

**PERFORMANCE OF CENTRE PIVOT SPRINKLER IRRIGATION SYSTEM: A
CASE STUDY OF UBOMBO SUGAR ESTATE, SWAZILAND**



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**A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN
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EXTENDED ABSTRACT

The centre pivot irrigation system is increasingly becoming popular among farmers around the world on account of the benefits the system can offer compared to other methods. Hence evaluation of system performance with the ultimate aim of attaining greater irrigation efficiency and better manage irrigation is paramount. The study evaluated the performance of centre pivot sprinkler irrigation system and its effect on sugarcane yield at Ubombo Sugar Estate in the Lubombo Region of Swaziland. Four centre pivots (EEL09, NKA21, CAS02 and SMB) were selected from 106 centre pivot machines for purposes of evaluation. Information collected included meteorological data, design parameters, water application uniformity, system operating pressure, tyre pressure, system flow rate, sprinkler nozzle discharge and pressure, crop data and planted area, harvesting programs, pumps and motor specifications, pumping hours, cost of power and actual flow rates. Drive speeds of 15%, 20%, 30% and 40% of the centre pivot systems were examined to determine their significance on system performance parameters on the basis of common field operations. Water and power budgeting systems utilized were assessed to determine adequacy of irrigation water supply and implications on system and crop performance. Irrigation water quality, soil physical and chemical properties, soil infiltration characteristics and soil compaction were also examined to determine their influence on system performance and sugarcane yields. Data analysis was carried out using Microsoft Excel, ETo Calculator, Instat, Statistical Package for Social Sciences (SPSS), ArcGIS and HPen32 software. Results demonstrated that centre pivots were accurately designed and properly installed as they adequately supplied water to meet sugarcane demand of 7.5 mm/day. Performance indicators showed that centre pivots were relatively performing well as uniformity indices (CU and DU) were within acceptable standards, i.e. above the base values of 85% for CU and 75% for DU. Recommended

application efficiencies (AELQ and PELQ) were only achieved by CAS02 and SMB centre pivot systems as they were above the minimum of 90%. Speed effect results showed a general decline in CU and DU with an increase in centre pivot speed as opposed to an increase in application efficiency. CU for SMB declined from 88.9% at 15% speed to 86.9% at 40% speed setting. A similar trend was evident for both NKA21 and EEL09. PELQ for SMB increased from 93.1% to 98.0% and AELQ from 92.6% to 100%. A parallel trend was also observed for NKA21 and EEL09. Analysis of variance for these results showed that the performance indicators were not significantly different ($p < 0.01$) among treatments. This demonstrated the ability of the centre pivot irrigation system to apply water uniformly and efficiently across the field at different speeds. Water and power budgets were not satisfactory in meeting estate crop water demand since they did not capture and consolidate relevant parameters needed to accurately define budgets. Water supply was determined by capacities of irrigation structures used and losses were incurred during periods of low demand. Electricity budgets were based on historical power records which affected overall water supply and caused water stress to the crop. Quality of irrigation water was within acceptable levels and had no negative impact on system, crop and soil. Soil physical and chemical properties indicated that soils were inherently sandy and ideal for sugarcane growth save for shallow profiles with low water holding capacities. Soil compaction as a result of mechanical harvesting was a major cause of significant reduction in soil infiltration rates, water storage capacity and hence runoff. Significantly higher soil compaction values at 0 to 15 cm depth ($p < 0.01$) were associated with EEL09 centre pivot with an average of 3 210 kPa compared to those of NKA21 at 596 kPa, CAS02 at 447 kPa and SMB at 1 389 kPa. Identical observations were made at 0 to 30 cm depth where higher compaction values were associated with EEL09 and SMB. EEL09, a sandy textured field measured a basic infiltration rate of 6 mm/h as a result of compaction while the other less compact sandy textured fields had

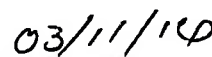
infiltration rates greater than 70 mm/h. Yields were variable as EEL09 achieved a low yield of 71 t/ha against 147 t/ha for CAS02, 124.8 t/ha for NKA21 and 106 t/ha for SMB. Findings indicate that centre pivots are performing well although potential system performance and sugarcane yields are constrained by limited water and power supply, pressure variations, clogging of sprinklers, rutting of un-gravelled tracks, soil compaction, low water holding capacities, reduced infiltration rates and game encroaching sugarcane fields. It is therefore recommended that constant system checks, improvement of traction on centre pivot wheels, development of new model for water and power budgets as well as undertaking of extensive research on the effects of mechanical harvesting be done so as to improve centre pivot irrigation system performance and sugarcane yields at Ubombo Sugar Estate.

DECLARATION

I, Sandile Trevor Msibi, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.



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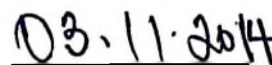


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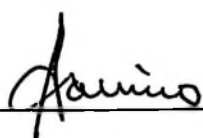
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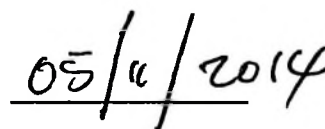
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DEDICATION

This work is dedicated to my wife Nozipho Cherrone Mahlalela-Msibi and our unborn child for their uniform love and continued support during the process as they endured all pain and suffering. The work is also dedicated to my late father Jethro Themba Msibi who laid the foundation for my education and family members who were in full support before, during and after this work, may the Lord Almighty bless them forever.

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LIST OF PUBLISHED PAPERS

Paper One: **S.T. Msibi**, N.I. Kihupi, A.K.P.R. Tarimo and A.M. Manyatsi (2014).
Evaluation of Speed Effect on the Technical Efficiency of Centre Pivot Irrigation at
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DECLARATION

I, Sandile Trevor Msibi, do hereby declare to the Senate of Sokoine University of Agriculture that the above listed papers that make this dissertation summarize my independent efforts, it is my own original work and will not be part of another dissertation in the "Published Papers" format in any other University.

CHAPTER ONE

1.0 INTRODUCTION

1.1. Background Information

Despite the impetus and technological advancements in the irrigation industry, the performance of irrigation systems remains a serious concern in many parts of the world and has attracted the attention of researchers, planners and managers in recent years (Ntanos and Karpouzos, 2010). Irrigation system performance plays a significant role in crop performance, water use efficiency, cost of production and income generation (Mudima, 2001; Smith, 2010). Although centre pivots are becoming the most commonly used irrigation method, Sabah *et al.*, (2011) reported that most irrigation equipment in the United States has not been evaluated for system uniformity hence low system performance. Field measurements of water distribution for low pressure spray nozzle indicate that rotational uniformity appears to be a problem as opposed to nearly identical uniformities of high pressure and low pressure impact sprinklers (King and Kincaid, 1997). Key factors that limited achievement of benchmarked yields under centre pivot irrigation systems in Southern Riverina include sodic non self-mulching heavy textured soils and inadequate system capacities during peak demand (North, 2012). Porter and Marek (2009) studied the relationship between centre pivot sprinkler depth of water application and water holding capacity and observed that optimizing centre pivot irrigation performance relies on system management. Water application uniformity measurements in Brazil demonstrated that performance parameters varied according to conditions imposed by climate, operating pressure, speed and direction of rotation of the machine and also the type of nozzle utilized (Sandri and Cortez, 2009). It has also been reported in Egypt that better water distribution and application rates are associated with operating pressure adjustments closer to ideal pressures (Safwat, 1988).

In Iran, Mohammad (2012) observed that accurate design and installation of centre pivot sprinkler irrigation systems could optimize performance particularly through careful consideration of flow situations in centre pivot pipes. The design of the system is crucial for future operation and management of the irrigation system and the potential for efficient irrigation as reported by Edkins (2006) in New Zealand. In Australia, Smith and North (2009) argued that knowledge of changes in the magnitude of water applied over time is important to determine the causes of deficiencies in application rates and uniformities. Non-uniform water application leads to over or under irrigation in various parts of the field which can result in wasted water, energy and the potential for nitrogen leaching. Sloping terrain conditions and development of deep ruts in the wheel tracks affected the lifespan of gearboxes and motors in Mauritius and this has transformed the centre pivot irrigation technology into a standing monument of inefficiency (Teeluck, 1998). Spatial variability in soil properties has been reported to be responsible for the variable crop yields under centre pivot irrigation in Saudi Arabia (Al-Gaadi, 2013). Al-Ghobari (2011) also observed differences in the effect of water quality on soil salinity depending on the irrigation water, soil type and leaching requirement under centre pivot irrigation in the Arid region of Saudi Arabia.

Reuben *et al.*, (2010) reported that the poor performance of centre pivot sprinkler irrigation system, low water holding capacities and soil acidity were the major factors contributing to low sugarcane yields in Tanzania and suggested that systems have to be correctly managed to ensure that the distribution uniformity and efficiencies are within acceptable levels. Performance measurements of water applications and distribution were generally lower than expected standards and further research was needed to identify causes in Sudan (Ali, 2012). Idris (2010) and Salih (2013) studied the effect of operational speed on centre pivot performance in the Northern State of Sudan and

concluded that there is a general increase in the coefficient of uniformity and distribution uniformity with an increase in rotational speed although a decline in application efficiency was observed.

In South Africa, Griffiths (2006) discovered that the main factors which contributed to centre pivot irrigation systems having lower than expected application efficiency and distribution uniformity values were poor irrigation system design, poor irrigation system management, non-existent or inadequate maintenance schedules and non-existent water testing procedures. Reinders (2001) also outlined the reasons for centre pivots having lower than expected performance indicators as a result of a combination of incorrect pressures, worn out sprinklers and inaccurate designs. Lecler (2004) suggested that to ensure the long term viability of the sugarcane industry in Zimbabwe, development and adoption of strategies to improve the performance of the various water management and irrigation systems was needed. In countries like Mozambique, Malawi and Zambia, centre pivot irrigation has been recently adopted (Mayerhofer *et al.*, 2010) with limited documentation on performance measurements.

