1979). For centre pivot irrigation, system pressure can be read from the system pressure gauge that is installed at the pump station and at the pivot point. Pressure variations throughout the system cause the overall efficiency of the system to be lower than the efficiency in the test area. An estimate of the efficiency reduction (Eq. 2) can be calculated from the maximum, minimum, and average system pressures by the equation given by Merriam and Keller (1978) as follows:

$$ER = \frac{0.2 \times (M_a - M_i)}{P_{av}} \tag{2}$$

Where

ER = efficiency reduction (Kpa);

M_a = Maximum pressure (Kpa);

M_i = Minimum pressure (Kpa); and

P_{av} = Average system pressure (Kpa).

The ratio of the average low quarter sprinkler discharges to the average sprinkler discharge in the system is approximately equal to 1 – ER. Therefore, according to Magongo (1995), the system PELQ can be approximated as follows:

$$\textit{System PELQ} = (1 - ER) \times \textit{test PELQ} \tag{3}$$

Where

PELQ= Potential Application Efficiency of Low Quarter (%); and

ER= Efficiency Reduction

ii) Wind Effects

Wind distorts the application rate pattern and affects irrigation uniformity of sprinklers. Computer simulation of composite wind-affected application rate patterns under a centre pivot indicates that application uniformity is not significantly reduced for wind speeds up to 15 km/h due to the multiple sprinkler overlap required to obtain good uniformity with low- pressure sprinklers and to a limiting sprinkler height of about 1.8 m (King *et al.*, 1997).

2.3 Operation of Centre Pivot

2.3.1 Centre pivot speed at the end drive unit

Centre pivot speed can affect irrigation uniformity, application amount as well as irrigation efficiencies. In general, the tower farthest from the pivot point controls the speed of the entire machine which is the basis of proper system performance. According to Evans (2001) the rotation hours are commonly between 14 and 20 hours (2 to 3 m/min at the outer tower). The irrigator controls the speed of the centre pivot depending on the irrigation water requirement whereas the minimum application amount is equal to the local crop evapotranspiration (ET) of the crop being irrigated (Phocaides, 2007).

In order to attain good uniformity throughout, the irrigator must be moving in the normal speed throughout the test by setting the required speed at the control panel (Smith, 2007). During the installation of the system, the calibration of the centre pivot speed should be done in order to check if the actual system speed agrees with the one set at the control panel.

2.3.2 Time per revolution

Time per revolution for a centre pivot is the time taken by a system to complete one cycle. The design irrigation interval can also determine how long the system will take to complete one revolution depending on the type of the crop, climatic factors, soil characteristics, topography, and water availability.

According to Merriam and Keller (1978), the time per revolution for centre pivot irrigation can be estimated by using the following formula:

C (4)

Where

T = Time per revolution (hours);

C = Circumference to the end radius (mm); and

S = Set speed (mm/hour).

The time taken by a centre pivot to complete its cycle is a measure of its speed set at the end drive unit. It is an important factor for decision making on water application rate and irrigation interval.

2.4 Performance of Centre Pivot

The performance of centre pivot sprinkler irrigation system can be quantified by application efficiency, potential application efficiency, distribution uniformity and uniformity coefficient. These are briefly discussed in the following sections.

2.4.1 Application Efficiency of Low Quarter (AELQ)

Application efficiency of low quarter (AELQ) achieved in the field indicates how well the irrigaition system is being used (Merriam and Keller, 1978). AELQ is defined as follows:

$$AELQ = \frac{d_{lq}}{d_{av}} \times 100 \qquad (5)$$

Where

AELQ = Application Efficiency of Low Quarter (%);

d_{lq} = Average low quarter depth of water stored in the root zone (mm); and

d_{av} = Average depth of water applied (mm).

When the average low quarter depth of irrigation water infiltrated exceeds soil moisture deficit, which is the storage capacity of the root zone. The recommended AELQ is at least 90% (Evans, 2001) and it is expressed as follows (Merriam and Keller, 1978):

$$AELQ = \frac{SMD}{d_{av}} \times 100 \quad (6)$$

Where

SMD = Soil Moisture Deficit (mm).

2.4.2 Potential Application Efficiency (PELQ)

The PELQ is a precise measure of AELQ when the low quarter depth of water infiltrated is just sufficient to satisfy the soil moisture deficit (SMD). This is when SMD is equal to MAD in all parts of the field (Merriam and Keller, 1978). It can be calculated using the equation by Merriam and Keller, (1978). The recommended system potential application efficiency for centre pivot with spray sprinklers is at least 90% (Savva and Frenken, 2002). The equation is as follows:

$$PELQ = \frac{d_{lq}}{d_{av}} \times 100 \quad (7)$$

Where

PELQ = Potential application efficiency of the low quarter (%);

d_{lq} = Average low quarter depth caught (mm); and

d_{av} = Average depth of water applied (mm).

2.4.3 Distribution uniformity (DU)

Centre pivot irrigation systems have been largely assumed to be properly operating if the pivot point pressure and flow rate are set at the design operating specifications. Routine evaluation of the centre pivot sprinkler packages are seldom performed after installation (Rogers *et al.*, 2005).

Normally, catch cans are used to determine DU. Containers are placed so that water from a complete pass of the centre pivot is collected (Rogers *et al.*, 2005). The distribution uniformity coefficient (DU) can be calculated based on the equation by Merriam and Keller (1978):

$$DU = \frac{d_{lq}}{d_w} \times 100 \qquad (8)$$

Where

DU = Distribution Uniformity (%);

d_{lq} = average weighted low quarter catch (mm); and

d_w = average weighted system catch (mm).

According to Ascough and Kiker (2002), the distribution uniformity for centre pivot systems should be at least 75%.

2.4.4 The Coefficient of Uniformity (CU)

The coefficient of uniformity (CU) is a measure of the average absolute deviation from the average irrigation amount (Delirhasannia *et al.*, 2010). It can be calculated from the amount of water collected in each catch can after the irrigation system has completely passed over the aligned catches (Dechmi *et al.*, 2003). The catch cans experiment is used to quantify how close the system is to a theoretical ideal in which all cans would contain exactly the same amount of water (McCann and Adkins, 2007).

The uniformity coefficient can be calculated using the formula by James *et al.* (1982):

$$CU = \frac{1 - \sum X}{M \times N} \times 100 \qquad (9)$$

Where:

CU = the Coefficient of Uniformity (%);

X = absolute deviation of the individual observations from the mean (mm);

M= mean depth of observation (mm); and

N= number of observations.

Another way of finding the Uniformity coefficient is to use the relationship between uniformity coefficient and the distribution uniformity (Markley and Allen, 2002), that is:

$$Cu = 100 - 0.63(100 - DU) \quad (10)$$

Where

CU = Christiansen's Coefficient of Uniformity (%); and

DU = the distribution uniformity (%).

According to Harrison and Perry, (2010) the coefficient of uniformity recommended for spray nozzle sprinkler centre pivots should be at least 85%.

2.5 Soil Properties

Soil is an unconsolidated mass of organic and inorganic material, water and air. Inorganic material is measurably different from its parent material in physical and chemical properties that exhibits layering. Soil is formed from the weathering processes of the parent material caused by weathering agents for example rainfall, wind, temperature. Weathering processes alter the physical and chemical properties of parent material (Lemke, 2002). Soil properties are divided into physical and chemical properties as discussed in the following sections.

2.5.1 Physical properties

Soil physical properties influence rooting depth and volume, they also affect nutrient availability and plant growth. Physical properties also provide information related to the soil's ability to withstand physical forces associated with splashing raindrops or rapid water entry into soil that contribute to aggregate breakdown, soil dispersion, and erosion (Andrews *et al.*, 2002).

i) Soil Organic Matter

Organic matter is the most important of all the components that make up the soil. Organic matter plays a major role in moisture retention, helping crops withstand drought, contributes to the chemical and biological properties of the soil. It is also a source of and exchange site for nutrients that affect the fate of applied pesticide and contributes to the physical properties of the soil organic matter that provide glue-like substances that act to stick individual particles together to form stable aggregates and good soil structure (Ontario, 2009). Due to its properties, soil organic matter minimizes runoff of water from irrigated fields and hence increases water availability to plants.

ii) Bulk Density

Bulk density is the weight of soil (oven dry) per unit volume. Volume is measured when the soil is at field moisture capacity (Arkansas, 2002). Weight is determined after drying the soil at 105°C. The estimated moist bulk density of each major soil horizon is expressed in grams per cubic centimetre of soil material that is less than 2 millimetres in diameter. Bulk density data are used to compute shrink-swell potential, available water capacity, total pore space, and other soil properties. The moist bulk density of soil indicates the pore space available for water and roots (Yildirim *et al.*, 2006).

Bulk density of un-disturbed soil sample can be measured in the laboratory by drying the soil sample in the oven at (105 - 110) °C for 24 hours and cool it to ambient temperature in desiccators, then measure its weight (Moberg, 2001). Finally the bulk density can be calculated using the following formula:

$$\rho = \frac{M_d}{V} \tag{11}$$

Where

ρ = Bulk density (g/cm^3);

M_d = mass of the oven dry soil (g); and

V = volume of the core (cm^3).

Bulk density of the soil is important in determining the application rate in sprinkler irrigation. When the bulk density of the soil is small, it implies that the soil has large pore spaces as the result of increase soil water storage capacity, reduced water runoff and increased infiltration rate.

iii) Particle Size Distribution

Soil texture refers to the relative proportion of sand, silt and clay size particles in a sample of soil. Clay size particles are the smallest being less than 0.002 mm in size. Silt is a medium size particle falling between 0.002 mm and 0.05 mm in size. The largest particle is sand with diameters between 0.05 mm for fine sand to 2.0 mm for very coarse sand (Rossela *et al.*, 2006). Soils that are dominated by clay are called fine textured soils while those dominated by larger particles are referred to as coarse textured soils (Skaggs *et al.*, 2001). Soil scientists, group soil into soil texture classes.

The larger the soil particle size, the better the drainage will be therefore the higher the application of irrigation water will be needed. On the other hand, very fine particles (clay and silt) tend to drain poorly, but hold more water in the soil system (Karlen *et al.*, 1997). Some methods which are used to measure soil texture are sieve analysis method and Bouyoucous hydrometer method (Day, 1965).

iv) Infiltration

Infiltration is the entry of water through the air – soil interface into the soil profile. This is very essential to irrigation systems design (Magongo, 1995). It is the infiltration capacity of the soil that can determine the rate that water can be applied in the soil without run off. The basic infiltration rate can be used to describe different soil types from an irrigation point of view because infiltration rate depends on sol texture and soil structure (Silva, 2007). The larger the soil particles and the longer the pores, the higher is the infiltration rate.

The infiltration rate can be measured by ring infiltrometer in the field. It consists of a metal cylinder that should be driven in the soil. It can contain single or double rings. According to Merriam *et al.* (1980) the cylinder should have a diameter of 150 mm, 310 mm high, and a wall thickness of 30 mm.

2.5.2 Chemical properties

Soils support a number of inorganic and organic chemical reactions. Many of these reactions are dependent on some particular soil chemical properties. One of the most important chemical properties influencing reactions in a soil is pH (Astaraei, 2008); others include soil salinities, sodicity, and other soil nutrients.

i) Soil pH

Soil pH is a measure of how acidic or alkaline the soil is. Soil pH is measured on a scale of 1 to 14. For instance, if the soil has a pH value of less than 7 then the soil is acidic. On the other hand if the soil has a pH value of greater than 7 then it is alkaline. A pH value of 7 is neutral, meaning the soils neither acidic nor alkaline (Harris, 2005).

The pH in the soil has both direct and in direct effects on crops, in case the soil is too acidic or too alkaline there can be toxic effects on the plants themselves and an unfavourable balance between acid and alkaline elements needed by plants (Harris, 2005). Also soil acidity can have an effect on one or more of availability of essential elements, activity of soil microorganisms, solubility and potency of toxic elements and prevalence of plant diseases.

Soil acidity can be due to rainfall and leaching, acidic parent material, organic matter decay, and harvest of high yielding crops. Soil is said to be acid when there is an abundance of acidic cations, like hydrogen (H^+) and aluminium (Al^{3+}) present compared to the alkaline cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+) (Johnson, 2002).

Soil pH can be measured in the laboratory by pH meter (Moberg, 2001). This method consists of placing of the electrodes in the soil suspension that influence both pH measured and the stability of measurement.

The analytical procedure for measurement of soil pH using pH_{H2O} is by weighing 10.00 g of soil on laboratory balance and placed into 100 ml broad necked plastic bottle. Then 25 ml of water are added by dispenser or pipette. Close the bottle and shake the content for 30 minutes. After settlement of the suspension measure its pH by placing the glass electrode in the suspension and the reference electrode in the clear solution above. If a combined electrode is used, place as far as possible, the glass electrode in the suspension and the reference part of the electrode, so that the outlet of the salt-bride is located in the clear solution above (Moberg, 2001).

ii) Soil Salinity

Salinity is the accumulation of salts into the root zone to the level that it affects crop yield (FAO, 1985). Salinity is the sum of all ionized dissolved salts in the soil water without specific references to ions present (James, 1988). Salts occur in the soil in one of the following three forms: salt ions dissolved in the soil water, cations adsorbed on the negatively charged surface of the soil particles and precipitated salts (Smedema, 1990). The main salt ions found in the soils solution of salty salts include the following cations: potassium, sodium, calcium and magnesium. Anions include, chloride, sulphate, carbonate, bicarbonate and nitrate (FAO, 1985). Sodification involves the replacement of other cations on the adsorption complex by sodium. Significant replacement only occurs when sodium becomes the dominant soluble cations in the soil solution. This may occur when the salinizing source is sodium rich or when for other reasons the salinization process favours accumulation of sodium (FAO, 2000). When irrigated fields are properly designed, sprinkler irrigation leaches out salts, as the result soils remain good for plant growth. However poor drainage system of the land can increase salinity problems.

iii) Saline Soils

Saline soils have electric conductivity (ECe) higher than 4 decisiemen per metre (dS/m) at 25°C, exchangeable sodium percentages (ESP) lower than 15, and a pH generally below 8.5. Such quantities affect adversely crops. White salt crusts may be found on the soil surface, main anions being chloride, sulphate and to a lesser extent bicarbonates and nitrates. Insoluble carbonate and sulphate may be present (FAO, 2000). The range that affects crop growth is shown in Appendix 7.

iv) Saline Sodic Soils

These have ECe higher than 4dS/m at 25oC, ESP higher than 15, pH seldom higher than 8.5. crop growth is seriously impeded. Soil structure is usually fair but may deteriorate on leaching. The soil may then become strongly alkaline (Moberg, 2001). The soil particles will disperse and the permeability diminishes markedly and suitability for tillage is reduced.