Although mainly used by large scale growers, centre pivot sprinkler irrigation system has also proved suitable for small scale growers in organized associations in Swaziland due to water scarcity (Magwenzi and Nkambule, 2003). Recent analyses show that centre pivots are both economically and financially viable under the current pricing system in Swaziland (Magwenzi, 2002). However, no performance evaluation of the systems has been conducted since their introduction in Swaziland about 15 years ago. Irrigation research in Swaziland has been largely focused on feasibility studies aimed at developing national irrigation schemes. Major constraints identified include application rates that exceed the infiltration capacity of most soils in Swaziland and the limitations imposed by

the need to irrigate outfall areas on existing rectangular fields (Magwenzi and Nkambule, 2003). Evaluation of centre pivot sprinkler irrigation system performance at Ubombo Sugar Estate was therefore crucial to establish knowledge base on performance and its influence on sugarcane production to justify adjustments on configurations and management that will optimize water use and sugarcane yields, hence the purpose of this study.

1.2. Objectives

1.2.1. Main objective

The overall objective of the study was to evaluate the performance of centre pivot sprinkler irrigation system at Ubombo Sugar Estate in Swaziland.

1.2.2. Specific objectives

The specific objectives included to:

1. Determine the performance parameters of centre pivot sprinkler irrigation system.
2. Examine the influence of soil and water characteristics on centre pivot sprinkler irrigation system performance.
3. Determine the influence of centre pivot sprinkler irrigation system performance on sugarcane yields.
4. Determine factors affecting the performance of centre pivot sprinkler irrigation system and recommend optimal system configurations and management.

CHAPTER TWO

2.0 PUBLISHED PAPERS

PAPER ONE

2.1. Evaluation of Speed Effect on the Technical Efficiency of Centre Pivot Irrigation at Ubombo Sugar estate, Swaziland

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EVALUATION OF SPEED EFFECT ON THE TECHNICAL EFFICIENCY OF CENTRE PIVOT IRRIGATION AT UBOMBO SUGAR ESTATE, SWAZILAND

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ABSTRACT

As part of an ongoing research on centre pivot irrigation system performance at Ubombo Sugar estate, this paper reports on the results of an evaluation of speed effect on the technical efficiency of the system. Four speeds (15%, 20%, 30% and 40%) were studied on three centre pivot systems to compare maximum water application depth required to prevent runoff, revolution time, net depth of application, distribution uniformity (DU), coefficient uniformity (CU) and application efficiency which were adopted as indices for the determination of technical efficiency. Results revealed a general decline in CU and DU with an increase in centre pivot speed as opposed to an increase in application efficiency. SMB declined from a CU of 88.9% at 15% speed to 86.9% at 40% speed setting. This was evident for both NKA21 and EEL09. PELQ for SMB increased from 93.1% to 98.0%, AELQ from 92.6% to 100% and a parallel trend was observed for NKA21 and EEL09. Analysis of variance for these results showed that the performance indicators were not statistically significant at ($P = 0.01$) between treatments although a general trend was evident. This demonstrated the ability of centre pivot irrigation system to apply water uniformly and efficiently across the field at different speeds, hence the system can be used with ease for other field operations such as fertigation and chemigation which might require some adjustments on speed.

Key words: centre pivot, efficiency, irrigation, speed, sugarcane, Ubombo

INTRODUCTION

The centre pivot is increasingly becoming the most commonly used irrigation system around the world. 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 Swaziland, adoption of centre pivot irrigation dates back into the late 90s although a tremendous increase in the system usage became significant in the recent years. Ubombo Sugar estate in particular, is leading in the Swazi sugar industry with 106 centre pivot systems physically on the ground and the number is set to rise to 120 by the end of the centre pivot conversion project and anticipated strategic future developments of the estate. The project has been implemented for the past five years where poorly performing

furrow and dragline sprinkler systems are being replaced with centre pivot and a semi-solid set sprinkler system in the outfall of the pivots to better manage water and improve sugarcane yields.

For 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. 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 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.

Centre pivots are not only useful for irrigation but also for applying nutrients and chemicals to the crop through 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.

MATERIALS AND METHODS

Description of study site

The experiments were conducted in the season of 2013/14 at Ubombo Sugar estate in the south-east of Swaziland in the Lubombo region. The project had a net planted area of 11,200 ha under sugarcane with centre pivot irrigation occupying 47% of the area. Centre pivot systems ranged from 25 to 100 ha with semi- solid set sprinkler systems in the outfall of some of the pivots.

Experimental design

The completely randomized design (CRD) technique was used to generate a representative sample. Four different speeds including 15%, 20%, 30% and 40% were selected for experimentation and were replicated on three centre pivot irrigation systems through random selection from 106 centre pivot systems in the estate. The treatments were selected for purposes of investigating operational efficiency of centre pivot irrigation at field conditions. These included heavy irrigation, light irrigation, fertigation and chemigation where the speed settings normally ranged between 15% and 40% for the centre pivot systems depending on field operations.

Determination of technical efficiency

Distribution uniformity, coefficient of uniformity, application efficiency, net depth of application, maximum depth of water application required to prevent runoff and durations of system revolution were adopted as indices for determination of technical efficiency for centre pivot irrigation. These parameters were studied at the different speed settings for each centre pivot system through the volume of water caught in a radial of catch cans laid along the centre pivot lateral (Salah, 2013). Specialized techniques employed

to determine the performance indices were as discussed;

Maximum depth of application to prevent runoff

The maximum depth of water application to prevent run off for each treatment was estimated by the following equation.

$$Sr = \frac{24Dm}{DDIR} \quad (1)$$

Where: Sr = Rotational speed of centre pivot lateral (h/revolution)

Dm = Amount that can be applied per irrigation without runoff (mm/day)

DDIR = Design daily irrigation requirement (mm/day)

Travel speed and revolution time

The centre pivot speed was determined by measuring a defined length using a measuring tape along the path of the drive wheels and recorded the time taken by each centre pivot to complete the distance. Time per revolution for a centre pivot is a very important factor to take into consideration when designing centre pivot irrigation systems because it determines the rate of application to be considered as well as the irrigation interval for the system. The different speeds were set at the control point in the pivot panel and the actual speed was measured according to Merriam and Keller (1978).

Distribution Uniformity (DU)

The distribution uniformity was determined from catch cans data placed such that water from a complete pass of the centre pivot was collected (Rogers *et al.*, 2005). As the pivot was moving with catch cans aligned along the centre road, the length of the pivot was examined for leaks and sprinklers that may not be operating properly and it was noted in the data sheet. The distribution

uniformity coefficient (DU) was calculated based on the equation by ASAE (2003). According to Ascough and Kiker (2002), the distribution uniformity for centre pivot irrigation systems should be at least 75%.

Coefficient Uniformity (CU)

The uniformity coefficient, as a measure of the average absolute deviation from the average irrigation amount (Delirhasannia *et al.*, 2010) was determined from water collected from catch cans after the centre pivot has completely passed through the aligned cans. During calculations of the uniformity coefficient and other parameters, all gauges that did not collect water particularly because of physical clogging of nozzles were discarded during the determination of the performance parameters since they did not represent the system with regards to water application. The catch cans experiment is normally used to quantify how close the system is to a theoretical model in which all cans would contain exactly the same amount of water. The uniformity coefficient was calculated using the formula by James *et al.* (1982). According to Harrison and Perry, (2010) the coefficient of uniformity recommended for spray nozzle sprinkler centre pivots should be at least 85%.

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 centre pivot can be determined from how much of the applied water is stored in the soil and available for consumptive use and how uniformly is it applied. The recommended AELQ is at least 90% (Evans, 2001) and was achieved in the field at the

different speed settings and estimated according to Merriam and Keller (1978).

Potential Application Efficiency (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 according to Merriam and Keller (1978).

Statistical tool

The analysis of variance (ANOVA) was used to determine statistical significance of the results of each of the treatments obtained for the centre pivot systems.

RESULTS AND DISCUSSION

The results of the effects of the treatments on the technical efficiency of centre pivot irrigation system are presented in Tables 1 – 9. The trend is evident that with an increase in centre pivot speed, there is a general reduction in revolution times and the amount of water the irrigator can apply in the soil regardless of centre pivot size. The water application depth is crucial because it determines the volume of water stored in the soil and equilibrium must be reached between what the soil can take and what the system can apply to avoid over irrigation and runoff. Tables 1 – 3 demonstrate that gross application among centre pivots is usually higher than the maximum amount of water that can be applied at any particular speed to prevent the occurrence of runoff. Only NKA21 proved suitable to apply water within acceptable standards as opposed to SMB and EEL09 where the maximum limit was also exceeded by the net application at any given speed. Planting in circles, construction of furrow

dikes and maintaining trash in the field can reduce runoff and improve water intake through surface storage. Tables 4 – 6 also shows pressure variation at the pivot point of all the centre pivots. The results reveals pressure reduction with an increase in centre pivot speed as all systems had a pressure reduction in all four treatments.

Tables 7 – 9 present indicators of performance for the three centre pivot systems under the four treatments of 15%, 20%, 30% and 40% speed settings. The results indicate a reduction in CU and DU with an increase in centre pivot speed. SMB for example declined from CU of 88.9% at 15% speed to 86.9% at 40% speed setting. This is evident for both NKA21 and EEL09. Application efficiency on the other hand showed a remarkable increase with an increase in centre pivot speed where SMB had PELQ of 93.1% to 98.0%. The odd value of 93% at 40% speed setting is a result of a factor with the centre pivot configuration but not the treatments (speed) as PELQ and AELQ for NKA21 and EEL09 also increased steadily with an increase in centre pivot speed. In addition, these parameters of CU and DU were all satisfactory in all treatments as stated by Ascough and Kiker (2002) that centre pivot system DU should be at least 75% and CU should be at least 85%. In terms of application efficiency, only SMB met the requirements of 90% for PELQ and AELQ as stated by Savva and Frenken (2002). However, the analysis of variance (ANOVA) for these uniformity and efficiency measures were not statistically significant at ($P = 0.01$) between treatments although a general trend was evident. This demonstrates the ability of centre pivot irrigation system to apply water uniformly and efficiently across the entire field at different speeds. The differences among parameters on individual treatments might be attributed to pressure variations and depth of water applied during experimentation.