The ECe can be measured in the laboratory by soil/ water extract suspension, the best soil water ratio is 1:1, the higher the water/soil ratio may be used, the higher the risk that peptization, hydrolysis, cation exchange and mineral dissolution could occur (Moberg, 2001).

The analytical procedure for measurements is by weighing 40.00 g soil on a laboratory balance to a 100 ml plastic bottle with a wide neck; add 40 ml water by use of pipette. Close the bottle and shake the suspension for 1 hour in a shaker. Remove the cap and centrifuge at 5000 - 6000 rpm for 10 minutes. Decant the clear solution into another 100 ml plastic beaker, then measure the EC in the decanted solution, use a dry electrode. Calibrate the EC-instrument by means of 0.01 M KCl. Then the results can be expressed in dS/m or µS/cm.

2.5.3 Nutrients Requirements for Sugarcane

Sugar cane requires a well-drained, well-aerated, porous soil with pH of 6.5, bulk density of 1.1 to 1.2 g/cm^3 or 1.3-1.4 g/cm^3 in sandy soils (Krontal, 2006). The bulk density greater than 1.6 g/cm^3 affect root penetration, water and nutrient uptake. The crop is moderately sensitive to soil salinity. (Gilbert and Rice, 2009). Sugarcane can grow in areas with soil pH in the range of 5 to 8.5. Other nutrients required are total nitrogen, potassium, organic carbon, available phosphorous, cation exchange capacity; additional nutrients are shown in Appendix 7. They are briefly discussed in the following sections:

i) Total Nitrogen

The nitrogen may be present in the soils as a constituent of organic matter. A smaller amount may be present as exchangeable NH_4^+, a still small amount may be present as NO_3^- in the soil solution, besides this N_2 and in some cases also N_2O are present in the soil air. In positively charged low activity clay (LAC) soils the NO_3^- may also be retained as exchangeable anions as the NH_4^+ ion is approximately of the same size as the K^+ ion that may also be fixed in the interlayer of vermiculate and illite (Moberg, 2001).

Total nitrogen in the laboratory may be measured by semi-micro Kjeldahl digestion (Bremner, 1965) followed by ammonium distillation and titrimetric determinations. In this method the organic matter is broken down by the concentrated H_2SO_4 then $CuSO_4$ or a mixture of $CuSO_4$ and Se- and a salt like Na_2SO_4 catalysts can be added to increase the boiling point.

ii) Potassium

Sugarcane utilizes large quantities of potassium. Deficiencies are commonly observed on well-drained, coarse, sandy soils. In comparison to other nutrients, sugarcane response to K fertilization is usually most immediately apparent (Gilbert and Rice, 2009).

iii) Organic Carbon

Soil carbon is the generic name for carbon held within the soil, primarily in association with its organic content (Mcdonagh *et al.*, 2001). The term soil organic matter (SOM) is used to describe the organic constituents in the soil such as tissues from dead plants and animals, products produced as these decompose and the soil microbial biomass (Nortcliff, 2002). The term 'soil organic carbon' (SOC) refers to the C occurring in the soil organic matter. Soil organic carbon is important because it improves the physical properties of soil, increases the cation exchange capacity (CEC) and water-holding capacity of sandy soil and it contributes to the structural stability of clay soils by helping to bind particles into aggregates (Chan *et al.*, 2008). The amount of SOC depends on soil texture, climate, vegetation and historical and current land use/management. Soil texture affects SOC because of the stabilizing properties that clay has on organic matter. Organic matter can be trapped in the very small spaces between clay particles making them inaccessible to micro-organisms and therefore slowing decomposition. Soils with high clay content tend to have higher SOC than soils with low clay content under similar land use and climate conditions. Climate affects SOC amount as it is a major determinant of the rate of decomposition and therefore the turnover time of C in soils (Milne, 2008).

Determination of SOC can be done according to Walkley and Black (1965) by weighing 1 g of finely grained soil into a 500 ml wide-mouth conical flask. Using a pipette, add 10 ml of the potassium dichromate solution to the soil, and then add 20 ml of 96 - 98% of H_2SO_4 using a dispenser followed by swirling the flask and allow it to stand for 30 minutes. After that water is added to allow cooling followed by H_3PO_4. Finally the indicator is added to facilitate identification of color changes (Moberg, 2001).

iv) Available phosphorous

Phosphorus (P) is an essential element classified as a macronutrient because of the relatively large amounts of P required by plants (Brown *et al.*, 2000). It is one of the three nutrients generally added to soils in fertilizers. One of the main roles of P in living organisms is in the transfer of energy. Organic compounds that contain P are used to transfer energy from one reaction to drive another reaction within cells (Brown *et al.*, 2000). Therefore, P is very essential for plant growth. The available phosphorous can be measured in the laboratory by the method of Bray and Kurtz method no. 1 (Bray and Kurtz, 1945). The reagents used are hydrochloric acid solution, ammonium fluoride extraction solution, ammonium molybdate solution, superfloc solution, phosphate reagent, phosphate stock solution and phosphate standard solution (Moberg, 2001). The amount of phosphorous requirements is indicated in Appendix 7.

v) Cation Exchange Capacity and Exchangeable Bases

Cation exchange capacity (CEC) is the capacity of a soil for ion exchange of cations between the soil and the soil solution. It is used as a measure of fertility, nutrient retention capacity, and the capacity to protect groundwater from cation contamination (Al-Rumikhani, 2002). The higher CEC of the soil the higher is the quantities of clay and organic matter, thus the fertile is the soil (Camberato, 2001). The primary factors for determining CEC are the clay and organic matter content of the soil (Camberato, 2001). Higher quantities of clay and organic matter beget higher CEC. In most cases most cations are easily exchangeable, such as Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, and Al_3^{+}. The most common exchangeable anion are HCO_3^-, $NO3^-$, Cl^-, and SO_4^{2-} (Moberg, 2001).

According to Hesse (1971), the CEC can be measured in the laboratory by taking the representative soil sample, percolate with an excess of 1 M neutral ammonium acetate to saturate the colloidal complex with ammonium. The excess of ammonium acetate can then be washed out by ethyl alcohol, and the extracted cations calcium, magnesium, sodium and potassium can be determined from the ammonium acetate leachate by atomic adsorption spectrometry (Hesse, 1971). For the determination of CEC, the excess of ammonium ions can be replaced by percolation with acidified 1 M KCl solution. The ammonium in this percolate will be distilled and collected in boric acid 2%. The distilled ammonium solution will be titrated with sulphuric acid 0.01 M to get the cation exchange capacity (Walkley and Black, 1965).

2.6 Irrigation Water Quality

Suitability of water for irrigation depends on the total amount and kind of salts, ions and other toxic elements in the water (Ross, 1997). Suitability must also consider crops grown, irrigation water management, cultural practices, and climate factors.

Salinity or sodicity relates to water quality if the total quantity of salts in the irrigation water is high enough that salts accumulate in the crop root zone or on the plant and to the extent that crop growth and yield are affected (Ross, 1997). Where excessive soluble salts accumulate in the root zone, plants have increasing difficulty in extracting water from the soil profile.

In order to evaluate a salt hazard, a water sample should be analyzed for three major factors; these are total soluble salts, sodium hazard (SAR) and toxic ions. Total soluble salts measures the salinity hazard by estimating the combined effects of all the different salts that may be in the water. It is measured as the electrical conductivity (EC) of the water. Salty water carries an electrical current better than pure water, and EC rises as the amount of salt increases (Rhoades, 1977).

Sodium hazard is based on a calculation of the sodium adsorption ratio (SAR). This measurement determines if sodium levels are high enough to damage the soil or if the concentration is great enough to reduce plant growth. Sometimes a factor called the exchangeable sodium percentage (ESP) may be listed or discussed on a water test; however, this is actually a measurement of soil salinity, not water quality (Oster and Schroer, 1979).

Toxic ions include elements like chloride, sulfate, sodium and boron. Sometimes, even though the salt level is not excessive, one or more of these elements may become toxic to plants. Many p lants are particularly sensitive to boron. In general, it is best to request a water analysis that lists the concentrations of all major cations (calcium, magnesium, sodium, potassium) and anions (chloride, sulfate, nitrate, boron) so that the levels of all elements canbe evaluated (Oster and Schroer, 1979).

Victor and Al-Farsi (2001) carried out an analysis to determine the irrigation water quality in the laboratory using different water samples. Water electrical conductivity (EC) and pH were measured in the field using a salinity conductivity temperature (S-C-T) meter and a pH meter (Model 3010: Jenway-UK) respectively.

2.7 Synthesis from the Literature Review

Performance parameters of centre pivot spray nozzles irrigation systems have identified in this section. Measures of impact attempt to evaluate the consequences of the centre pivot irrigation system and its effects on sugarcane yield. Performance parameters identified include uniformity and efficiencies; other parameters are revolution time, application rates, nozzle size, operating pressure, sprinkler set used, sprinkler spacing, wind speed and evaporation effects. Hence a system performance evaluation of sprinkler irrigation system as any other irrigation method is emphasized so as to undertake corrective measures whenever a shortfall in objective is observed.

Soil parameters also are taken into account as they play a major role in plant growth. The review helps to know soil properties and nutrients requirements for sugarcane such as particle size distribution, cation exchange capacity, total nitrogen, organic carbon, water and infiltration in relation to sugarcane yield. Factors responsible for low sugarcane yield have been thoroughly identified; these include soil pH, toxicity and salinity hazards.

The quality irrigation water has identified to be that which has low levels of acidity, electro-conductivity (ECw), and other salts concentration such as carbonates, bicarbonates and sulphates. The limit of toxicity in irrigation water has identified and therefore will be taken into account in this research.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

Kagera Sugar Estate is situated at 1° S and 31 ° E. It is near Bunazi village in Misenyi district 80 km from Bukoba town, Kagera Region, north west of Tanzania (Fig. 1). The road to Kagera Sugar Estate joins the Tanzania - Uganda main Road and its junction is on the left side of this road at Bunazi between Kyaka and Mtukula wards.

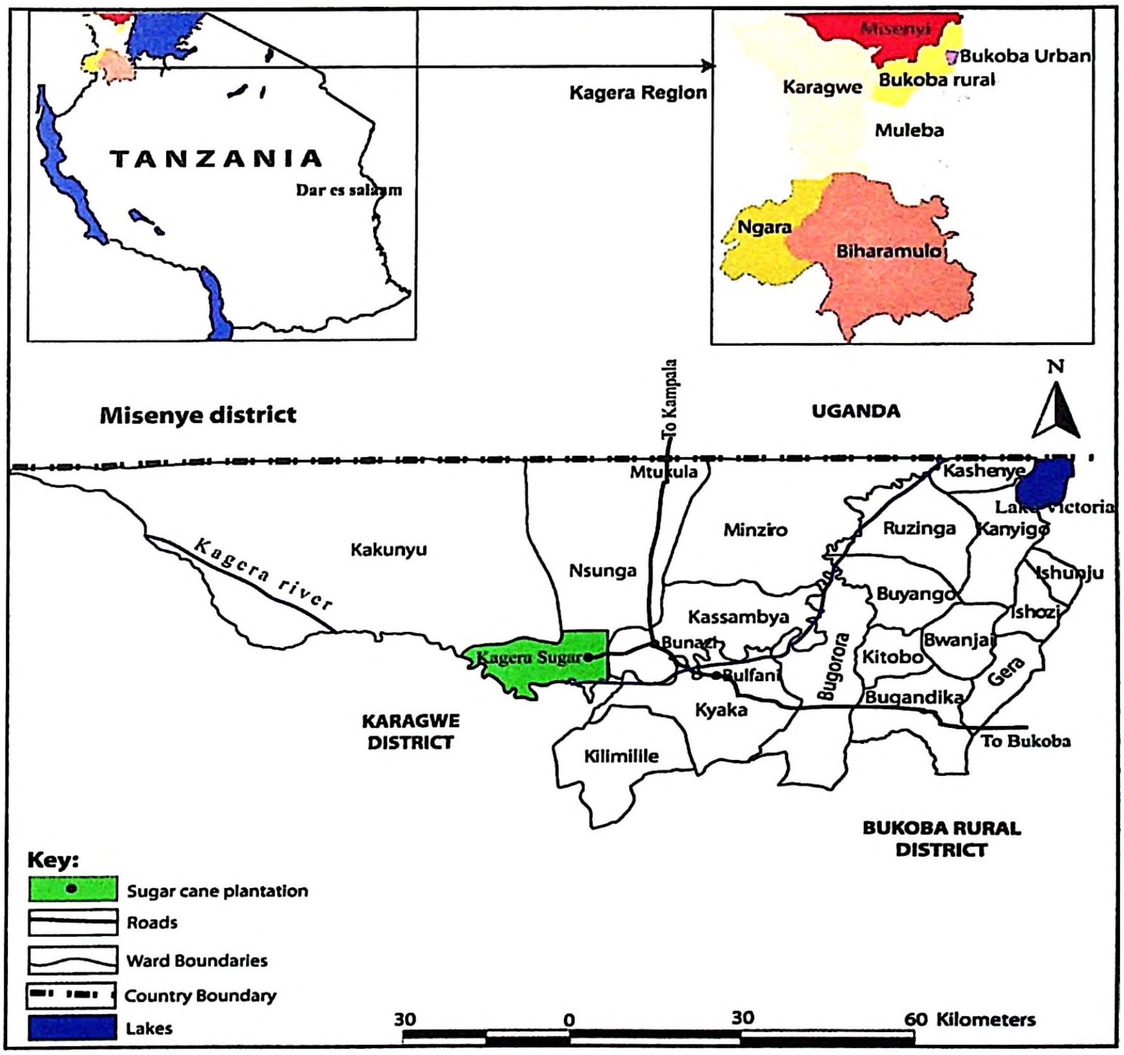

Figure 1: The location of Kagera Sugar Estate

3.1 Kagera Sugar Estate

Kagera Sugar Estate has a net planted area of 9066 ha. The areas under centre pivot spray sprinkler irrigation are 3058 ha whereas 2500 ha is irrigated by travellers irrigation system, 2000 ha is irrigated by sprinkler irrigation system and about 500 ha are flooded. The remaining area is under rain fed. The layout of Kagera Sugar Estate is as shown in Fig. 2 below. The field is divided into Eastern and Western zones so as to properly manage. In each zone the area is divided into sections supervised by section managers. Apart from Sugarcane plantations, the company grows vanilla. It also has cattle feedlot that keeps dairy cows for supplying milk for sugarcane cutting manpower and top position managers.

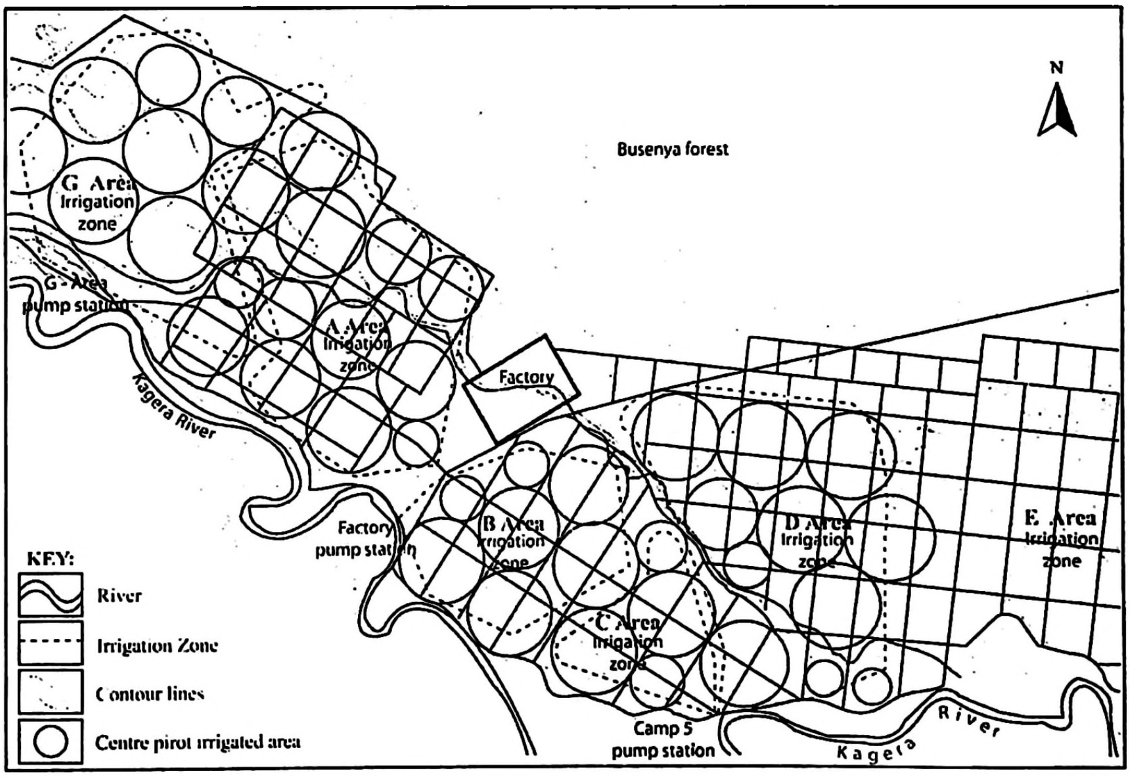

Figure 2: Layout of Kagera Sugar Estate

3.2.1 Topography

The average altitude of the estate is 1100 m above sea level and the general slope is towards Lake Victoria, South East of Kagera Sugar Estate. The main slope of Kagera Sugar Estate is not well pronounced, however, the general slope is not steep of about 5% and it is generalized as flat.

3.2.2 Soils of the area

The soils at Kagera Sugar Estate are generally medium textured soils. They are mainly sandy clayey loam in the top soil and clayey loam in the subsoil. They are non homogeneous in nature with acidic problems in some fields. In sandy textured areas frequent irrigation is needed for high yield of sugarcane because of large pores between soil particles as the result of high draining capacity.

3.2.3 Climate

The climate of Kagera Sugar is influenced by two main factors, these are its location in terms of latitude and position at the eastern edge of the African continent. Its location near the equator makes its climate to be truly tropical climate with high temperatures, low wind speeds, and high humidity and the absence of cold season are the most typical climate features.

i) Rainfall

The mean annual rainfall is 740 mm per year. Most of the rains occur during the summer (February to May). The long rain begins towards mid February and end in the late May or early June. Short rains start between October and December. The period June to October is commonly dry. The highest rains in the area were recorded in 1997; this was 1118 mm, while the lowest was rainfall was 531 mm in 1958.

ii) Temperature

Temperaturea at Kagera Sugar Estate are generally warm. The records of temperature show that the area has an average annual temperature of 22 degrees centigrade. This average temperature is good for cane growth, because at higher temperatures the rate of photosynthesis reduces and respiration increases. However for ripening, relatively low temperatures in the range of 12° to 14° are desirable, since this has a noticeable influence on the reduction of vegetative growth rate and enrichment of sucrose in the cane.

iii) Evaporation

The average evaporation of Kagera Sugar Estate is 5.4 mm / day. The lowest evaporation was 3.6 mm / day in 1973 whereas the highest evaporation was recorded in 1996 and it was 6.5 mm/day. These values of evaporation are moderately high and therefore require large application rates of irrigation water. The records show high variation in the evaporation distribution of the area.

iv) Relative humidity

The relative humidity of the area is high ranging from 78% to 82.4% (February to May) during rainy season and is moderately (75%) during the dry seasons (June to October). Relative humidity generally changes conversely to temperature reaching its highest values during the night, when it often is close to 94% percent.

3.2.4 Hydrology

Kagera Sugar estate lies along the Kagera River which is among the big rivers in Tanzania estimated to be 14 m deep and maintaining good flow rate all over the year, making it potential for irrigated agriculture. The river is located southern part of Kagera Sugar fields flowing towards Lake Victoria.

3.3 Centre Pivot Evaluation

Centre pivot performance is vital in sugarcane growth and yield. Poor performance of centre pivots can lead into low yield by cane stress and or water logging problems as the result of reduced income. On the other hand, nutrients can be leached out due to over irrigating, water table can be raised, and hence land can be abandoned. Thus it is important to evaluate the system regularly so as to improve its performance.

3.3.1 Site selection

The field production history in terms of ton per hectare under centre pivot spray nozzle sprinkler areas was studied. Physical survey of areas of interest were studied; then one of the field under centre pivot which have met the required yield per hectare and another field from low yield were chosen at random. However, selection of study centre pivots based on fields which were already harvested during the time of field work so as to easy data collection processes.

3.3.2 Centre Pivot Performance

The procedures for assessing centre pivot performance were done as follows: (i) Sampling of centre pivot (ii) laying out catch cans (iii) pressure measurement (iv) Measurement of speed of centre pivot (v) Estimating time per revolution (vi) Measurements of evaporation and (vi) Determining important parameters such as distribution uniformity, coefficient of uniformity, potential application efficiency of low quarter and application efficiency of low quarter from the data collected.

i) Sampling of centre pivot

Two centre pivots were selected by stratified random sampling. These centre pivot are GP7 which represented the centre pivot with high yield per hectare (123 tonnes / hectare) whereas CP BP5 represented the centre pivot (CP) with low yield (74 tonnes / hectare).

ii) Layout of catch cans

Cans were laid along the lateral to cover a distance of 9 m* 105 m by using a fixed grid system. A total of 108 cans were laid at 3 m apart (Fig. 3) and the layout was replicated three times. Data were collected by using centre pivot evaluation data sheet (Appendix 1 – 6). The test was conducted three times and the average value was found. The volume of water caught in each can was measured by using a measuring cylinder. It was then converted into depth per millimetre rate for easier comparisons. Data were then analyzed to find the performance indicators (uniformity coefficient, distribution uniformity, potential application efficiency, and actual application efficiency).

iii) Replications of catch cans layout

The selected centre pivot areas were replicated in three portions covering radii of 100 – 250 m, 250 – 400 m, and 400 – 550 m (Omary *et al.*, 1997). Then catch cans for collection of water were aligned in three lines along the lateral between 100 and 250 m from the pivot point in three lines (Plate 5). The spacing was 3 * 3 m between catch cans (Dechmi *et al.*, 2003). The system brought the irrigation system up to proper operating pressure, and letting the system pass over them according to Rogers *et al.* (2005). The procedures were repeated in the radii 250 – 400 m, and 400 – 550 m length of the pivot. The cans were fabricated from standard plastic pipe (heat resistant) materials of 100 mm diameter and 80 mm depth according to McCann and Adkins (2007).

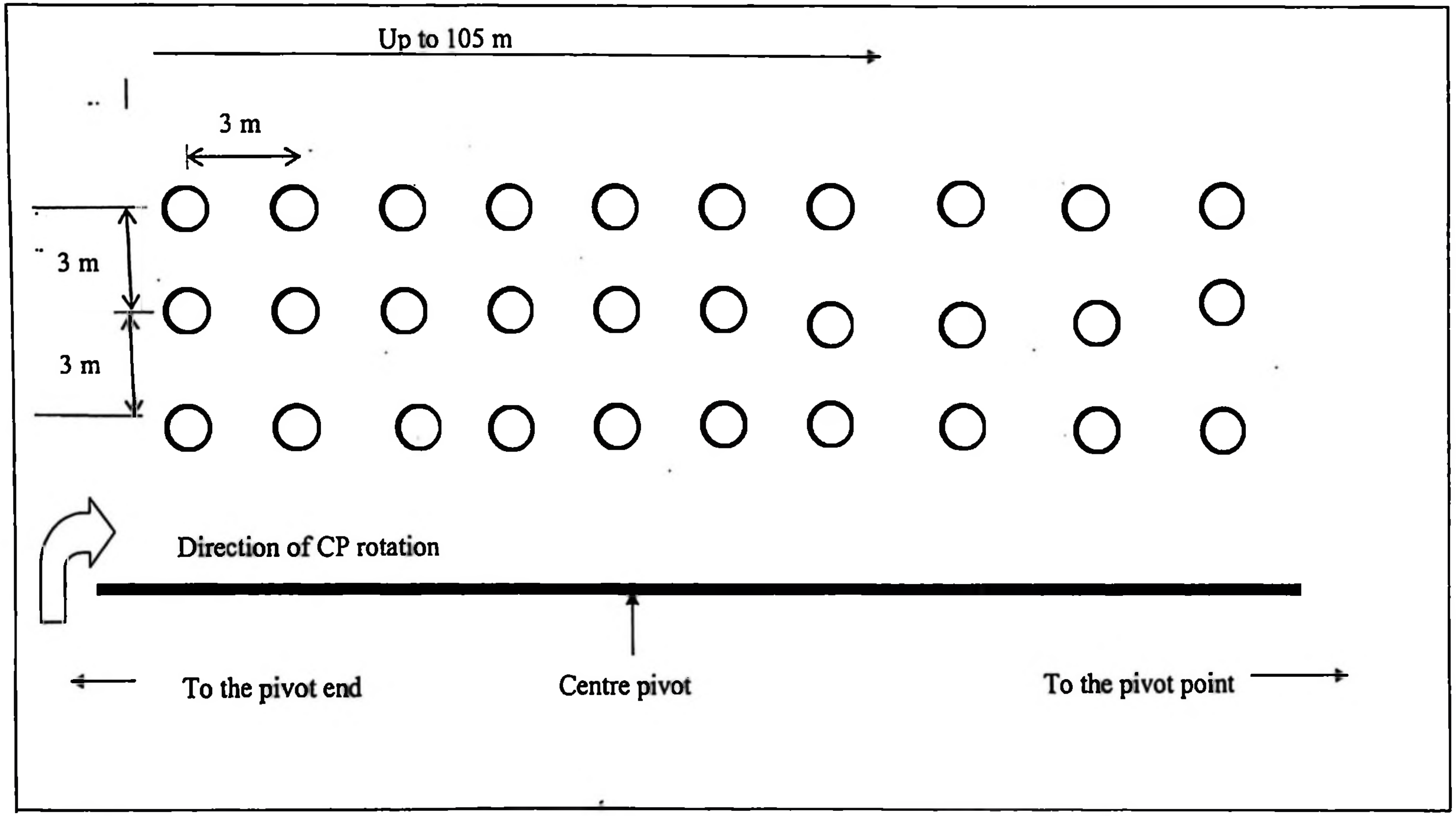

Figure 3: Layout of catch cans

Plate 5: Layout of catch cans along the lateral

3.3.3 Determination of evaluation parameters

The evaluation parameters such as distribution uniformity, coefficient of uniformity, potential application efficiency of low quarter and application efficiency of low quarter were determined as described in the following sections.