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Table 1: Maximum depth of application without runoff in the four treatments for SMB

Speed setting (%)	DDIR (mm/day)	Rev/time (hours)	Dm (mm/day)	Gross application (mm)	Net application (mm)
15	8.8	74.5	27.3	30.4	28.2
20	8.8	45.6	16.7	22.8	23.3
30	8.8	37.0	13.6	15.2	15.4
40	8.8	26.8	9.8	11.4	11.4

Table 2: Maximum depth of application without runoff in the four treatments for NKA21

Speed setting (%)	DDIR (mm/day)	Rev/time (hours)	Dm (mm/day)	Gross application (mm)	Net application (mm)
15	8.8	65.5	24.0	26.6	20.0
20	8.8	50.5	18.5	20.0	15.8
30	8.8	41.7	15.3	13.3	10.8
40	8.8	25.6	9.3	10.0	8.7

Table 3: Maximum depth of application without runoff in the four treatments for EEL09

Speed setting (%)	DDIR (mm/day)	Rev/time (hours)	Dm (mm/day)	Gross application (mm)	Net application (mm)
15	8.8	74.5	27.3	43.7	36.5
20	8.8	45.6	16.7	32.8	27.4
30	8.8	37.0	13.6	21.9	18.3
40	8.8	42.8	9.8	16.4	13.7

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Table 4: Revolution time and pressure variation for SMB in the four treatments

Speed setting (%)	Pressure (kPa)	Voltage (V)	CP speed (m/h)	Rev/time (hrs)
15	280	374	37.8	74.5
20	303	388	61.9	45.6
30	275	379	76.3	37.0
40	275	365	105.3	26.8

Table 5: Revolution time and pressure variation for NKA21 in the four treatments

Speed setting (%)	Pressure (kPa)	Voltage (V)	CP speed (m/h)	Rev/time (hrs)
15	365	402	37.7	65.5
20	350	421	48.9	50.5
30	340	413	59.2	41.7
40	340	417	96.3	25.6

Table 6: Revolution time and pressure variation for EEL09 in the four treatments

Speed setting (%)	Pressure (kPa)	Voltage (V)	CP speed (m/h)	Rev/time (hours)
15	320	393	21.0	74.5
20	320	401	28.1	45.6
30	315	409	42.1	37.0
40	310	415	56.1	42.8

Table 7: Performance parameters for SMB in the four treatments

Speed setting (%)	CU (%)	DU (%)	PELQ (%)	AELQ (%)	Actual depth (mm/day)	Target depth (mm/day)
15	88.9	88.7	93.1	92.6	28.2	30.4
20	88.9	87.3	98.7	100	23.3	22.8
30	88.0	86.1	98.0	100	15.4	15.2
40	86.9	85.0	93.0	100	11.4	11.4

Table 8: Performance parameters for NKA21 in the four treatments

Speed setting (%)	CU (%)	DU (%)	PELQ (%)	AELQ (%)	Actual depth (mm/day)	Target depth (mm/day)
15	91.4	91.2	73.3	75.3	20.0	26.6
20	91.4	90.3	73.0	78.8	15.8	20.0
30	90.2	91.3	78.9	81.5	10.8	13.3
40	89.7	87.7	87.0	86.7	8.7	10.0

Table 9: Performance parameters for EEL09 in the four treatments

Speed setting (%)	CU (%)	DU (%)	PELQ (%)	AELQ (%)	Actual depth (mm/day)	Target depth (mm/day)
15	92.0	93.2	76.3	75.1	36.5	43.7
20	91.6	92.4	76.8	78.8	27.4	32.8
30	90.2	91.3	78.9	81.5	18.3	21.9
40	89.7	89.2	84.8	83.5	13.7	16.4

CONCLUSION

The evaluation results demonstrate the ability of centre pivot sprinkler irrigation system to apply water more uniformly and efficiently at different speeds. The analysis of variance (ANOVA) for these results showed that the performance indicators were not statistically significant at ($P = 0.01$) between treatments although a general trend was evident. This therefore signifies the importance of using the system even for other field operations such as fertigation and chemigation due to high uniformity and efficiency which may require major adjustments on the system speed.

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PAPER TWO

**2.2. Technical Performance Evaluation of Centre Pivot Sprinkler Irrigation System
at Ubombo Sugar estate, Swaziland**

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TECHNICAL PERFORMANCE EVALUATION OF CENTRE PIVOT SPRINKLER IRRIGATION SYSTEM AT UBOMBO SUGAR ESTATE, SWAZILAND

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ABSTRACT

The study evaluated the performance of centre pivot sprinkler system to establish knowledge base on technical efficiency in order to justify pertinent managerial improvements and adjustments on system configurations that will optimize water use and sugarcane yields at Ubombo. Information was collected on a set of irrigation parameters that included water application uniformity, system operating pressure, tyre pressure, travel speed, system flow rate, sprinkler nozzle discharge and pressure as well as design parameters for four centre pivots. Data collected and analysed on weather parameters using Instat software included radiation, wind speed, relative humidity, maximum and minimum temperatures. The performance indicators used were the Distribution Uniformity (DU), the Coefficient Uniformity (CU), the Application Efficiency of Low Quarter (AELQ) and the Potential Application Efficiency of Low Quarter (PELQ). The performance was found satisfactory in terms of CU and DU for EEL09 (89.7%, 89.2%), NKA21 (94.6%, 95.7%) and SMB (88.7, 89.6%). CAS02 only achieved a CU of 80.5% and DU of 77.2% which was below recommended standards with regards to CU, DU was fair but on the lower side. The PELQ and AELQ were achieved by SMB and CAS02 although it was a result of over application with poor uniformity for CAS02. EEL09 and NKA21 did not meet the minimum requirement of 90% in both parameters. Pressure variations beyond nominal ranges at pivot points, tyres and sprinklers as well as excessive application rates due to sprinkler nozzle wear affected system performance. Based on the research findings it is recommended that operating pressure be checked against design pressure and corrected. The sprinkler nozzles should be checked for blockages, wear and tear, and application rates. Tyre pressure should be checked and corrected accordingly. Temporal and spatial evaluation procedures should be carried out for effective performance assessment of the centre pivot irrigation systems within the estate.

Key words: centre pivot, design specification, efficiency, irrigation, performance, water

INTRODUCTION

The performance of irrigation systems is of concern in many areas of the world and has attracted the attention of researchers, planners and managers of irrigation systems in recent years (Ntanos and Karpouzou, 2010). Irrigation system performance plays a significant role in crop performance, water use efficiency, cost of

production and income generation (Mudima, 2001; Smith, 2010). King and Kincaid (1997) studied optimal performance of centre pivot sprinkler system and proposed that low pressure spray sprinklers should replace original high pressure sprinklers, hence the evolution of the new low pressure spray nozzle centre pivot.

Porter and Marek (2009) reported the relationship between centre pivot sprinkler depth of water application and water holding capacity and concluded that optimizing centre pivot irrigation performance relies on system management.

Mohammad (2012) on the other hand observed that accurate design of centre pivot sprinkler irrigation systems could optimize performance particularly through careful consideration of flow situations in centre pivot pipes. The design of the system is crucial for future operation and management of the irrigation system and the potential for efficient irrigation as reported by Edkins (2006) in New Zealand. In Australia, Smith and North (2009) argue that knowledge of changes in the magnitude of water applied over time is important to determine the causes of deficiencies in application rates and uniformities. Non-uniform water application leads to over or under irrigation in various parts of the field which can result in wasted water, energy and the potential for nitrogen leaching (Sabah *et al.*, 2011).

Reuben *et al.*, (2010) reported that the poor performance of centre pivot sprinkler irrigation is a major factor contributing to low sugarcane yields in Tanzania. Systems have to be correctly managed to ensure that the distribution uniformity and efficiencies are within acceptable levels. Griffiths and Lecler (2001) found that the main factors which contributed to centre pivot irrigation systems having lower than expected application efficiency and distribution uniformity values in South Africa were poor irrigation system design, poor irrigation system management, non-existent or inadequate maintenance schedules and non-existent water testing procedures. Lecler (2005) observed that to ensure the long term viability of the sugarcane industry in Zimbabwe, development and adoption of strategies to improve the performance of the

various water management and irrigation systems was needed.

Although mainly used by large scale growers, centre pivot sprinkler irrigation system has also proved suitable for small scale growers in organized associations in Swaziland due to water scarcity (Magwenzi and Nkambule, 2003). Recent analyses show that centre pivots are both economically and financially viable under the current pricing system in Swaziland (Magwenzi, 2002). Qureshi *et al.*, (2002) also confirmed the profitability of centre pivot sprinkler irrigation systems for sugarcane under Australian conditions. However, no evaluation of technical performance of centre pivot sprinkler irrigation systems has been conducted since their introduction in Swaziland, particularly at Ubombo with the highest number (106) of centre pivots in the Swazi sugar industry. Evidence indicates that research has only been undertaken on furrow and conventional sprinkler irrigation systems where results show that there were no design parameters available for system design and poor performance is often attributed to poor management of irrigation systems. Magwenzi (2000) noted that there is a limitation in using efficiency as the only measure of irrigation system performance because it does not show the uniformity of distribution or the percentage of the area that was adequately irrigated. Irrigation research in Swaziland has been largely focused on feasibility studies aimed at developing national irrigation schemes with less emphasis on irrigation system performance.

The transition of commercial and smallholder farmers to centre pivot sprinkler irrigation necessitates extensive research on the technical performance of the system in order to attain greater irrigation efficiency, high water productivity and ultimate improvements on sugarcane yields. At Ubombo, centre pivot

irrigation occupies 47% of the net planted area with the remainder shared between furrow, dragline and semi-solid set sprinkler systems subsequent to a major conversion project where poorly performing fields under furrow and dragline sprinkler systems were converted into centre pivot and semi-solid set sprinkler systems. The ultimate goal was to improve water use efficiency to allow for expansion, increase sugarcane yields and reduce labour requirements. While the impetus was on centre pivot irrigation advancement, problems of the system has been observed at field level and includes uneven sugarcane growth, runoff and rutting of wheel tracks which often results in mechanical breakdowns and subsequent irrigation downtime. Evaluation of centre pivot sprinkler irrigation system performance at Ubombo was therefore crucial to establish knowledge base on the technical performance of the system to justify improvements on management and system configurations, hence the purpose of this study. Evaluations included analysis of meteorological data, design parameters, measurements of pressure and discharge at various points in the system, its operating speed, tyre pressures, water application and inspection of sprinkler package (Koegelenberg and Breedt, 2007) to determine system performance parameters and adequacy of irrigation water supply.