i) Determination of Distribution Uniformity (DU)

The performance of the centre pivot system was evaluated by measuring the uniformity of water application under the recommended operating conditions. The distribution uniformity was determined from catch cans data according to Merriam and Keller (1978). As the pivot is moving with catch cans aligned to the field, the length of the pivot was surveyed to look for leaks and sprinklers that may not be operating properly and it was noted in the data sheet. These notes will help you make recommendations for improvements.

ii) Determination of the coefficient uniformity (CU)

The uniformity coefficient was estimated from the relationship that exists between DU and CU (Markley and Allen, 2002); this also depends on water collected from catch can after the centre pivot has completely passed through the aligned cans. During calculation of the uniformity coefficient and other parameters, all gauges at the end of the system in which the volume of water collected began to drop drastically were disregarded because they do not represent the system.

iii) Determination of Net Application Rate

The net application rate for centre pivot irrigation was found from the catch can data according to Ross (1997). The net application rate of centre pivot irrigation depends on gross application in mm, time of centre pivot operation per day in hours, application efficiency of low quarter and time taken by a centre pivot to complete one revolution (hours).

iv) Pressure measurement

The operating pressure for the centre pivot was read from the centre pivot system using pressure gauges (Keller and Martin, 2000) and the result were analysed and compared with the design specifications. At Kagera Sugar centre pivot system, the design pressure at the pivot point of a centre pivot was 3 – 4 bars.

v) Evaporation

During the centre pivot evaluation field experiments, evaporation was estimated by using an evaporation pan. It was filled with the known volume of water and at the end of the experiment the evaporated amount of water was measured.

vi) Time per revolution

Time per revolution for a centre pivot is a very important factor to take into consideration when designing centre pivot (CP) because it can give the rate of application to be considered as well as the irrigation interval of the CP. The CP was set at the end drive unit and then the actual speed was measured according to Merriam and Keller (1978).

vii) Centre pivot speed at the end drive unit

The CP speed was measured by measuring a defined length using a measuring tape along the path of the drive wheels and recorded the time taken by a CP to complete that distance. Then the actual speed was compared to the set speed at the CP speed control point.

3.3.4 Quantifying performance (Efficiency)

The performance of centre pivot spray nozzle sprinkler irrigation system was quantified by calculating the application efficiency, potential application efficiency, distribution uniformity and uniformity coefficient.

Application Efficiency of Low Quarter (AELQ)

Application efficiency of low quarter (AELQ) is the ratio of average low quarter depth of irrigation water infiltrated and stored in the root zone to the average depth of water applied. Effectiveness of the use of CP can be determined from how much of the applied water is stored in the soil and available for consumptive use and how uniformly is applied. It was achieved in the field was estimated using Eq. 6 according to Merriam and Keller (1978).

Potential Application Efficiency of Low Quarter (PELQ)

The PELQ is expressed as a percentage when the average low quarter depth of water infiltrated equals the management allowed deficit (MAD). The PELQ is determined in order to evaluate how effectively the system can utilize the applied water. It was measured from the catch can field data, and calculated by Eq. 7 according to Merriam and Keller (1978).

3.3.5 Spray nozzle sprinkler set and spacing

The spray nozzle sprinkler set was studied by physical observation and information from the manufacturer. On the other hand the colour and the number of the sprinkler nozzle which indicated its size and hence location along the lateral was also observed. This was as important as the nozzle size along the lateral for uniformity and discharge from the spray nozzle sprinkler.

Spacing between spray nozzle sprinklers was measured using tape measure, observation was done to identify if variation of spray nozzle sprinkler spacing along the lateral existed. The analysed results were then compared with the design requirements.

3.4 Soil Properties

Different soil properties were studied from the selected fields and the representative samples at different depths from the selected areas with different rooting depths were taken and carried to the laboratory for analysis.

3.4.1 Soil Sampling and Physical-Chemical Characterisation

For the purpose of determining soil bulk density, soil samples were collected by core samplers at the depths between 0 and 20, 21 and 40 and 41 and 60 cm, while for the purpose of determining other soil properties, samples were collected from same depths without using core samplers from six blocks; three blocks from a well performing in terms of productivity centre pivot irrigated areas and the remaining three from the poorly producing centre pivot areas. Each soil sample was taken from points with similar characteristics chosen based on pedogeomorphic approaches which also ensured high representation of the study area. Eighteen composite samples were collected from each block, bulked and mixed.

A representative sample of soil from each site was then filled in a labelled plastic bag and sent to the Soil Science Laboratory at Sokoine University of Agriculture, in Morogoro Region, Tanzania for analysis. These samples were air dried and ground to pass through a 2 mm-sieve.

3.4.2 Physical properties

i) Particle size distribution analysis

Particle size analysis was determined by the Bouyoucos hydrometer method (Day, 1965). It involved the separation of the mineral fraction of the soil into various size fractions. The percentage of each fraction showed the type of soil and its relation to water holding capacity of the soil.

ii) Bulk density

Five soil core samplers of 100 cm^3 fitted with covers both ends, were used to collect soil samples from each of the depths 0 - 20, 21 - 40 and 41 - 60 cm. A driving head for pressing cores in the soil without disturbing the soil were used. Both ends of the core were trimmed with a knife after pressing core samplers in the soil such that just the amount of soil fit into the core holder is collected. Then Soil samples were collected to Soil Science Department laboratory at Sokoine University of Agriculture in Tanzania for analysis. Samples were dried in the oven at 105°C for 48 hours, and then the bulk density was determined by Eq. 11.

iii) Water infiltration

The infiltration rate of different soil types was measured in the fields using a single ring infiltrometer. The ring had a size according to Merriam *et al.* (1980). The cylinder was driven 150 mm in the soil, water was then added to the infiltrometer to the pre- determined depth. The fall in water depth and the time of measurement was recorded until a steady state was reached. The depth was taken after every 2 minutes for the first 12 minutes, after every 5 minutes for the next 30 minutes, then after every 10 minutes for the rest of the period (Magongo, 1995).

3.4.3 Chemical characteristics

i) Soil pH

Soil pH has both direct and indirect effects. Direct effects, can be critical that is, if the soil is too acid or too alkaline, there can be toxic effects on the plants themselves, and an unfavorable balance between acid and alkaline elements needed by plants. The soil pH was determined by a pH meter using soil to water ratio of 1: 2.5 as described by Moberg (2001). This method consists of placing of the electrodes in the soil suspension that influence both pH measured and the stability of measurement.

ii) Electrical Conductivity of the Soil (ECe)

The electric conductivity of the soil water suspension (ratio 1: 2.5) was then determined by electric conductivity meter as outlined by Hesse (1971). Soil samples were milled to pass through 2 mm sieve. 40.00 g of soil was weighed in the laboratory balance and placed into a 100 ml plastic bottle with a wide neck. 40 ml of water were added using a pipette. The bottle was closed and the suspension was shaken for 1 hour in a shaker. The cap was removed and centrifuged at 5000 - 6000 rpm for 10 minutes. Clear solution was decanted into another 100 ml plastic beaker.

iii) Exchangeable Cations and Cation Exchange Capacity

The soil samples were percolated with an excess of 1 M neutral ammonium acetate to saturate the colloidal complex with ammonium and the experiment was done according to Hesse (1971). For the determination of CEC, the excess of ammonium ions were replaced by percolation with acidified 1 M KCl solution and conducted according to Black (1965).

iv) Organic Carbon

Organic carbon was determined according to Walkley and Black (1965) wet acid dichromate digestion method (Allison, 1965). This was done by weighing 1 g of finely grained soil into a 500 ml wide-mouth conical flask. Using a pipette, 10 ml of the potassium dichromate solution was added to the soil, it was followed by 20 ml of 96 - 98% of H_2SO_4 using a dispenser and then swirling the flask and allowed to stand for 30 minutes. After that water was added to allow cooling followed by H_3PO_4. Finally the indicator was added to facilitate identification of colour changes (Moberg, 2001).

v) Available Phosphorus

The available phosphorous was measured in the laboratory by the method of Bray and Kurtz method No. 1 (Bray and Kurtz, 1945). The reagents used were hydrochloric acid solution, ammonium fluoride extraction solution, ammonium molybdate solution, superfloc solution, phosphate reagent, phosphate stock solution and phosphate standard solution (Moberg, 2001).

vi) Total Nitrogen

Total nitrogen was measured by semi-micro Kjeldahl digestion (Bremner, 1965) followed by ammonium distillation and titrimetric determinations. In this method the organic matter was destroyed by the concentrated H_2SO_4 then $CuSO_4$. Na_2SO_4 salt catalyst was added to increase the boiling point.

3.5 Irrigation Water Quality Analysis

Water samples were collected from the centre pivot spray nozzle sprinklers in September, December, March and June so as to see the quality variation in different periods of the year by using a container and placed in a clean bottle. These samplers were carried to Soil Science laboratory at Sokoine University of Agriculture for analysis and the results was compared with the standard values (Appendix 8). The determined factors include water pH, its electrical conductivity, specific ion toxicity and sodium adsorption ratio. The irrigation water quality analysis was done according to Victor and Al-Farsi (2001).

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Results of Centre Pivot Evaluation

The results of evaluation for performance of centre pivot for high (CP GP7) and low (CP BP5) yielding areas are presented in this chapter. The measured performance parameters include coefficient of uniformity, distribution uniformity, potential application efficiency of low quarter and application efficiency of low quarter. Other parameters influencing efficiency including application rate, operating pressure, wind speed and infiltration rate of the soil. Soil factors affecting yield of sugarcane were also determined; they included soil fertility, soil texture, soil pH, organic matter, cation exchange capacity (CEC) and water quality.

4.1.1 Catch can results

The water collected from catch cans was measured by a 100 ml measuring cylinder, the catch results for both centre pivot were recorded in appendices 1 – 6 and the overall distribution of water caught by catch cans from the centre pivot spray nozzle sprinkler system is shown in Fig. 4 and Fig. 5.

Fig. 4 shows that the overall application amount for CP GP7 was low near the pivot point and the amount increased gradually away from the pivot point. The catch amount was not uniform due to miss-allocation of certain nozzles. The amount of water caught by cans was high at about 1/3 (180 m) of the lateral length from the pivot point, then reduced midway and increased to the highest amount (174 ml) shortly after midway to three quarter way (400 m) along the lateral. The catch amount decreased in the last towers of each centre pivot.

Fig. 5 shows the overall distribution of water caught by catch cans as a function of position along the lateral from CP BP5. The catch amount has shown to increase gradually away from the pivot point to the highest (185 ml) between 1/3 (180 m) and the mid (275 m) of the CP. It was also found that, there was misallocation of the nozzles whereby the larger nozzle was allocated at that point. Generally, the amount of water caught by cans was low (53 ml) near pivot centre and at the 2/3 distance (365 m) of the length of the centre pivot and increased to 120 ml to the end of the lateral.

In general, the sprinklers in these two centre pivots should be checked and replaced or adjusted as needed so as to attain the required uniformity (85%) and overall system efficiencies.

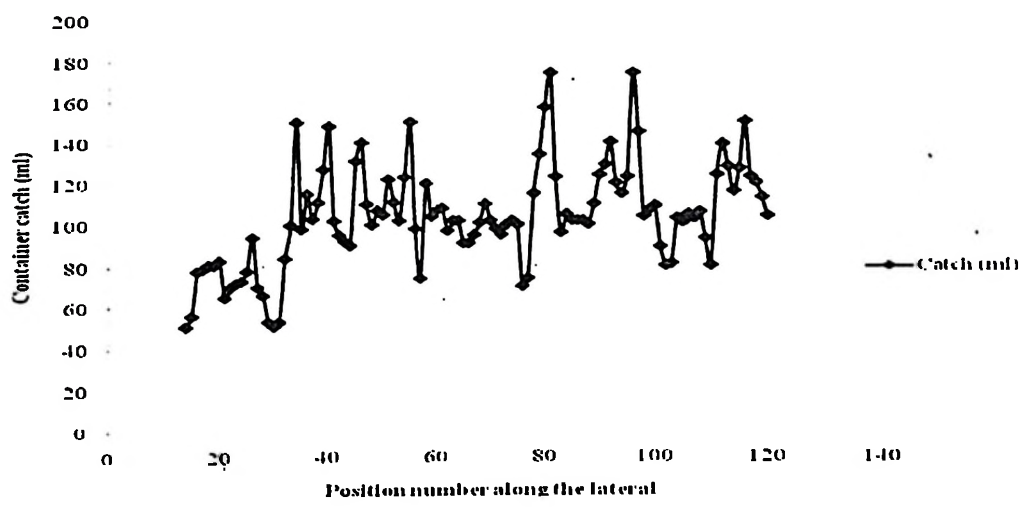

Figure 4: Distribution of water caught by catch cans from centre pivot GP7 spray nozzle sprinkler as a function of position for cans along the lateral