Study area

Ubombo Sugar estate is situated in Big Bend in the south - east of Swaziland on longitude 32°52' east and latitude 26°45' south with average altitude of 107 m above mean sea level. The estate has a net planted area of about 11,200 ha under sugarcane for sugar production. It is divided both spatially and administratively into three areas; North, Central and South and each varies according to the number and size of sections contained. Each of the areas is serviced by a weather station where meteorological data is

received. The rainfall regime is unimodal with mean annual rainfall of about 600 mm which normally occurs during summer between October and March. Mean annual temperature is 21^o C and peaks to 39^o C in summer. Soils vary considerably from shallow sands to deeper loam depending on the composition of the volcanic lavas forming the bedrock (Mwendera *et al.*, 2002).

Water supply for irrigation is from the Great Usutu River through a main gravity canal approximately 39 km long which then subdivides into two primary canals to command the different areas. Ubombo Sugar estate is essentially the downstream user with the largest demand in the consortium after two other commercial irrigation schemes. Major balancing dams, the Van Eck and Sivunga Dam with net storage capacities of 10.4 x 10⁶ m³ and 6.9 x 10⁶ m³ respectively along with night storages of various capacities effectively command the entire estate.

MATERIALS AND METHODS

Selection of centre pivot irrigation systems

Out of 106 centre pivots that were operational, four centre pivot systems were purposively selected for the study (Figure 1). The criteria was to have a sample of centre pivots which were to be harvested at the beginning of the harvesting season, spatial representation of the net area under centre pivot irrigation and the different age categories among centre pivot machines.

Field parameters determined and data collection

The parameters that were determined included system performance, adequacy of irrigation water supply, net application rate, system operating pressure, travel speed and revolution time, spray nozzle sprinkler set and spacing, sprinkler discharge and pressure, and tyre pressure. The

system operating pressure, tyre pressure, travel speed, system flow rates, sprinkler nozzle discharge and pressure were measured on each centre pivot systems. The effective radii of the systems were measured together with pump flow rates, pump operating pressures as well as centre pressures at pivot points.

The net application rate for centre pivot irrigation was estimated from the catch can data according to Ross (1997). The net application rate of centre pivot irrigation depends on gross application in millimetres, 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).

Operating pressure for the centre pivots was read from the pivot point in the system using pressure gauges (Keller and Martin, 2000) and the results were analysed and compared with the design

specifications. At Ubombo Sugar estate, the design pressure at the pivot point of a centre pivot was 140 kPa – 350kPa depending on the size and topography of the field as well as the location of the pumping plant in relation to the field.

The centre pivot speed was determined by measuring a defined length using a measuring tape along the path of the drive wheels and recorded the time taken by each centre pivot to complete the distance. Time per revolution for a centre pivot is a very important factor to take into consideration when designing centre pivot irrigation systems because it determines the rate of application to be considered as well as the irrigation interval for the system. The speed was set at the control point in the pivot panel and a signal is normally sent to the end drive unit, then the actual speed was measured according to Merriam and Keller (1978).

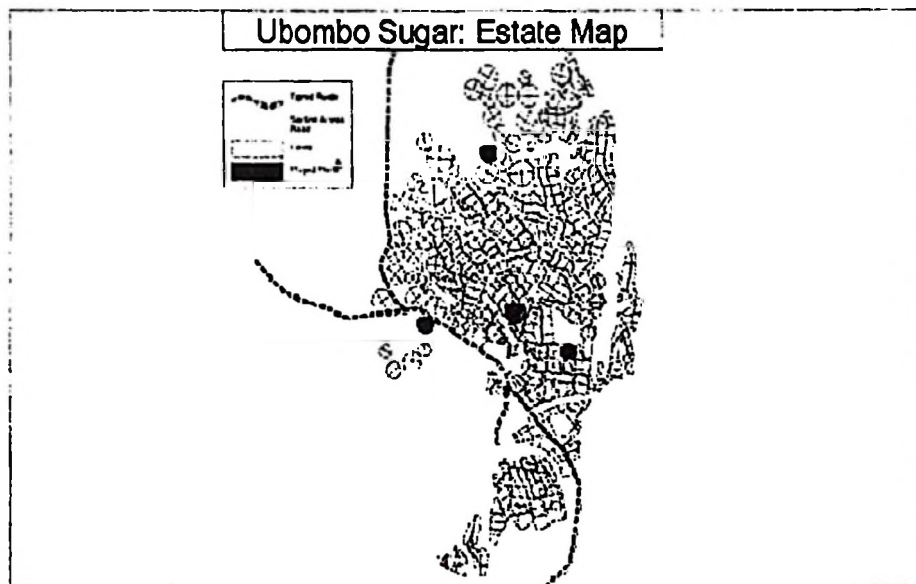


Figure 1: Layout of Ubombo Sugar estate and the centre pivots studied

The spray nozzle sprinkler set was studied by physical observation and information from the manufacturer in the design specifications. 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 a measuring wheel under the sprinklers. Observations were done to identify if variation of spray nozzle sprinkler spacing along the lateral existed. The analysed results were then compared with the design requirements.

The discharge of each sprinkler along the centre pivot lateral was measured using a container of specified capacity and time to fill the container was measured and recorded. Since the sprinkler model for most centre pivots at Ubombo is the Senninger I- Wobbler, a pipe was used as a water conveyance from the discharging sprinkler to the container ensuring no water losses. A standard pressure gauge with fittings to connect below the pressure regulator was used to measure sprinkler operating pressure for each sprinkler along the centre pivot lateral.

Pressure in the tyres of centre pivots was measured using a portable pressure gauge while the system was in operation including tyre sizes. All the centre pivots were equipped with single wheels as opposed to dual wheels. Readings were recorded in the evaluation data sheet for assessment of the system performance.

Meteorological data collected from the weather stations included radiation, wind speed, relative humidity, maximum and minimum temperatures. Weather parameters were analysed using Instat software coded with Penman Monteith equation to assess design parameters in terms of crop water requirements. The design specifications for each

system were also analysed and validated against field measurements to determine adequacy of the systems in terms of water supply for sugarcane production.

Performance indicators

The performance indicators used were the Distribution Uniformity (DU), The Coefficient Uniformity (CU), the Application Efficiency of Low Quarter (AELQ), and the Potential Application Efficiency of Low Quarter (PELQ).

The Distribution Uniformity was determined from catch cans data placed such that water from a complete pass of the centre pivot was collected (Rogers *et al.*, 2005). As the pivot was moving with catch cans aligned along the centre road, the length of the pivot was examined for leaks and sprinklers that may not be operating properly and it was noted in the data sheet. These notes normally help when making recommendations for improvements in the system. The distribution uniformity coefficient (DU) was calculated based on the equation by Merriam and Keller (1978):

$$DU = \frac{d_{lq}}{d_w} \times 100 \quad (1)$$

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 irrigation systems should be at least 75%.

The Uniformity Coefficient, as a measure of the average absolute deviation from the average irrigation amount (Delirhasannia *et al.*, 2010) was determined from water collected from catch cans after the centre pivot has completely passed

through the aligned cans. During calculations of the uniformity coefficient and other parameters, all gauges at that did not collect water particularly because of physical clogging of nozzles were discarded during the determination of the performance parameters since they do not represent the system with regards to water application. The catch cans experiment is normally used to quantify how close the system is to a theoretical model in which all cans would contain exactly the same amount of water. The uniformity coefficient was calculated using the formula by James *et al.* (1982):

$$CU = \frac{1 - \sum X}{M \times N} \times 100 \quad (2)$$

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 determining the uniformity coefficient is to use the relationship between uniformity coefficient and the distribution uniformity (Markley and Allen, 2002) as:

$$Cu = 100 - 0.63(100 - DU) \quad (3)$$

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%.

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 centre pivot can be

determined from how much of the applied water is stored in the soil and available for consumptive use and how uniformly it is applied. The recommended AELQ is at least 90% (Evans, 2001) and was achieved for some centre pivots in the field and estimated according to Merriam and Keller (1978).

$$AELQ = \frac{SMD}{d_{av}} \times 100 \quad (4)$$

Where: SMD = Soil Moisture Deficit (mm)

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

The Potential Application Efficiency of Low Quarter (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. (5) according to Merriam and Keller (1978).

$$PELQ = \frac{d_{lq}}{d_{av}} \times 100 \quad (5)$$

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).

RESULTS AND DISCUSSIONS

Performance of centre pivot irrigation systems

Table 1 and 2 presents the performance indicators for the selected centre pivot sprinkler systems. The evaluation results reveal that centre pivots were performing relatively well as parameters of CU and DU for three systems were within acceptable standards. CUs for EEL09, NKA21

and SMB were 89.7%, 94.6% and 88.7% respectively and concur with Harisson and Perry (2010) that centre pivot CU should be larger than 85.0% under the recommended wind speed. CAS02 did not meet the acceptable standards with a CU of 80.5%. The DU for all systems was within recommended standards with EEL09, NKA21, CAS02 and SMB having 89.2%, 95.7%, 77.2% and 89.6% respectively. According to Ascough and Kiker (2002), centre pivot system DU should be at least 75%. However, on the other hand the recommended PELQ and AELQ were only met by CAS02 and SMB with 93.3%, 98.2% and 94.4%, 90.8% respectively. EEL09 and NKA21 did not meet the recommended performance standards as stated by Savva and Frenken (2002) that spray nozzle sprinkler centre pivot PELQ and AELQ should be at least 90%.

The results showed a general variation in the performance parameters obtained under normal system evaluation and those obtained under temporal and spatial evaluation procedures. The CU and DU for all centre pivots in both evaluation methods had a significant difference in that performance values obtained under normal evaluation were lower than those for temporal and spatial method. These lower values tend to underestimate the system by inducing an averaging effect on portions performing within acceptable standards and mask underperforming or faulty sections along the lateral length. The CU, DU, PELQ and AELQ results for all systems indicate that performance measurements should be carried out systematically along the lateral to specifically identify underperforming towers or components within a centre pivot.

Design net system capacity used by Ubombo Sugar is 7.5 mm/day and the gross application rate depends on irrigation system efficiency. Centre pivots normally apply a gross amount of 8.8 mm/day and during each irrigation event, the normal irrigation practice is to apply 25mm/day.

For purposes of evaluation, a minimum of 16 mm/day was used and it agreed with the base value of 15 mm/day reported by Merriam and Keller (1978). Tables 1-3 presents the irrigation depth (D), centre pivot speed, revolution time (T) at each evaluation for all four centre pivots. Figure 2 shows the water distribution profile for all four centre pivots against a target amount. EEL09, CAS02 and SMB performed better in terms of satisfying a target depth of water although the distribution was very poor for CAS02. NKA21 did not meet the target depth but it was excellent in terms of water distribution. This is attributed to lower than design operating pressure on the pump which affected the centre pressure required at the pivot point. The system flow rate was measured and found satisfactory in relation to the wetted area as 48.9 l/s was obtained in the delivery pipeline of the pump dedicated for NKA21 (Table 4 and Figure 4). Using a hydro model of 1.0 l/s/ha derived from the gross application of 8.8 mm/day, the flow was adequate to irrigate a net area of 45.6 ha for NKA21 and this was evident for all systems (Table 5).

Figure 3 shows the different application rates for sprinkler package configurations used in each of the systems. It was evident that sprinklers for NKA21, CAS02 and SMB were applying water slightly above the design application rates. A desk review of the design specifications for each centre pivot, sprinkler package in particular indicated matching configurations from the inspections in the field except for cases where sprinklers were removed near the pivot point or at the towers to avoid wetting wheel tracks or irrigation of bare land at the pivot point. The relatively high application rates are a result of nozzle wear and replacements are essential. The high application rates were due to the fact that the design application rates for the systems were exceeded by actual application rates particularly towards the end of the lateral (Table 6). In

contrast, EEL09 had no specifications for sprinklers on the design hence no benchmark for assessing performance of the sprinklers (Figure 3). Furthermore, there was no soil infiltration data on the design reports where the sprinkler packages could have been determined for the pivots. Predisposing factors for higher application rates included among others, the sprinkler operating pressure which for some sprinklers

were found operating beyond the threshold of 100 to 140 kPa. Parallel observation was also made on the tyres where the recommended operating pressure of 100 kPa was not achieved for some systems as they recorded pressures of up to 200 kPa. Generally, this does not only affect the rims and gearboxes but also the distribution uniformity of water application along the centre pivot lateral.

Table 1: Performance parameters for centre pivots EEL09, NKA21, CAS02 and SMB under normal evaluation procedures

	CU (%)	DU (%)	PELQ (%)	AELQ (%)	D (mm/day)	T (hours)
CP	CU (%)	DU (%)	PELQ (%)	AELQ (%)		
EEL09	89.7	89.2	84.8	83.5	13.7	42.8
NKA21	94.6	95.7	81.3	80.0	12.8	42.3
CAS02	80.5	77.2	93.3	98.2	16.2	34.9
SMB	88.7	89.6	94.4	90.8	14.7	46.3

Table 2: Temporal and spatial parameters for centre pivots EEL09, NKA21, CAS02 and SMB

CP	Area	CU (%)		DU (%)		PELQ (%)		AELQ (%)		D (mm/day)	T (hours)
		CU (%)	CUn	DU (%)	DU _n	PELQ (%)	PELQ _n	AELQ (%)	AELQ _n		
EEL09	1/3	89.8	89.7	93.3	89.2	86.6	84.8	82.9	83.5	13.6	16.7
	2/3	91.1	89.7	100	89.2	86.6	84.8	87.2	83.5	14.3	33.5
	Last	89.3	89.7	93.5	89.2	84.2	84.8	79.9	83.5	13.1	41.9
Average		90.1	89.7	95.6	89.2	85.8	84.8	83.3	83.5	13.7	
NKA21	1/3	97.0	94.6	95.2	95.7	80.0	81.3	81.3	80.0	13.0	16.7
	2/3	94.5	94.6	100	95.7	79.4	81.3	80.0	80.0	12.8	34.4
	Last	93.7	94.6	98.3	95.7	77.5	81.3	78.8	80.0	12.6	42.3
Average		95.1	94.6	97.8	95.7	80.0	81.3	80.0	80.0	12.8	
CAS02	1/3	75.7	80.5	100	77.2	78.1	93.3	62.4	98.2	12.9	17.8
	2/3	77.4	80.5	97.7	77.2	100	93.3	100	98.2	19.3	29.6
	Last	84.6	80.5	87.2	77.2	100	93.3	100	98.2	18.1	34.9
Average		79.2	80.5	95.0	77.2	92.7	93.3	87.5	98.2	16.8	
SMB	1/3	90.0	87.7	93.4	89.6	97.5	94.4	90.9	90.8	15.0	14.2
	2/3	91.1	87.7	96.6	89.6	94.4	94.4	93.2	90.8	15.1	34.8
	Last	87.8	87.7	93.1	89.6	86.4	94.4	85.8	90.8	13.9	46.3
Average		89.6	87.7	94.4	89.6	92.8	94.4	90.0	90.8	14.7	

Table 3: Performance parameters for centre pivots EEL09, NKA21, CAS02 and SMB

CP	Wetted area (ha)	Time per rev. (hrs)	CP speed (mm/min)	P (bar)
EEL09	49.1	42.8	935.0	3.1
NKA21	45.6	42.3	973.3	3.3
CAS02	36.5	34.9	973.3	1.4
SMB	70.4	46.3	1013.3	3.0

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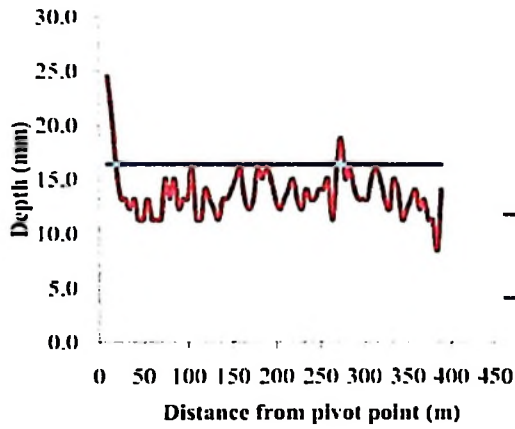
Table 4: System capacities and net crop water demand for centre pivots EEL09, NKA21, CAS02 and SMB

CP	Design rate(m ³ /h)	Flow Actual flow rate (m ³ /h)	Flow rate (l/s)	Flow rate (ML/day)	Crop demand (mm/day)
EEL09	191.9	178.6	49.6	4.3	7.5
NKA21	200.0	176.0	48.9	4.2	7.5
CAS02	130.0	133.6	37.1	3.2	7.5
SMB	253.1	257.0	71.4	6.2	7.5

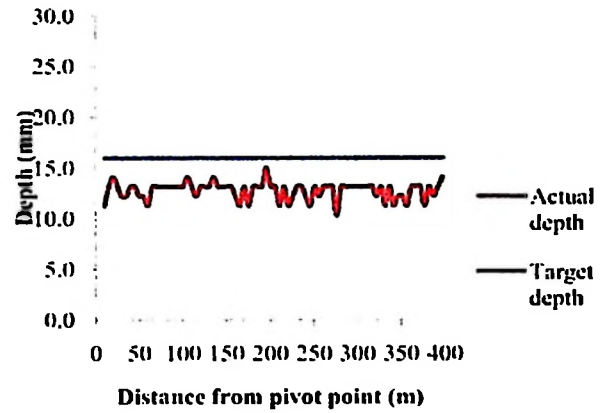
Table 5: Crop water requirement and adequacy of water supply for centre pivots EEL09, NKA21, CAS02 and SMB

Parameter	EEL09	NKA21	CAS02	SMB	
	49.1 ha	46.5 ha	37.1 ha	70 ha	
ET _o (mm/day)	6.0	6.0	6.0	6.0	
K _c (sugarcane)	1.25	1.25	1.25	1.25	
Net application (mm/day)	7.5	7.5	7.5	7.5	
Gross application (mm/day)	8.8	8.8	8.8	8.8	
Equivalent flow rate (l/s/ha)	1.0	49.6	48.9	37.1	71.4

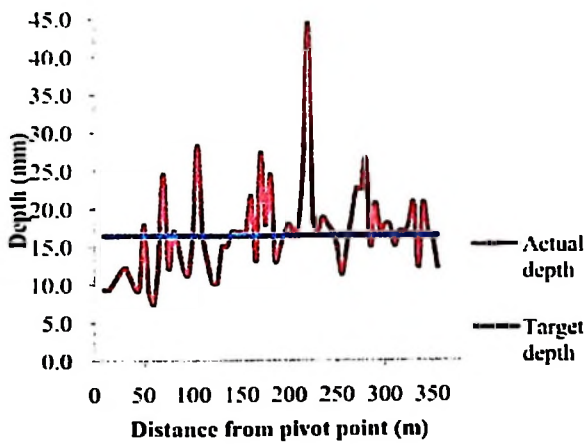
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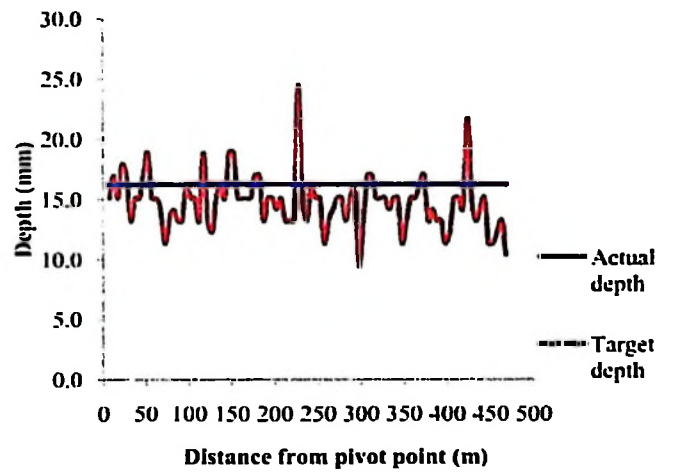
(a) EEL09 water application