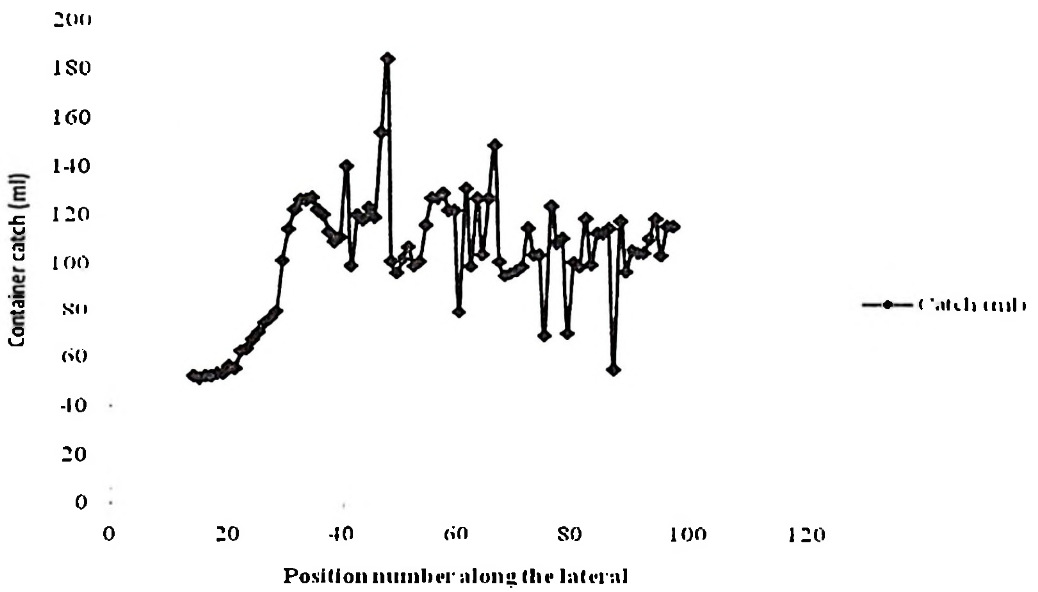

Figure 5: Distribution of water caught by catch cans from centre pivot BP5 spray nozzle sprinkler as a function of position for cans along the lateral

4.1.2 Investigating performance parameters

Performance parameters evaluated in this study were CU, DU, PELQ, and AELQ. Others were system net application rate, system operating pressure, time per revolution, spray nozzle sprinkler set used, wind speed and centre pivot speed at the end drive unit. The analysed data for both systems are shown in Tables 2 to 5.

i) Coefficient of Uniformity (CU)

Tables 2 and 3 show the computed CU for the areas covered under radii of 100 - 250, 250 - 400 and 400 - 550 m for CP GP7 and BP5, respectively. The results of CU were 91.4%, 99.5%, and 99.8% for GP7 and 59.24%, 99.8%, and 99.8% for BP5. According to Harisson and Perry (2010) centre pivot CU should be larger than 85.0% under the recommended wind speed. Thus, these two results show that, centre pivot GP7 had good uniformity in the whole area whereas centre pivot BP5 had poor uniformity in the area near pivot point while the remaining area had good uniformity.

The observation from centre pivot showing poor CU results were associated with low application rate and operating pressure, miss allocation of nozzle and nozzle clogging problems.

Table 2: Performance parameters for centre pivot GP 7

	CU (%)		DU (%)		PELQ (%)		AELQ (%)		D	T
	CU (%)	SD	DU (%)	SD	PELQ (%)	SD	AELQ (%)	SD	(mm/day)	(hours)
1/3 area	91.4	5.6	86.4	10.5	74.0	15.2	55.6	25.2	15.9	39.0
2/3 area	99.5	11.5	99.2	13.2	94.7	5.6	70.4	7.4	25.0	39.0
Last towers	99.8	11.7	99.7	16.2	91.8	1.8	68.9	8.9	24.5	40.0
Average	96.9	9.6	95.1	13.3	86.8	7.5	64.9	13.8	21.8	39.3

Table 3: Performance parameters for centre pivot BP5

	CU (%)		DU (%)		PELQ (%)		AELQ (%)		D	T
	CU (%)	SD	DU (%)	SD	PELQ (%)	SD	AELQ (%)	SD	(mm/day)	(hours)
1/3 area	59.2	32.0	35.3	31.8	55.7	12.8	41.8	37.8	9.5	48.9
2/3 area	99.8	11.7	99.7	16.2	96.0	2.5	72.0	21.2	21.4	50.0
Last towers	99.8	11.7	99.7	16.2	85.7	5.7	64.2	14.9	17.1	50.0
Average	86.3	18.5	78.2	21.4	79.1	7.0	59.4	24.6	10.0	49.6

Table 4: Performance parameters for centre pivot GP7

	Time per rev. (hrs)	Wind speed (km/h)	CP speed (mm/min)	P (bar)
1/3 area	48.9	10.0	1287.0	3.5
2/3 area	50.0	8.5	1287.0	3.5
Last towers	50.0	11.3	1285.5	3.5
Average	49.6	9.9	1286.5	3.5

Table 5: Performance parameters for centre pivot BP 5

	Time per rev. (hrs)	Wind speed (km/h)	CP speed (mm/min)	P (bar)
1/3 area	39.0	6.2	1362.0	2.5
2/3 area	39.0	10.0	1348.0	2.2
Last towers	40.0	7.5	1348.0	2.2
Average	39.3	7.9	1352.7	2.3

ii) Distribution Uniformity (DU)

Tables 2 and 3 show the computed DU for the areas covered under radii of 100 - 250, 250 - 400, and 400 - 550 m of CP GP7 and GP5, respectively. The results of DU were 86.4%, 99.2%, and 99.7% for GP7 whereas for BP5 it was 35.3%, 99.7%, and 99.7%, respectively. According to Ascough and Kiker (2002), CP system DU should be at least 75%. This indicated that CP GP7 had good uniformity in water application in the whole area whereas CP BP5 had poor DU in areas covered under radius of 100 - 250 m of the CP and the remaining area had good uniformity.

iii) Potential Application Efficiency of Low Quarter (PELQ)

The average potential application efficiency for CP GP7 was 74.0%, 94.7% and 91.8% (Table 2) for areas under radii of 100 - 250, 250 - 400 and 400 - 550 m of the CP whereas for the CP BP5 was 55.7%, 96.0% and 85.7% (Table 3). According to Savva and Frenken (2002), the spray nozzle sprinkler centre pivot PELQ should be at least 90.0%. From these results, both centre pivots had poor performance in areas covered under radius of 100 - 250 m of the CP and good performance in the remaining areas. However in comparison, CP GP7 was better than that of BP5.

iv) Application Efficiency of Low Quarter (AELQ)

The average application efficiency for CP GP7 was 55.6%, 70.4%, and 68.9% (Table 2) in areas covered under radii of 100 - 250, 250 - 400, and 400 - 550 m of the CP, whereas that of CP BP5 was 41.8%, 72.02%, and 64.26% (Table 3). In both CP, the average application efficiency was lower than the recommended AELQ which is at least 90% for spray nozzle sprinkler centre pivot irrigation (Evans, 2001). However, in comparison GP7 had better AELQ than BP5.

v) Application Rate

The measured application rate (D) was 15.9, 25.0, and 24.5 mm/day (Table 2) for areas covered under radii of 100 - 250, 250 - 400, and 400 - 550 m for the CP GP7 whereas for CP BP5 was 9.5, 21.4, 17.1 mm/day (Table 3). The design irrigation interval used by Kagera Sugar Estate is one day; thus the design application rate applied was 15 mm/day to meet the potential evapotranspiration of 6 mm/day and other losses. Thus, centre pivot GP7 met the requirements while BP5 did not meet the requirement especially in areas near the pivot point that caused stress to sugarcane. This was contributed by CP speed at the end drive unit. The actual speed for GP7 was 1287 mm/min whereas for BP5 was 1362 mm/min (Table 4 and 5). In both CP the actual speed was less than the design speed which was 2100 mm/min, thus longer time was taken to complete one revolution.

vi) Operating Pressure

The operating pressure at the pivot point for the centre pivots was found to be 3.5 bar (Table 4) during data collection of areas under radii of 100 - 250, 250 - 400, and 400 - 550 m of CP GP7; and 2.5, 2.2 and 2.2 bar for BP5 (Table 5). According to the operating manual for centre pivots, the operating pressure required at pivot point for centre pivots with 8 - 10 towers is 3 - 4 bars. Therefore, CP GP7 operated within the range while BP5 operated below the range. This could have contributed to the less application in the areas near the pivot to the radius of 250 m of the lateral of BP5. On the other hand, the operating pressure at the pump station was within the required range of 530 - 550 Kpa.

vii) Time per Revolution

The actual time per revolution was 48.9, 50.0, and 50.0 hours under areas covered by GP7 (Table 4) whereas the actual time per revolution for CP BP5 was 39.0, 39.0, and 40 hours (Table 5). In comparison, the time taken by CP GP 7 was higher than that of BP5. In both

CP, the time per revolution was higher than the design time of 24 hours as per design at Kagera Sugar Estate. This is because the actual speed is less than the design speed of 2100 mm/min set at the end drive unit, thus longer time is taken for the CP to complete one revolution, this result into sugarcane stress and water logging in some parts and hence low yield of sugarcane.

viii) Spray nozzle sprinkler set and spacing

It was observed that the number of sprinkler nozzles ranged from 9 to 45 from the pivot point to the tenth (outermost) tower. Different nozzle colour relative to its location was used to identify nozzles. It was also observed that the spray nozzle sprinkler set employed was D3000 (3000 series) manufactured by Nelson Irrigation Corporation of Australia.From the observation the spray nozzle sprinkler set and a uniform spacing of 2.5 m along the lateral were proper, but misallocation of certain nozzles was identified as the result of non-uniformity and low efficiency. The reason of misallocation was found to be shortage of spray nozzle sprinkler required for placement when the existing sprinkler was worn out. This resulted into sugarcane stress and water logging in some areas and hence affected sugarcane yield.

ix) Wind Speed

The average wind speed during the days of test for CP GP7 under areas covered by radii of 100 - 250, 250 - 400, 400 - 550 m of the CP was 10.0, 8.5, and 11.3 km/h (Table 4) whereas during the days of testing for CP BP5 was 6.2, 10.0 and 7.5 km/h (Table 5). Both values of wind speed are acceptable because they are less than the recommended value of 15 km/h for CP irrigation (King *et al.*, 1997) and hence wind speed was not the factor responsible for poor performance for centre pivot irrigation.

x) Centre pivot speed at the end drive unit

The actual CP GP7 speeds found at the end drive unit during the test of areas covered under radii of 100 - 250, 250 - 400, and 400 - 550 m of the CP GP7 were 1287, 1287 and 1285.5 mm/min (Table 4) whereas for CP BP5 were 1362, 1348 and 1348 mm/min (Table 5). In both CP the actual operation speeds were less than the recommended design speed (2100 mm/min). However, both speed control units of the two systems were set at the design speed. This might be due to the worn out of system as a result of lack of proper system repair and maintenance, lack of replacement of the worn out parts and general poor system management. Therefore, regular check up of systems and calibration are required so as to set the system at the recommended speed of 2100 mm/min.

xi) Comparison of results for centre pivots GP7 and BP5

The performance parameters (CU, DU, PELQ and AELQ) for GP7 of areas under radius of 100 - 250 m of the CP from the pivot point were higher than those obtained for BP5 (Fig. 6). At the radius of 250 - 400 m, all performance parameters were almost equal (Fig. 7) whereas at radius of 400 - 550 m, the CU and DU were almost equal in both centre pivots, while PELQ and AELQ were higher in CP GP7 than BP5 (Fig. 8).

The average CU, DU, PELQ and AELQ were higher in CP GP7 than in BP5. For instance CU, DU, PELQ and AELQ for GP7 were 96.91%, 95.1%, 86.83% and 64.97% whereas for CP BP5 were 86.28%, 78.23%, 79.14% and 59.36%, respectively (Fig. 9). Most of the parameters in CP GP7 were adequate except for AELQ. In CP BP5 almost all parameters were not adequate. This could be due to system head losses as CP BP5 is located at longer distance than CP GP7 which is closer to the pump station with higher operating pressure at the pivot (3.5 bar) than at CP BP5 (2.2 bar). This could also be contributed by misallocation of some spray nozzle along the pivot.

Wind was not a factor that contributed to poor performance of BP5 though wind speed in the two CP was different. The average wind speed for CP GP7 was 10.0 km/h whereas the average wind speed for CP BP5 during measurements was 7.9 km/h. However in both CP the speed were in the acceptable range (King *et al.*, 1997).

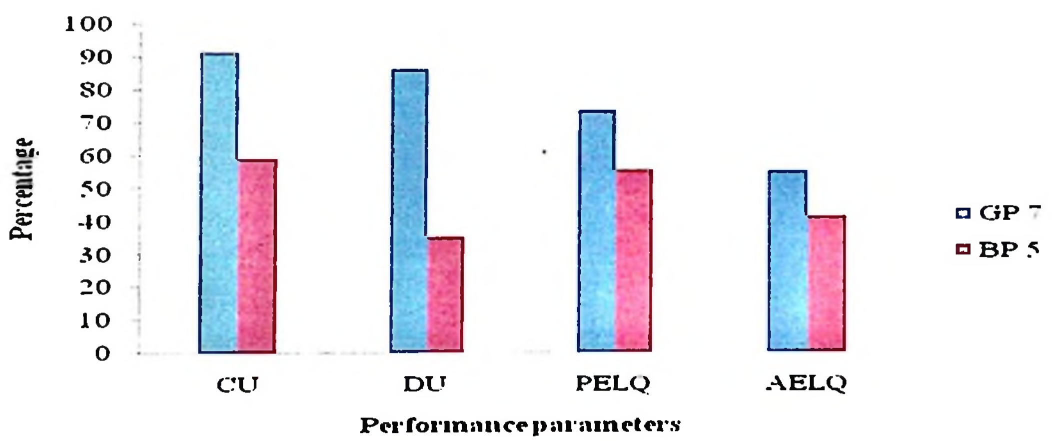

Figure 6: Comparison of the system performance parameters at radius of 100 - 250 m of the CP

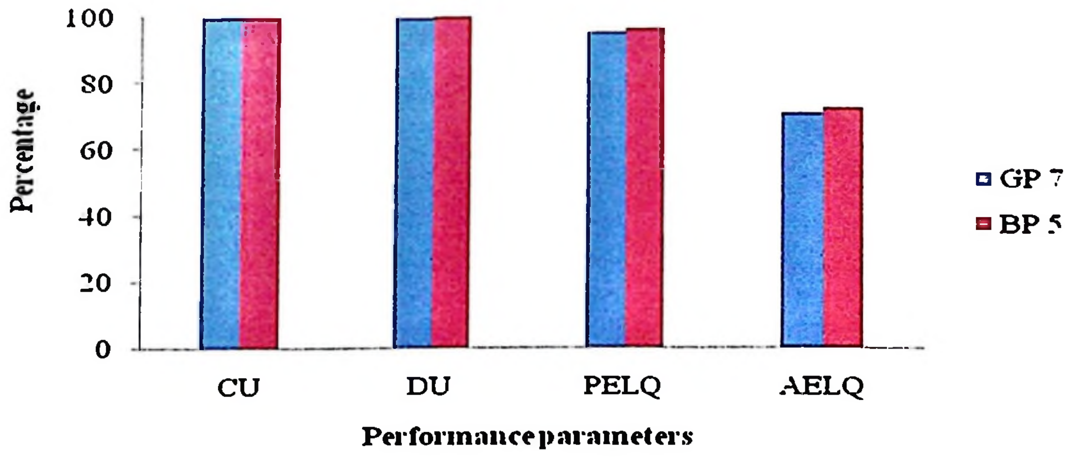

Figure 7: Comparison of the system performance parameters at radius of 250 – 400 m of the CP

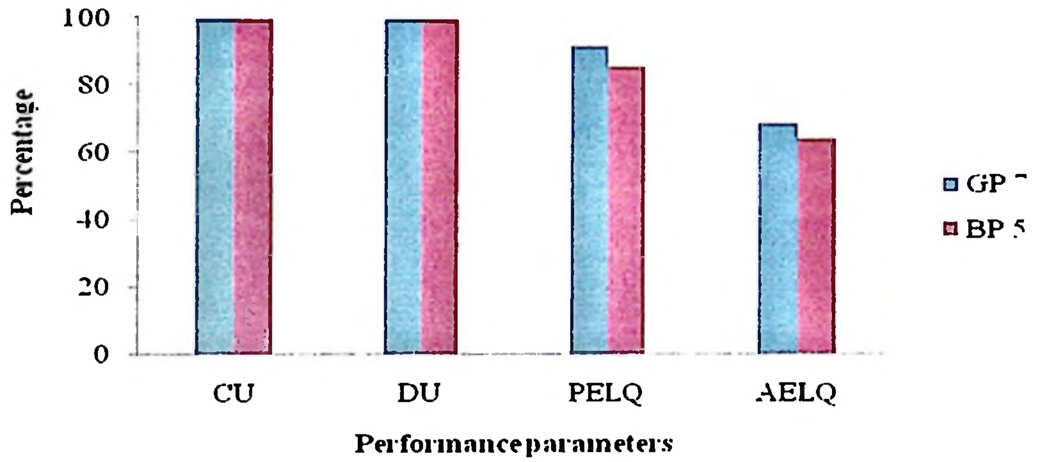

Figure 8: Comparison of the system performance parameters at radius of 400 - 550 m of the CP

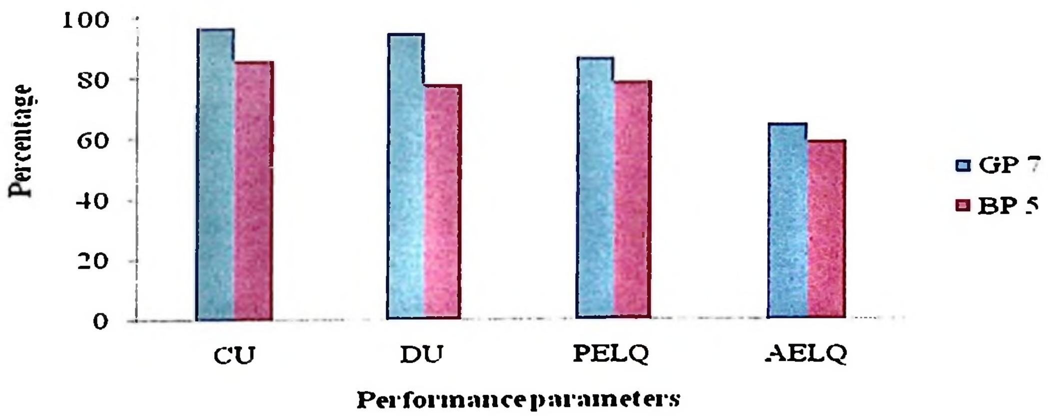

Figure 9: Comparison of the system overall performance parameters

4.2 Soil Parameters Influencing Cane Yield

Soil properties are among factors responsible for good or poor sugarcane yield in the fields. The study studied both physical and chemical properties of the soils as discussed below.

4.2.1 Soil physical properties

i) Particle size distribution

Fields BP5B, BP5C and BP5D were sandy textured soils of up to 65% sand in the top layer (Tables 6 to 8). The amount of sand decreased with depth whereas the amount of clay was also significant and it increased with depth. The amount of silt was small; it was almost 18% in the top layer. This sandy texture could not affect sugarcane growth because it helped the soil to be well drained. However, if the application rate was less than the requirements, it could cause sugar cane to grow under water stress as the water holding capacity of sandy soils was low.

Fields GP7A and GP7B were clay loam and almost clayey in the field GP5C (Tables 9 to 11). The amount of sand was high in the field GP7B (63%) which decreased slowly with increasing depth. The amounts of clay in the field GP7C were 43% in the top soil and increased with depth to 62% in the subsoil and hence made the soil denser. The amount of loam in the soil was almost 49% in the topsoil and decreased with increasing depth.

Table 6: Soil physical properties for CP BP5 B field

Soil depth (cm)	Bulk density (g/cm3)	Particle size distribution (%)			
		Clay	Silt	Sand	Text. Class
0 - 20	1.07	23	12	65	scl
21 - 40	1.11	31	16	53	scl
41 - 60	1.87	56	15	29	c

Table 7: Soil physical properties for CP BP5 C field

Soil depth (cm)	Bulk density (g/cm3)	Particle size distribution (%)			
		Clay	Silt	Sand	Text. Class
0 - 20	0.85	31	18	51	scl
21 - 40	1.01	39	14	47	scl
41 - 60	1.56	52	12	36	cl

Table 8: Soil physical properties for CP BP5 D field

Soil depth (cm)	Bulk density (g/cm3)	Particle size distribution (%)			
		Clay	Silt	Sand	Text. Class
0 - 20	1.09	25	12	61	scl
21 - 40	1.14	27	12	63	scl
41 - 60	1.92	40	10	50	cl

Table 9: Soil physical properties for CP GP7 A field

Soil depth (cm)	Bulk density (g/cm3)	Particle size distribution (%)			
		Clay	Silt	Sand	Text. Class
0 - 20	1.02	29	49	22	cl
21 - 40	1.25	30	38	32	cl
41 - 60	2.48	39	4	57	c

Table 10: Soil physical properties for CP GP7 B field

Soil depth (cm)	Bulk density (g/cm3)	Particle size distribution (%)			
		Clay	Silt	Sand	Text. Class
0 - 20	1.12	23	14	61	scl
21 - 40	1.15	25	14	63	scl
41 - 60	2.23	45	12	43	c

Table 11: Soil physical properties for CP GP7 C field

Soil depth (cm)	Bulk density (g/cm3)	Particle size distribution (%)			
		Clay	Silt	Sand	Text. Class
0 - 20	0.77	43	42	15	cl
21 - 40	0.83	55	26	20	c
41 - 60	1.25	62	23	15	c

ii) Bulk Density

The bulk densities of the soils of fields BP5B, BP5C, BP5D which were irrigated by centre pivot BP5 were low to high (0.85 - 1.92 g/cm^3), (Tables 6 to 8). The bulk density increased gradually with soil depth. High bulk density in these soils was attributed partly to the sand texture and compaction by farm machinery. The tendency of bulk densities of the soil to increase with depth could be either due to the low organic matter content, less aggregation and root penetration. For adequate sugarcane growth bulk density of less than 1.4 g/cm^3 is recommended (Trouse and Humbert, 1961). High densities have shown to have deleterious effects on sugarcane root growth. The bulk densities on the fields GP7A, GP7B, GP7C which were irrigated by centre pivot GP7 was also low to high (0.8 to 2.4 g/cm^3) and increased with soil depth, (Tables 9 to 11). This high density might be attributed to compaction by farm machinery. High bulk density has impacted sugarcane roots penetration and hence low yield.

iii) Infiltration of water in the soil

The basic infiltration rates of soil were generally found to be higher than the application rate. However, in some areas, especially those dominated by clayey soils, the infiltration rate was lower than the application rate resulting into water logging problems. The results are summarized in Table 12. Comparing the results with the actual application rate, the application rate was generally less than the infiltration rate as required by the design principles of centre pivot irrigation and therefore it is not the factor responsible for low cane yield.

Table 12: Soil infiltration rate in different areas of CP BP5 and CP GP7

Field	Soil type	Basic infiltration rate (mm/h)
BP5 B	Sandy clay loam	9
BP5 C	Sandy clay loam	8
BP5 D	Sandy clay loam	9
GP7 A	Clayey loam	7
GP7 B	Sandy clay loam	9
GP7 C	Clayey loam	6.5
GP7 D	Clay	4

4.2.2 Soil chemical properties

i) Soil pH

The soil in the fields BP5B, BP5C, BP5D was very strongly acidic to medium acidic (pH 4.76 to 5.66) in the top layer and extremely acidic to strongly acidic (pH 3.98 to 5.16) in the sub soil (Tables 13 to 15). The low pH in the top soil was probably due to frequent application of inorganic fertilizer, rainfall and leaching, organic matter decay and the presence of acidic parent material (Johnson, 2002). The low pH in the soil of the fields under CP BP5 affected the amount of nutrients in the soil solution available for plant use, and it also affected soil microbial activity, solubility of toxic elements (Harris, 2005 and Ross, 1997), which was one of the factors that significantly caused low cane yield.

The low pH in the field under CP BP5 was caused by the presence of toxic elements such as aluminium and manganese which usually cause crop failure especially in acidic soils. These elements are a problem in acidic soils because they are more soluble at low pH (Johnson, 2002). In other words, more of the solid form of these elements dissolves in water when the pH is low (acidic). There might be lot of aluminium present in soils because it is a part of most clay particles (Johnson, 2002). And hence this was not a significance factor to cause low cane yield.

In fields GP7A, GP7B and GP7C (Tables 16 to 18) the soil was slightly acidic to neutral (pH 6.2 to 6.89) in the top layer and strongly acidic to medium acidic (pH 5.04 to 5.86) in the sub-soil. According to FAO (1985), a pH range of 5.5 to 7.0 is preferred for most crops. This is because the toxic elements remain in solid form and not available for affecting crops (Johnson, 2002).

Generally when the soil pH is above 5.5, the aluminium in soils remains in a solid combination with other elements and is not harmful to plants. As the pH dropped below 5.5, aluminium containing materials began to dissolve and continued to dissolve more as the pH became less. For this reason, some crops might seem to do very well, but then failed completely with just a small change in soil pH (Johnson, 2002). Thus, high value of pH in the top soil was not significant to affect soil nutrients availability for plant growth and hence good sugarcane yield.