(b) NKA21 water application

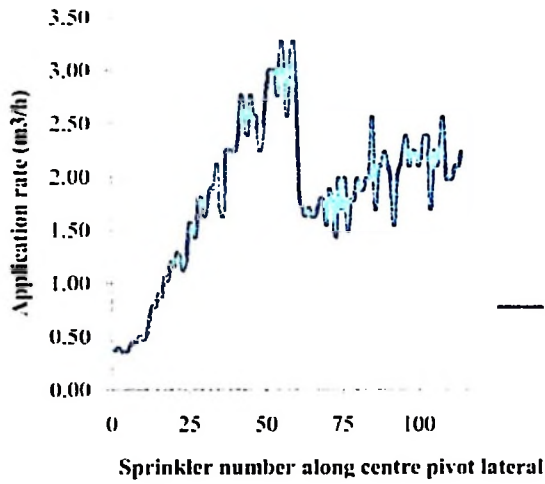


(c) CAS02 water application

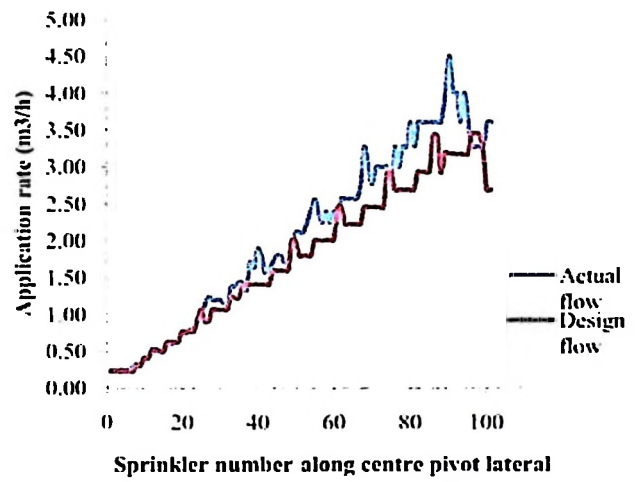


(d) SMB water application

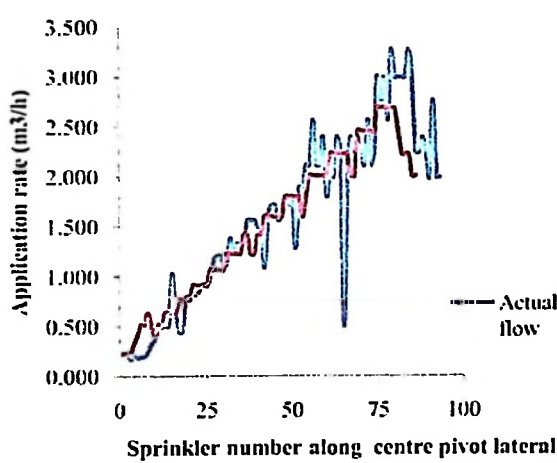
Figure 2: Water distribution profile along the lateral radii of EEL09, NKA21, CAS02 and SMB centre pivots



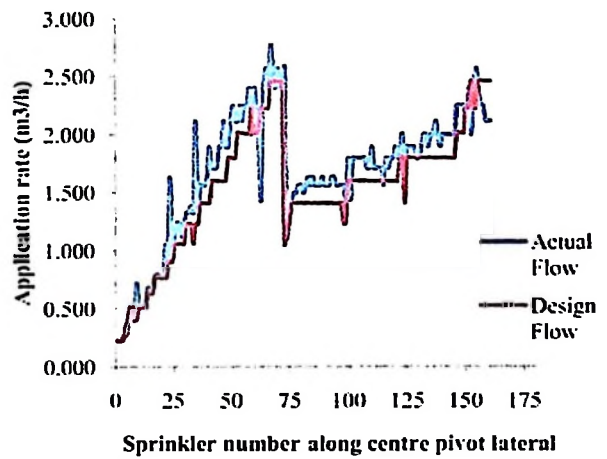
(a) EEL09 sprinkler application rate



(b) NKA21 sprinkler application rate



(c) CAS02 sprinkler application rate



(d) SMB sprinkler application rate

Figure 3: Sprinkler application rate along the lateral of EEL09, NKA21, CAS02 and SMB centre pivots

Table 6: Flow variation synopsis for EEL09, NKA21, CAS02 and SMB centre pivots

Span No.	Area (ha)	Measured Flow (m ³ /h)	Design Application (m ³ /h/ha)	Actual Application (m ³ /h/ha)
1	0.9	4.67	0	5.00
2	2.8	12.12	0	4.33
3	4.7	22.04	0	4.72
4	6.5	29.30	0	4.49
5	8.4	36.62	0	4.36
6	10.3	40.96	0	3.99
7	12.1	51.91	0	4.28
O/H	3.4	12.49	0	3.65
EEL09	49.1			
1	0.8	3.31	3.91	3.92
2	2.5	9.54	3.74	3.77
3	4.2	18.62	3.50	4.42
4	5.9	26.14	3.74	4.43
5	7.6	34.55	3.47	4.55
6	9.3	43.50	3.74	4.69
7	11.0	52.90	3.46	4.83
O/H	5.3	20.29	3.79	3.84
NKA21	46.6			
1	0.9	1.92	3.71	2.20
2	2.9	9.90	3.74	3.40
3	4.5	17.41	3.47	3.84
4	6.8	24.31	3.66	3.56
5	8.2	29.03	3.43	3.55
6	9.2	33.57	3.56	3.66
O/H	3.8	33.31	3.77	8.66
CAS02	36.3			
1	0.8	2.67	3.80	3.44
2	2.3	7.99	3.57	3.49
3	3.8	15.97	3.57	4.20
4	6.0	22.73	3.73	3.76
5	7.0	30.31	3.58	4.32
6	8.5	25.82	3.48	3.03
7	10.0	41.02	3.57	4.08
8	12.3	43.82	3.59	3.55
9	15.4	51.62	3.61	3.36
O/H	4.2	24.74	3.60	5.89
SMB	70.4			

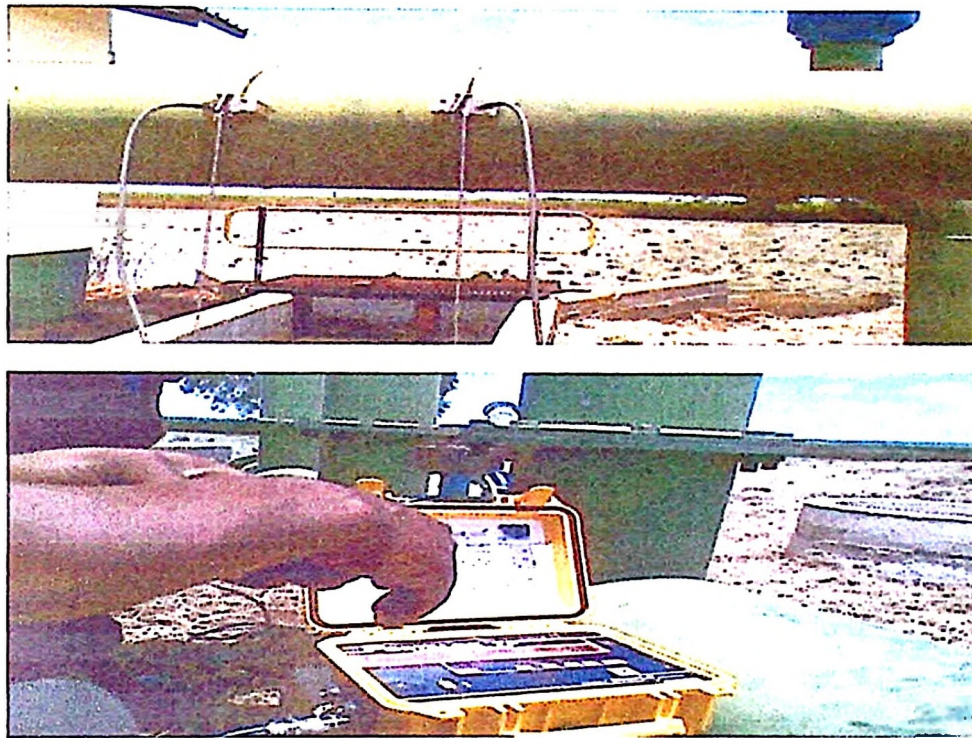


Figure 4: Pump flow rate measurement in the delivery pipe using a Portalok

CONCLUSION

All the centre pivots evaluated could be used to apply water efficiently if they were properly designed and managed. Shortfalls in pressure greatly affected the water application of the systems and hence non uniformities in water distribution along the centre pivot and the resultant fields. Sprinkler nozzle wear was responsible for the larger than design application rates for the pivots resulting in excessive water application, runoff and soil erosion. Temporal and spatial evaluation procedures for centre pivot irrigation could improve spotting poorly performing components for improvements within a centre pivot as opposed to standard evaluation procedures normally used.

RECOMMENDATIONS

Based on the evaluations, centre pivot irrigation system operations and management should involve constantly checking operating pressure against design pressure. The sprinkler nozzles should be checked for blockages, wear and tear, and application rates. The tyre pressure should be checked and corrected accordingly. Spatial and temporal evaluation procedures should be carried for effective performance assessment of the centre pivot irrigation systems within the estate.

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PAPER THREE

2.3. An Appraisal of Water and Power Budgeting Systems for Sustainable Irrigation at Ubombo

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Abstract

An analysis is given of the water and power budgeting systems used at Ubombo Sugar estate for sustainable irrigation water supply. A desk review of the approaches used to establish water and power budgets was carried and a new model was developed parallel to existing budgets to establish discrepancies. The development process constituted a broad set of parameters such as meteorological data, crop data and planted area, harvesting programs, irrigation systems, pumps and motor specifications, pumping hours, cost per kilowatt hour and actual flow rates. Water and power budgets were found not satisfactory with regards to satisfying crop water demand. Actual water inflows and pumping were determined by capacities of structures used for conveyance and losses were incurred during periods of low demand due to continuous flow type of delivery system. Electricity budgets were often based on historical power records which affected overall water supply as 70% of the estate is under pressurized irrigation. The new model developed from first principles of water and power demand demonstrated that existing budgeting systems limited the use of the resources particularly electricity and caused severe losses on irrigation water. Inaccurate supply-demand indices also affected decision making on bulk water management. Consequently, a new and improved budgeting model needs to be developed and adopted for sustainable irrigation water supply and sugarcane yields.

Keywords: Budget, irrigation, power, sugarcane, water supply, Ubombo.