Table 13: Chemical properties of soils under CP BP5 B

Field number	Depth	Soil pH (H_2O)	ECe	Total N	Org. Carbon	Org. Matter	Ext. P (PBrl)	CEC	Exch. Bases cmol(+)/kg			
	(cm)		mS/cm	%	%	%	mg/kg	cmol(+)/kg	Ca+	Mg+	K+	Na+
BP5B	0 – 20	5.66	0.05	0.09	1.17	2.01	6.1	5.8	4.45	1.97	0.31	0.38
	21 – 40	5.01	0.01	0.06	0.27	0.46	4.03	10.7	2.65	0.85	0.06	0.33
	41 – 60	4.89	0.03	0.06	0.21	0.36	6.21	11.5	3.83	1.02	0.21	0.45

Table 14: Chemical properties of soils under CP BP5 C

Field number	Depth	Soil pH (H_2O)	ECe	Total N	Org. Carbon	org. Matter	Ext. P (PBrl)	CEC	Exch. Bases cmol(+)/kg			
	(cm)		mS/cm	%	%	%	mg/kg	cmol(+)/kg	Ca+	Mg+	K+	Na+
BP5C	0 - 20	4.9	0.01	0.08	0.55	0.95	18.12	12.6	2.02	0.56	0.05	0.38
	21 - 40	5.16	0.07	0.08	0.47	0.81	12.85	18.8	9.64	3.28	0.15	0.74
	41 - 60	3.98	0.06	0.08	0.51	0.88	5.28	15.52	10.12	3.85	0.12	0.82

Table 15: Chemical properties of soils under CP BP5 D

Field number	Depth	Soil pH (H_2O)	ECe	Total N	Org. Carbon	org. Matter	Ext. P (PBrl)	CEC	Exch. Bases cmol(+)/kg			
	(cm)		mS/cm	%	%	%	mg/kg	cmol(+)/kg	Ca+	Mg+	K+	Na+
BP5D	0 - 20	4.76	0.15	0.21	0.98	1.69	18.38	14.6	4.64	2.31	0.57	0.33
	21 - 40	4.73	0.04	0.18	1.99	3.42	6.21	24.6	7.5	3.9	0.43	0.34
	41 - 60	4.62	0.08	0.25	1.87	3.22	15.39	22.53	9.32	4.15	0.38	0.42

Table 16: Chemical properties of soils under CP GP7 A

Field number	Depth	Soil pH (H_2O)	ECe	Total N	Org. Carbon	org. Matter	Ext. P (PBrl)	CEC	Exch. Bases cmol(+)/kg			
	(cm)		mS/cm	%	%	%	mg/kg	cmol(+)/kg	Ca+	Mg+	K+	Na+
GP7A	0 - 20	6.89	0.06	0.08	1.09	1.87	21.2	10.8	2.89	1.52	0.46	0.29
	21 - 40	5.7	0.03	0.07	0.43	0.74	17.07	13.2	2.07	0.84	0.23	0.27
	41 - 60	4.62	0.05	0.06	0.38	0.65	9.86	14.21	1.98	0.74	0.21	0.25

Table 17: Chemical properties of soils under CP GP7 B

Field number	Depth	Soil pH (H_2O)	ECe	Total N	Org. Carbon	org. Matter	Ext. P (PBrl)	CEC	Exch. Bases cmol(+)/kg			
	(cm)		mS/cm	%	%	%	mg/kg	cmol(+)/kg	Ca+	Mg+	K+	Na+
GP7B	0 - 20	6.5	0.08	0.11	1.37	2.36	17	14.5	4.68	2.26	0.82	0.25
	21 - 40	5.86	0.02	0.06	0.39	0.67	10.74	11.8	3.18	1.32	0.22	0.44
	41 - 60	4.96	0.01	0.04	0.29	0.50	10.05	12	3.06	1.23	0.17	0.51

Table 18: Chemical properties of soils under CP GP7 C

Field number	Depth	Soil pH (H_2O)	ECe	Total N	Org. Carbon	org. Matter	Ext. P (PBrl)	CEC	Exch. Bases cmol(+)/kg			
	(cm)		mS/cm	%	%	%	mg/kg	cmol(+)/kg	Ca+	Mg+	K+	Na+
GP7C	0 - 20	6.2	0.06	0.21	2.11	3.63	7.72	26.6	11.19	5.11	0.65	0.43
	21 - 40	5.04	0.04	0.09	0.99	1.70	5.95	14	3.72	1.57	0.09	0.04
	41 - 60	4.27	0.01	0.05	0.72	1.24	4.79	12.2	2.94	0.26	0.07	0.03

ii) Soil Salinity

Salt affected soils are generally classified using electrical conductivity of the soil-water extract, ECe, as the basis. The electrical conductivity of the soil ranged from 0.01 mS/cm to 0.08 mS/cm in the fields BP5B, BP5C, BP5D (Tables 13 to 15) and in fields GP7A, GP7B, GP7C (Tables 16 to 18). According to FAO (1985), moderately sensitive crops like sugarcane begin to lose yields between 1.3 and 2.0 dS/m. That meant the salt concentration in the soil for the Estate was very low and did not affect sugarcane yield.

iii) Total Nitrogen

The total nitrogen in the fields BP5B, BP5C, BP5D (Tables 13 to 15) ranged from 0.06 to 0.25 percent. This amount of nitrogen was very low to medium whereas in the fields GP7A, GP7B, GP7C (Tables 16 to 18) ranged from very low to low (0.04 to 0.21) percent. These low values of total nitrogen caused low cane yield especially in the fields under BP5.

iv) Organic Carbon

The amount of organic carbon in the fields BP5B, BP5C and BP5D (Tables 13 to 15) ranged from very low to medium (0.21 to 1.99) percent, while in fields GP7A, GP7B, GP7C (Tables 16 to 18) it ranged from 0.29 to 2.11 percent which was also very low to medium. Organic carbon increases aggression and improves soil structure, decreases soil density, and hence increases available water content (Ross, 1997). In sandy soils, organic carbon provides fine particles, which effectively reduces average particle size (Ross, 1997). The small amount of organic carbon was probably due to burning of sugarcane fields during harvesting and hence less amount of organic matter was decomposed. These low values of organic carbon caused low cane yield especially in the fields under BP5.

v) Available Phosphorous

The available phosphorous in the fields BP5B, BP5C, BP5D (Tables 13 to 15) for the top soil ranged from low to medium (6.1 to 18.38) mg/kg (Appendix 7), while in fields GP7A, GP7B, GP7C, it ranged from medium to high (7.72 to 21.2) mg/kg. The high amount of phosphorous in the field under CP GP7 (Tables 16 to 18) might be contributed by large values of soil pH (Harris, 2005). In both fields, the available phosphorous decreased with depth. These low values of available phosphorous caused low cane yield especially in the fields under BP5.

vi) Cation Exchange Capacity

The cation exchange capacity is a measure of the ability of a soil to retain cations, some of which are plant nutrients (Ross, 1997). The cation exchange capacity from the fields BP5B, BP5C, BP5D (Tables 13 to 15) ranged from 5.8 to 24.6 cmol(+)/kg which was very low to medium (Appendix 7), whereas in the fields GP7A, GP7B, GP7C (Tables 16 to 18) it ranged from 10.8 to 6.6 cmol(+)/kg, which was low to high. These values of CEC showed that in field under CP GP7, there was low to high clay and organic matter in the soil (Ross, 1997). The high amount of clay and organic matter was observed in the field that was irrigated by CP GP7. Field under CP BP5 might need more frequent application of fertilizer than under CP GP7 due to its low CEC (Ross, 1997). The lower the cation exchange capacity the lower the crop yields as in field BP5.

vii) Exchangeable Bases (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+})

The exchangeable calcium ions in the fields BP5B, BP5C, BP5D (Tables 13 to 15) ranged from 2.02 to 10.12 cmol(+)/kg which was very low to high (Appendix 7). The exchangeable magnesium ranged from 0.56 to 4.15 cmol(+)/kg which was low to high and the exchangeable potassium ranged from 0.05 to 0.57 cmol(+)/kg which was very low to medium. The exchangeable sodium ranged from 0.33 to 0.82 cmol(+)/kg which was medium to high. In the fields GP7A, GP7B, GP7C (Tables 16 to 18) the exchangeable calcium ranged from 2.07 to 11.19 cmol(+)/kg, which was low to high and the exchangeable magnesium ranged from 0.26 to 5.11 cmol(+)/kg which was very low to high. The exchangeable potassium ranged from 0.07 to 0.82 cmol(+)/kg which was very low to medium. The exchangeable sodium were also ranged from 0.03 to 0.51 cmol(+)/kg; which was very low to medium (Appendix 7). These results indicated that, calcium and magnesium were in deficiency as the result of low cane yield, thus requiring supplements through fertilizer or sugarcane pulp application.

4.3 Irrigation Water Quality

4.3.1 pH and ECw of Water

The irrigation water quality was primarily determined by the analysis of water pH and the electrical conductivity of irrigation water which were found to be the major water quality determining factors. The water pH was 7.12 which were within the normal range (6.5 to 8.4) while the electrical conductivity of irrigation water was 0.14 mS/cm which was less than 0.7 dS/m indicating that there was no significant salt concentration in the irrigation water. Therefore, water pH and ECw were not factors responsible for low sugarcane yield.

4.3.2 Specific ion toxicity

The sodium content in irrigation water was very low (0.3 meq/l). Also the Chloride ions in the irrigation water was low (1.5 meq/l), whereas the amount of boron was very low (0.5 mq/l). Moreover, the amount of bicarbonates was very low (0.53me/l). Therefore, specific ion toxicity was not factors responsible for low sugarcane yield.

4.3.3 Sodium adsorption ratio (SAR)

The relative concentration of sodium to calcium and magnesium was found from the equation of their relationship (McFarland *et al.*, 1998). The calcium content in irrigation water was 3.5 meq/l, whereas the magnesium content was 2.6 meq/l. Then SAR was found to be 0.17, which was moderate. Thus, the irrigation water is of very high quality.

4.4 Statistical Comparison Between Recommended with Measured Parameters

The statistical Z – distribution (Carver, 1978) was used to compare the recommended parameters to the measured ones. It was found that at 0.05 level of significance, the measured parameters for GP7 had no significance difference between the recommended and the observed ones while for BP5 there is significant differences.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following are the conclusions from the study:

1) The average uniformity was found to be higher for the centre pivot GP7 than for BP5. However, it was difficult to obtain a complete description of the spray pattern because of its discontinuous nature. The observation from centre pivot which showed poor CU were associated with low application rate and operating pressure, CP speed at the end drive unit misallocation of nozzles and nozzle clogging in some of sprinklers. The average actual PELQ found at Kagera Sugar Estate for both centre pivots was lower than the recommended minimum.

2) The AELQ was lower than PELQ in both systems. For instance, it was less by 18.4% and 13.9% for GP7 and BP5. This could be the factor contributing to more water application especially in the mid and outermost spans hence more losses as the result of water logging especially in the CP BP5 which was poorly levelled. This also could be the factor responsible for high level of acidity and might later cause salinity problem.

3) To improve the uniformity of application and efficiencies, the sprinkler package should be reviewed and the operating pressure should be calibrated to the required range of some centre pivot irrigated fields. On the other hand, both pivot and pump operators should be trained on how they should operate so as to attain the required uniformity and efficiencies. The system should also be provided with automatic

water pressure control valves at the water pump stations so as to avoid system damage in case of high system pressure above the threshold value hence give pump operators confidence of the running the system at high pressures to improve uniformity, discharge and hence high efficiencies of the system.

4) Though the basic infiltration rate was higher than the application rate, there were still run off problems especially in the last towers. This could have been attributed by sprinkler package used and soil compaction by farm machinery and poor soil structure and the actual set speed of the centre pivot. In some areas there was less application due to clogging of sprinkler nozzles showing that water was not well filtered from the pump stations and poor inspection by centre pivot operators.

5) Generally soils at Kagera Sugar Estate were good for sugarcane growth. Currently, they are saline free, however, in future this problem may exist due to water logging problems caused by poor levelling of the land as recognized in some parts of the CP BP5. The CP BP5, soils were sandy textured and the application rate was lower than the crop evapotranspiration; this could be one of the factors responsible for poor yield of sugarcane due to water stress. The bulk density of the soil in some areas was found to be high which might increase the resistance to sugarcane root penetration, due to the reduced total volume of soil pores.

6) Another problem identified in the soil was the acidic nature of the soils. This acidity was high to allow solubility of toxic elements such as aluminium and some nutrients such as phosphorous were not soluble resulting in low yields.

7) Organic carbon in both fields was very low to medium showing that the amount of organic matter was very low requiring improved methods of land conservation such as using sugar cane trashes instead of burning them after harvesting.

8) Generally it showed that CP BP5 was more disadvantaged in terms of nutrients availability than CP GP7 due to difference in soil quality. On the other hand, irrigation water from Kagera river basin was of good quality that it could not be the factor responsible for poor yield in some of the fields.

5.2 Recommendations

The following are the recommendations from the study:

1) To improve the uniformity of application and efficiencies, the spray nozzle sprinkler set should be reviewed and the operating pressure should be adjusted to the required range of some centre pivot irrigated fields. On the other hand, both pivot and pump operators should be trained on how they should operate so as to attain the required uniformity and efficiencies.

2) The system should be provided with automatic water pressure control valves at the water pump stations so as to avoid system damage in case of high system pressure above the threshold value hence give pump operators confidence of the running the system at high pressures to improve uniformity, discharge and hence high efficiencies of the system. Also centre pivot speed should be calibrated so that the actual speed equals to set speed in order to allow the system to complete the design revolution at the required time (24 hours) per revolution.

3) Drainage system should be designed and constructed to avoid salinity problems in future, reduce the rise of water table and hence less water logging. Currently, the drainage system is not well designed and hence the company uses a lot of manpower particularly for drainage work during rainy season.

4) In future, centre pivot installations should increase the irrigation interval from one to two days maintaining 24 hours to complete one revolution by changing the sprinkler set. The second day should be used for maintenance in case of any damage; this will ensure the system to continue working. Unlike nowadays where the design does not provide time for maintenance resulting into sugarcane wilt in case of serious damage of the system.

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APPENDICES

Appendix 1: Catch results of CP GP7 at a distance between 100 - 250 m from the pivot

Container catch data in units of ml, volume/depth 100 ml, span length 55 m, container spacing 3 m.

Evaporation: Initial: 200 Initial: 200

Final: 192 Final: 194.5

Loss: 8 Loss: 5.5 Average loss: 6.75

Position no.	Span no.	Catch (ml)	Weighted catch (ml)
14	3	51	714
15	3	56	715
16	3	78	1170
17	3	79	1171
18	3	81	1296
19	3	81	1297
20	3	83	1298
21	3	65	1299
22	3	70	1300
23	3	72	1301
24	3	73	1302
25	3	78	1303
26	4	94	1304
27	4	70	1305
28	4	66	1306
29	4	53	1307
30	4	51	1308
31	4	53	1309
32	4	84	1310
33	4	100	1311
34	4	150	1312
35	4	98	1313
36	5	115	1314
37	5	103	1315
38	5	111	1316
39	5	127	1317
40	5	148	1318
41	5	102	1319
42	5	95	1320
43	5	92	1321
44	5	90	1322
45	5	131	1323
46	5	140	1324
47	5	110	1325
48	5	100	3100

Appendix 2: Catch results of CP GP7 at a distance between 250 - 400 m from the pivot

Container catch data in units of ml, volume/depth 100 ml, span length 55 m, container spacing 3 m.

Evaporation: Initial: 200 Initial: 200

Final: 185 Final: 190.4

Loss: 15 Loss: 9.6 Average loss: 12.3

Position no.	Span no.	Catch (ml)	Weighted catch (ml)
49	5	107	3424
50	5	105	3425
51	6	122	3426
52	6	111	3427
53	6	102	3428
54	6	123	3429
55	6	150	3430
56	6	98	3431
57	6	74	3432
58	6	120	3433
59	6	104	3434
60	6	107	3435
61	6	108	3436
62	6	97	3437
63	6	102	3438
64	6	102	3439
65	7	91	3440
66	7	91	3441
67	7	95	3442
68	7	101	3443
69	7	110	3444
70	7	102	3445
71	7	98	3446
72	7	95	3447
73	7	100	3448
74	7	102	3449
75	7	100	3450
76	7	70	3451
77	8	74	3452
78	8	115	3453
79	8	134	3454
80	8	157	3455
81	8	174	3456
82	8	123	3457
83	8	96	3458

Appendix 3: Catch results of CP GP7 at a distance between 400 - 550 m from the pivot

Container catch data in units of ml, volume/depth 100 ml, span length 55 m, container spacing 3 m.

Evaporation: Initial: 200 Initial: 200

Final: 192 Final: 186.9

Loss: 8 Loss: 13.1 Average loss: 9.3

Position no.	Span no.	Catch (ml)	Weighted catch (ml)
84	8	105	5250
85	8	102	5251
86	8	102	5252
87	8	102	5253
88	8	100	5254
89	8	110	5255
90	9	124	5256
91	9	129	5257
92	9	140	5258
93	9	120	5259
94	9	115	5260
95	9	123	5261
96	9	174	5262
97	9	145	5263
98	9	104	5264
99	9	107	5265
100	9	109	5266
101	9	89	5267
102	9	80	5268
103	9	81	5269
104	10	103	5270
105	10	101	5271
106	10	105	5272
107	10	103	5273
108	10	106	5274
109	10	93	5275
110	10	80	5276
111	10	124	5277
112	10	139	5278
113	10	128	5279
114	10	116	5280
115	10	127	5281
116	10	150	5282
117	10	123	5283
118	10	120	5284
119	10	113	5285
120	10	104	5286

Appendix 4: Catch results of CP BP5 at a distance between 100 - 250 m from the pivot

Container catch data in units of ml, volume/depth 100 ml, span length 55 m, container spacing 3 m.

Evaporation: Initial: 200 Initial: 200

Final: 191.1 Final: 191.9

Loss: 8.9 Loss: 8.1 Average loss: 8.5

Position no.	Span no.	Catch (ml)	Weighted catch (ml)
14	3	53	742
15	3	52	780
16	3	53	848
17	3	53	901
18	3	54	972
19	3	54	1026
20	3	57	1140
21	3	56	1176
22	3	63	1386
23	3	64	1472
24	4	68	1632
25	4	71	1775
26	4	75	1950
27	4	77	2079
28	4	80	2240
29	4	102	2958
30	4	115	3450
31	4	123	3813
32	4	127	4064
33	4	127	4191
34	4	128	4352
35	4	123	4305
36	4	121	4356
37	4	114	4218
38	5	110	4180
39	5	112	4368
40	5	141	5640

Appendix 5: Catch results of CP GP7 at a distance between 250 - 400 m from the pivot

Container catch data in units of ml, volume/depth 100 ml, span length 55 m, container spacing 3 m.

Evaporation: Initial: 200 Initial: 200

Final: 189.5 Final: 192.1

Loss: 10.5 Loss: 7.9 Average loss: 9.2

Position no.	Span no.	Catch (ml)	Weighted catch (ml)
41	5	100	3612
42	5	121	3613
43	5	119	3614
44	5	124	3615
45	5	120	3616
46	5	155	3617
47	5	185	3618
48	5	102	3619
49	6	97	3620
50	6	103	3621
51	6	108	3622
52	6	100	3623
53	6	102	3624
54	6	117	3625
55	6	128	3626
56	6	128	3627
57	6	130	3628
58	6	123	3629
59	7	123	3630
60	7	80	3631
61	7	132	3632
62	7	100	3633
63	7	128	3634
64	7	105	3635
65	7	128	3636
66	7	150	3637
67	7	102	3638

Appendix 6: Catch results of CP GP7 at a distance between 400 - 550 m from the pivot

Container catch data in units of ml, volume/depth 100 ml, span length 55 m, container spacing 3 m.

Evaporation: Initial: 200 Initial: 200

Final: 188.6 Final: 187.4

Loss: 11.4 Loss: 12.6 Average loss: 10.3

Position no.	Span no.	Catch (ml)	Weighted catch (ml)
68	7	96	4032
69	7	97	4033
70	7	98	4034
71	7	100	4035
72	8	116	4036
73	8	105	4037
74	8	105	4038
75	8	70	4039
76	8	125	4040
77	8	110	4041
78	8	112	4042
79	8	71	4043
80	8	102	4044
81	8	100	4045
82	8	120	4046
83	8	101	4047
84	9	114	4048
85	9	114	4049
86	9	116	4050
87	9	56	4051
88	9	119	4052
89	9	98	4053
90	9	107	4054
91	9	106	4055
92	9	106	4056
93	9	112	4057
94	9	120	4058
95	9	105	4059
96	9	117	4060
97	9	117	4061
98	End	141	Omit

Appendix 7: Guidelines to general evaluation of soil chemical and physical properties

1. Organic matter and total nitrogen

	very low	Low	Medium	High	very high
Organic matter %	<1.00	1.00 - 2.00	2.10 - 4.20	4.30 -6.00	>6.00
Organic C %	<0.60	0.60 - 1.25	1.26 - 2.50	2.51 -3.50	>3.50
Total N %	<0.10	0.10 - 0.20	0.21 - 0.50	.0.50	

C/N ratios give more information about the availability of nitrogen than total N levels only.

C/N ratios indicate the quality of the organic matter:

C/N 8 - 13 : good quality

C/N 14 - 20 : moderate quality

C/N > 20 : Poor quality

2. Soil reaction

Soil reaction (pH H_2O) is classified as follows:

extremely acid	pH below 4.5	Neutral	pH 6.6 - 7.3
very strongly acid	pH 4.5 - 5.0	mildly alkaline	pH 7.4 - 7.8
strongly acid	pH 5.1 - 5.5	moderately alkaline	pH 7.9 - 8.4
medium acid slightly acid	pH 5.6 - 6.0	strongly alkaline	pH 8.5 - 9.0
slightly acid	pH 6.1 - 6.5	very strongly alkaline	pH above 9.0

very slightly acid	pH 6.6 - 6.9
neutral	pH 7.0
very mildly alkaline	pH 7.1 - 7.3

3. Available phosphorous (P)

mg/kg	Low	Medium	High
Availa. P (Bray-Kurtz I)	<7	7 - 20	>20
Avail. P (Olsen)	<5	5 - 10	>10

Available phosphorous is determined by the Bray-Kurtz I method if the pH H_2O of the soil is les than 7.0. In soils with a pH H_2O of ore than 7.0 the Olsen method is used.

4. Cation exchange capacity (CEC)

me/100 g	very low	Low	Medium	High	very high
CEC	<6.0	6.0 -12.0	12.1- 25.0	25.0 - 40.0	>40.0

CEC is determined using 1M ammonium acetate in soils with pH less than 7.5. In soils with pH greater than 7.5 CEC is determined using 1M sodium acetate.

5. Exchangeable calcium (Ca)

me/100 g	very low	Low	Medium	High	very high
Ca (clayey soils rich in 2:1 clays)	<2.0	2.0 - 5.0	5.1 - 10.0	10.1 - 20.0	>20.0
Ca (loamy soils)	<0.5	0.5 - 2.0	2.1 - 4.0	4.1 - 6.0	>6.0
Ca (kaolinitic and sandy soils)	<0.2	0.2 - 0.5	0.6 - 2.5	2.6 - 5.0	>5.0

6. Exchangeable magnesium (Mg)

me/100 g	very low	Low	Medium	High	very high
Mg (clayey soils)	<0.3	0.3 - 1.0	1.1 - 3.0	3.1 - 6.0	>6.0
Mg (loamy soils)	<0.25	0.25 - 0.75	0.75 - 2.0	2.1 - 4.0	>4.1
Mg (sandy soils)	<0.2	0.2 - 0.5	0.50 - 1.0	1.1 - 2.0	>2.0

The desired saturation level of exchangeable Mg is 10 to 15 percent: for sandy and kaolinitic soils 6 to 8 percent Mg saturation is still sufficient.
Ca/Mg ratios of 2 to 4 are favorable.

7. Exchangeable potassium (K)

me/100 g	very low	Low	Medium	High	very high
K (clayey soils)	<0.2	0.2 - 0.4	0.41 - 1.2	1.21 - 2.0	>2.0
K (loamy soils)	<0.13	0.13 - 0.25	0.26 - 0.8	0.81 - 1.35	>1.35
K (sandy soils)	<0.05	0.05 - 0.1	0.11 - 0.4	0.41 - 0.7	>0.7

The desired saturation level of exchangeable K is 2 to 7 percent.
Favourable Mg/K ratios for most crops are in the range of 1 to 4.

8. Exchangeable sodium (Na)

me/100 g	very low	Low	Medium	High	very high
Na	<0.1	0.1 - 0.3	0.31 - 0.7	0.71 - 2.0	>2.0

More important than the absolute level of exchangeable Na is the exchangeable sodium percentage (ESP) calculated by dividing exchangeable Na by CEC (* 100). ESP values are a measure of the sodicity of the soil.

9. Soil sodicity

	Non-sodic	Slightly sodic	Moderately sodic	Strongly sodic	Very strongly sodic	Extremely sodic
ESP %	<6	6 - 10	11 - 15	16 - 25	26 - 35	>35

ESP 16 - 25 %	up to 50 percent yield reduction of sensitive crops (maize, beans, sugarcane, sorghum)
ESP 35%	up to 50 percent reduction yield of semi-tolerant crops (rice, wheat)
	up to 50% yield-reduction of tolerant crops (barley, cotton)

10. Basic infiltration rate (IR)

IR <0.1 cm/h	extremely slow
IR 0.1-0.3 cm/h	very slow
IR 0.3-0.5 cm/h	slow
IR 0.5-2.0 cm/h	moderately slow
IR 2.0-6.5 cm/h	moderately slow
IR 6.5-12.5 cm/h	moderately rapid
IR 2.5-25.0 cm/h	rapid
IR >25.0 cm/h	very rapid

Basic infiltration rate is the constant rate at which water enters the (pre-wetted) soil and which develops after 3 to 5 hours of infiltration.

11. Available water capacity (AWC)

AWC	<25 mm/m	extremely low
AWC	25-50 mm/m	very low
AWC	50-100 mm/m	low
AWC	100-150 mm/m	medium
AWC	150-200 mm/m	high
AWC	>200 mm/m	very high

Available water capacity is the capacity of the soil to store water that is readily available for uptake by plant roots: usually expressed in millimeters of water per metre depth of soils: technically the difference between the percentage of soil water at field capacity (normally taken as the water content at pF 2.2) and the percentage at wilting point (taken as the water content at pF 4.2).

Source: Bray and Kurtz (1945)

Appendix 8: Guidelines for interpretation of water quality for irrigation[1]

Potential Irrigation Problems	Units	Degree of Restriction on use		
Salinity (effects of crop water availability)[2]		None	Slight to moderate	Severe
ECw (or)	dS/m	<0.7	0.7-3.0	>3.0
TDS	g/l	<450	450-2000	>2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using ECW and SAR together[3]				
SAR0 to 3 and ECW		>0.7	0.7-0.2	<0.2
3 to 6		>1.2	1.2-0.3	<0.3
6 to 12		>1.9	1.9-0.5	<0.5
12 to 20		>2.9	2.9-1.3	<1.3
20 to 40		>5.0	5.0-2.9	<2.9
Specific Ion Toxicity (affects sensitive crops)				
Sodium (Na)[4]				
surface irrigation	SAR	<3	3 - 9	>9
sprinkler irrigation	me/l	<3	>3	
Chloride (Cl)[4]				
surface irrigation	me/l	<4	4 - 9	>10
sprinkler irrigation	me/l	<3	>3	
Boron (Br)5	mg/l	<0.7	0.7 - 3.0	>3.0
Trace Elements (see Table 21)				
miscellaneous Effects (*affects susceptible crops*)				
Nitrogen (NO_3 - N)[6]	mg/l	<5	5 - 30	>30
Bicarbonate (HCO_3) (Overhead sprinkling only)	me/l	<1.5	1.5 - 8.5	>8.5
pH			Normal Range 6.5 - 8.4	

1 Adapted fro University of California Committee of Consultants 1994

2 ECW means electrical conductivity, a measure of water salinity, reported in deciSiemens per meter at 25°C (dS/m)or in units millimhos per centimetre (mmho/cm). Both are equivalent. TDS means total dissolved solids, reported in milligrams per litre (mg/l).

3 SAR means sodium adsorption ratio. SAR is sometimes reported by the symbol RNa. At a given SAR, infiltration rate increases as water salinity increases. Evaluation of potential infiltration problem by SAR as modified by ECw. Adopted fro Rhodes 1977. and Oster and Sehroer 1979.

4 For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride: use the values shown. Most annual crops are not sensitive: use the salinity tolerance crops. For chloride tolerance of selected fruit crops. With the overhead sprinkler irrigation and low humidity (< 30%), sodium and chloride ay be absorbed through the leaves of sensitive crops.

5 Boron tolerances

6 NO_3 - N means nitrate nitrogen reported in terms of elemental nitrogen (NH_4 - N and Organic - N should be included when waste water is being tested.

Source: Bray and Kurtz (1945).