Introduction

Ubombo Sugar estate depends heavily on irrigation for sustainable sugarcane production as annual rainfall meets approximately 50% of crop water demand. Bulk water sources are also increasingly becoming unreliable due to erratic rains and by virtue of the estate being at the downstream of all irrigation schemes in the Usutu River Basin. Extreme pressure is normally experienced during peak demand when the crop evapotranspiration is generally high which often coincides with periods of low rainfall and the common practice is for upstream farmers to abstract more water at the expense of the tail enders. On the other hand, impetus for strategic developments such as expansion of area under sugarcane and conversion of conventional irrigation methods is still on. These challenges prompts for a review of the bulk water management systems normally used to establish sustainable water management systems that will meet crop water needs, minimize water losses and energy costs and cope with prevalent unpredictable weather patterns. Irrigation water management has become an urgent issue in irrigated agricultural sectors worldwide to increase irrigation water use efficiency¹. Water shortages increase rapidly as industrial and agricultural needs rise in line with socio-economic development, population growth and poor water management^{2,3,4}. Improper irrigation water management practices cause not only wastage of water but a significant reduction in crop yield, quality and water use efficiency⁵. Bulk

water management helps in guiding the application of water; to meet crop needs, in ensuring the correct amount is held in the soil and made available to crop⁶. However, some studies reported that irrigation water management is rarely practised in large-scale farming thus neglecting large quantities of water for irrigation⁷.

Proper management of irrigation water prevent irrigation induced problems such as waterlogging through application of water in amounts that can be held by the soil and crop and salinization⁸. Soil salinity results when the evapotranspiration rate is higher than precipitation and therefore makes it difficult for plants to uptake water. The amount of water the sugar cane needs, its consumptive use, is equal to the quantity of water lost through evapotranspiration⁹. The water budget is a tool that can be used to assist irrigation decision makers in applying proper irrigation water management taking into account of the crop type, area reference evapotranspiration, precipitation and irrigation system design¹⁰. The water budget reflects balances between the input and the output of water to and from the root zone taking cognisance of the efficiency of systems and structures used to apply water, hence proper irrigation management is required for efficient and profitable use of water for irrigating agricultural crops. A major part of any irrigation management program is the decision-making process for determining timing for irrigation and or how much water should be applied to the field for each irrigation and this can be achieved through water

budgeting techniques. Therefore, it is essential to develop bulk water management strategies to utilize water resources efficiently and effectively¹¹.

Since about 70% of the estate net area is under pressurized irrigation systems, most of the water requires maximum lifting to effectively command the different areas. Electricity becomes a limiting factor as pumping costs tend to be exorbitant particularly during peak demand and hit hard on budgets. The tendency is to then limit power allocation through telemetry system (ACES) which eventually induces water stress to the crop. The annual power budgets have over the years been developed through historical power records which had some limitations as it failed to accurately capture additional power requirements as a result of expansions and conversions of furrow systems to centre pivot and semi solid set sprinkler systems in the recent years. Development of a new budgeting model for water and power could improve the challenges of water supply and distribution, power allocation and management. Evaluating the existing budgeting systems utilized could form basis for suggesting any improvements in the systems hence the purpose of the review. The assessment constituted analysis of meteorological data to determine crop water and irrigation requirements, net planted area and harvesting program, types of irrigation systems, capacities of pumps and motors, pumping hours, electricity costs, actual water abstractions and water distribution practices. The data was solicited to allow for the development of a water budget from first principles of crop water demand as a function of command area, pumping hours and the cost of pumping water on an annual basis to ultimately develop an accurate power budget. This could improve the performance of irrigation systems and sugarcane yields within the estate.

Material and Methods

Description of study area: Ubombo Sugar estate is situated in Big Bend in the south - east of Swaziland on longitude 32°52' east and latitude 26°45' south with an average altitude of 106 m above mean sea level. The estate has a net planted area of about 11, 200 ha under sugarcane for sugar production. It is divided both spatially and administratively into three areas; North, Central and South and each varies according to the number and size of sections contained. Meteorological data is obtained from three weather stations each located in one of the areas. The rainfall regime is unimodal with mean annual rainfall of about 600 mm which normally occurs during summer between October and March. Mean annual temperature is 21°C and peaks to 39°C in summer¹². Water supply for irrigation is from the Great Usutu River through a main gravity canal approximately 39 km long which then subdivides into two primary canals to command the different areas. Ubombo Sugar estate is essentially the downstream user with the largest demand in the consortium after two other commercial irrigation schemes. Major balancing dams, the Van Eck and Sivunga Dam with net storage capacities of 10.4

x 10⁶ m³ and 6.9 x 10⁶ m³ respectively along with night storages of various capacities effectively command the entire estate. Filling of Van Eck Dam and a couple of night storages is achieved by pumping through a number of pumping plants from the primary canals while the Sivunga Dam and other reservoirs are primarily supplied through gravity owing to their spatial location. Irrigation systems comprise 106 centre pivot machines with average size of 50 ha, semi solid set in the outfall of the pivots, conventional sprinkler and furrow irrigation to some extent.

Appraisal of water and power budgeting systems: Parameters appraised included meteorological data to determine crop water and irrigation requirements, area under sugarcane by individual blocks and harvesting program for 2013/14 cropping season, irrigation system type, capacities of pumps and motors, pumping hours, electricity costs, actual water abstractions and distribution practices. As a basis for analysis, a 23 year (1991 – 2013) time series data for radiation, wind speed, relative humidity, rainfall, minimum and maximum temperatures from Ngogo Meteorological station were analysed using Instat software and validated by ETo calculator software to determine the reference evapotranspiration (ETo) for the estate. Canopy factors for sugarcane were integrated with rainfall data to determine sugarcane water and irrigation requirements. The area planted under sugarcane was obtained through composite blocks contained by sections. Harvesting program for the period was used to determine the harvest dates for individual blocks to enable determination of water requirements for the different blocks as influenced by cutting dates. Irrigation systems were studied for the different blocks to establish their efficiencies in terms of water supply. Pump flow rates and motor sizes were also used to determine the maximum hours required to adequately meet crop water demand and power used.

The water and power budget model was developed on Microsoft Excel spread sheet taking into account the ETo, rainfall, canopy factors for sugarcane, empirical efficiencies of irrigation systems per block (sprinklers efficiency-75%, centre pivots- 85% and furrow- 60%)¹³. Net crop water demand was calculated in line with harvest dates of the individual blocks. The irrigation requirement for all cane included the demand for mill cane and seed cane, water supply required excluding losses (gross ML/ha), losses as a function of irrigation system efficiency and total supply required. The annual power usage for all operating pumps was calculated in line with the cost of a kilowatt hour for 2013/14 to determine an annual power budget for the estate. Actual water supply versus crop demand was assessed to determine if the current water management system adequately meets sugarcane water requirements through analysis of monthly water reports for the season. The resultant water and power requirements were then compared with previous budgets to determine their effectiveness of in terms of adequacy of irrigation water supply.

Results and Discussion

Tables 1 – 3 present results of the determination of sugarcane water and irrigation requirements at Ubombo Sugar estate. The output from Instat and ETo calculator programs showed no significant differences in the reference evapotranspiration (ETo). The maximum ETo at peak demand was found to be approximately 6 mm/day (figure-1). Annual ETe was 1167 mm with 461 mm of effective rainfall (table-3). The irrigation requirement for sugarcane is 7 ML/ha which must be applied effectively over the entire period of the growing season. Irrigation systems were found to be satisfactory in applying the target amount as they ranged between 6.5 and 7.1 ML/ha (table-4). The water budgeting model indicates that there are major limitations in the approaches used for agricultural water budgeting at Ubombo. River abstractions are normally determined by capacities of intake structures and during periods of low demand, water is stored in major balancing dams while the rest flows by continuous flow into primary canals and back to natural streams. This approach demonstrates that water inflow into the estate is limited by capacities of abstraction and conveyance structures and little effort is done to determine if part of the abstracted water is effectively supplied into the crop. An equivalent observation was made where improper estimation of canal discharges caused extensive damage to crop yields and loss of life in India¹¹. Development of a water budget model from first principles of crop water demand as a function of command area and pumping requirements enabled estimation of actual seasonal water requirements and the power required to lift the water.

The demand, as influenced by dry off periods and harvesting dates were determined with corresponding power requirements to calculate the annual power budgets (tables-4 to 6). Analysis of actual water inflows against crop water demand also demonstrated to have some shortfalls as supply-demand indices were over 100% as a result of inaccuracies in the methodologies used (figure-2). Tail water was often incorporated as supply and the absence of water measuring structures for domestic water abstracted from the bulk water system resulted into higher water supplies than it is for actual irrigation and these results tend to mislead decisions on bulk water management. The ideal approach could be to deduct this portion of water from total estate inflows since the demand factor in the model is only for sugarcane and not for other uses. The total annual water budget for the estate appeared to be slightly higher than the total actual water supply and this prompts for stringent and innovative water management strategies to effectively command the different areas. Power budgeting was also discovered to be based on historical records with some inflation added each year. The major irrigation systems conversions and expansion of area under sugarcane were not factored in the models hence a major difference between current power budgets and the new model developed from first principles. Consequently, the new model could be used as a basis for future budgeting of both water and power as it relatively captures all parameters needed to effectively decide on future water and power requirements for sustainable water supply for irrigation within the estate.

Table-1
Average weather parameters from 1991-2013 for Ngogo Meteorological station

	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Max °C	29.4	27.8	25.8	25.7	27.5	29.4	29.2	30.9	32.0	32.6	32.5	31.4
Min °C	16.9	12.5	8.5	8.4	11.2	15.1	17.6	19.4	20.6	21.3	21.2	20.1
RH Max %	88.8	91.6	91.8	90.3	85.0	78.4	74.4	75.5	77.5	82.0	83.2	85.2
RH Min %	53.1	48.7	46.2	44.0	41.8	45.0	53.4	54.5	55.9	58.0	56.2	56.2
Radiation (MJ/Kg)	16.5	13.7	12.1	12.9	15.5	17.9	18.6	20.7	21.7	23.0	22.1	19.5
Wind Speed (km/day)	63.4	53.9	53.1	64.7	88.8	111.3	112.8	109.5	101.1	92.0	86.4	74.6
Rainfall (mm)	43.2	16.9	11.5	9.9	17.4	23.9	60.5	97.3	104.7	99.9	84.3	70.7

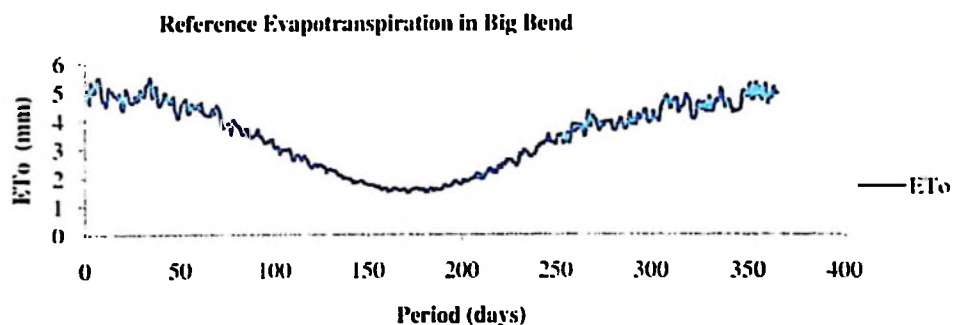


Figure-1
Reference evapotranspiration (ETo) for Big Bend

Table-2
Canopy factors (ETcane / ETo) for cane harvested in different months in Swaziland.

Harvest	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Apr	0.4	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May		0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0	1.0
Jun			0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0
Jul				0.4	0.4	0.4	0.7	1.0	1.0	1.0	1.0	1.0
Aug					0.4	0.4	0.6	0.9	1.0	1.0	1.0	1.0
Sept						0.4	0.4	0.7	1.0	1.0	1.0	1.0
Oct							0.4	0.4	0.8	1.0	1.0	1.0
Nov								0.4	0.5	0.8	1.0	1.0
Dec									0.4	0.5	0.8	1.0

Table-3
Sugarcane water and irrigation requirements in Big Bend

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
ETo	156	134	158	91	69	53	63	90	116	128	141	107	1306
c/f	1.0	1.0	1.0	0.4	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	
ETc	156	134	158	36	28	32	50	81	116	128	141	107	1167
R	99.9	84.3	70.7	43.2	16.9	11.5	9.9	17.4	23.9	60.5	97.3	104.7	640
Re	80	67	42	26	10	7	6	10	14	36	78	84	461
IRR	76	67	116	11	18	25	44	70	102	91	63	23	706

^aETo = reference evapotranspiration (mm/month) c/f = canopy factor, ETc = cane evapotranspiration (mm/month), R = rainfall (mm), Re = effective rainfall (mm), IRR = irrigation requirement (mm)

Table-4
Water and power budget for Mamba 2 and 3 centre pivots extracted from composite model
Water Requirements FOR 1st APRIL 2013 - 31st March 2014
Ubombo Water Requirements & Crop Factors

	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	TOTAL
ETo	91	69	53	63	90	116	128	141	107	156	134	158	1306
Gross Rainfall	43	17	12	10	17	24	61	97	105	100	84	71	640
Effective Rainfall	26	10	7	6	10	14	36	78	84	80	67	42	461
1. APRIL CUT - c/f	0.4	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	10
mm	75	18	25	44	70	102	91	63	23	76	67	0	654
2. MAY CUT - c/f	1.0	0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0	1.0	10
mm	0	75	14	19	35	79	91	63	23	76	67	116	658
3 JUNE CUT - c/f	1.0	1.0	0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0	10
mm	65	0	75	19	26	44	66	63	23	76	67	116	639
4. JULY CUT - c/f	1.0	1.0	1.0	0.4	0.4	0.4	0.7	1.0	1.0	1.0	1.0	1.0	10
mm	65	59	0	75	26	32	53	63	23	76	67	116	654
5. AUGUST CUT - c/f	1.0	1.0	1.0	1.0	0.4	0.4	0.6	0.9	1.0	1.0	1.0	1.0	10
mm	65	59	46	0	75	32	40	49	23	76	67	116	648
6. SEPTEMBER CUT - c/f	1.0	1.0	1.0	1.0	1.0	0.4	0.4	0.7	1.0	1.0	1.0	1.0	11
mm	65	59	46	57	0	75	15	21	23	76	67	116	619
7. OCTOBER CUT - c/f	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.4	0.8	1.0	1.0	1.0	11
mm	65	59	46	57	79	0	75	21	1	76	67	116	620
8. NOVEMBER CUT - c/f	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.5	0.8	1.0	1.0	11
mm	65	59	46	57	79	102	0	75	30	45	67	116	681
9. DECEMBER CUT - c/f	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.5	0.8	1.0	11
mm	65	59	46	57	79	102	91	0	75	2	40	116	729
Total mm	531	446	344	386	469	567	524	375	183	573	576	927	5903
Mean mm	59	50	38	43	52	63	58	42	20	64	64	103	656
Net crop water demand	656												
Application/ha (mm)	656												

LSI. Water Requirements & Crop Factors

	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	TOTAL LS
E To	91	69	53	63	90	116	128	141	107	156	134	158	1306
Gross Rainfall	43	17	12	10	17	24	61	97	105	100	84	71	640
Effective Rainfall	26	10	7	6	10	14	36	78	84	80	67	42	461
1. APRIL CUT - <i>ci</i>	0.4	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	10
Mm	75	18	25	44	70	102	91	63	23	76	67	0	654
2. MAY CUT - <i>ci</i>	1.0	0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0	1.0	10
Mm	0	75	14	19	35	79	91	63	23	76	67	116	658
3 JUNE CUT - <i>ci</i>	1.0	1.0	0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0	10
Mm	65	0	75	19	26	44	66	63	23	76	67	116	639
4. JULY CUT - <i>ci</i>	1.0	1.0	1.0	0.4	0.4	0.4	0.7	1.0	1.0	1.0	1.0	1.0	10
Mm	65	59	0	75	26	32	53	63	23	76	67	116	654
5. AUGUST CUT - <i>ci</i>	1.0	1.0	1.0	1.0	0.4	0.4	0.6	0.9	1.0	1.0	1.0	1.0	10
Mm	65	59	46	0	75	32	40	49	23	76	67	116	648
6. SEPTEMBER CUT - <i>ci</i>	1.0	1.0	1.0	1.0	1.0	0.4	0.4	0.7	1.0	1.0	1.0	1.0	11
Mm	65	59	46	57	0	75	15	21	23	76	67	116	619
7. OCTOBER CUT - <i>ci</i>	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.4	0.8	1.0	1.0	1.0	11
Mm	65	59	46	57	79	0	75	21	1	76	67	116	620
8. NOVEMBER CUT - <i>ci</i>	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.5	0.8	1.0	1.0	11
Mm	65	59	46	57	79	102	0	75	30	45	67	116	681
9. DECEMBER CUT - <i>ci</i>	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.5	0.8	1.0	11
Mm	65	59	46	57	79	102	91	0	75	2	40	116	729
Total mm	531	446	344	386	469	567	524	375	183	573	576	927	5903
Mean mm	59	50	38	43	52	63	58	42	20	64	64	103	656

LSI. Irrigation Requirements (MI) for Millicane from 1/04/2013 - 31/03/2014

Ha	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	TOTAL LS
APR	75	18	25	44	70	102	91	63	23	76	67	0	654
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	75	14	19	35	79	91	63	23	76	67	116	658
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUN	65	0	75	19	26	44	66	63	23	76	67	116	639
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUL	65	58.98 86957	0	75	26	32	53	63	23	76	67	116	654
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUG	65	58.98 86957	46	0	75	32	40	49	23	76	67	116	648
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEP	65	58.98 86957	46	57.053 24111	0	75	15	21	23	76	67	116	619
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCT	65	58.98 86957	46	57.053 24111	79.457 3913	0	75	-21	1	76	67	116	620
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOV	65	58.98 86957	46	57.053 24111	79.457 3913	101.83 65217	0	75	30	45	67	116	681
114.6	75	68	53	65	91	117	0	86	35	51	77	133	780
DEC	65	58.98 86957	46	57.053 24111	79.457 3913	101.83 65217	91	0	75	2	40	116	729
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL MI													
114.6	75	68	53	65	91	117	0	86	-35	51	77	133	780

USI. Irrigation Requirements (M) for Non Harvest from 1/04/2013 - 31/03/2014

H ₂	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	TOTAL LS
PRE-APR	75	18	25	41	70	102	91	63	23	76	67	124	778
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUL	65	59	100	75	26	32	53	63	23	76	67	116	754
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	70	1	0	1	1	1	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0	70	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL (M)													
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0

USI. Irrigation Requirements (ml) for all Cane from 1/4/2013 - 31/03/2014

	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	TOTAL LS
DEMAND ALL CANE (M)	75	68	53	65	91	117	0	86	-35	51	77	133	780
REGN (M)	0	0	0	0	0	0	0	0	0	0	0	0	0
SUPPLY REQUIRED (M)	75	68	53	65	91	117	0	86	35	51	77	133	780
LOSSES (M) (@ 0.15%)	11	10	8	10	14	18	0	13	5	8	12	20	117
TOTAL SUPPLY REQUIRED (M) (INCLUDING LOSSES @ 0.15%)	86	78	61	75	105	134	0	99	40	59	88	153	897
PUMP - IRRIG. DEPI (L.S)	33	30	23	29	40	52	0	38	16	23	34	59	
Running Pumps Required	2	2	2	2	2	2	0	2	2	2	2	2	
Kw	90	90	90	90	90	90	0	90	90	90	90	90	
Kwh	1648	14915	1163	14426	20091	25749	0	18963	7709	1129	1693	29305	172087
Cost/kWh	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	
Cost	1219	11037	8607	10675	14867	19054	0	14033	5705	8357	1253	21686	
Cost/ha	106.4	96.31	75.1	93.15	129	166.2	0.00	122.4	49.78	72.9	109	189.23	
													Total M/ha (net)
													6.81

PUMP
PS
Kw Capa- Capa- No. of Total Flow
 city of city of pump (L/s)

	each pump (m ³ /hr)	each pump (L/s)	s		1 pump running All pumps running
45	220	61	1	61	
45	210	58	2	119	

Field	Approx. Harvest date	Sub Area	Ha
UMM 02	14-Nov-13	P1	60.00
UMM 03	27-Nov-13	P2	54.60
			114.60

Table-5

Total water requirements for Chombo Sugar in Mega Litres (ML)

USL Net MI	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	Total
Total MI	13,602	12,865	12,105	12,163	14,128	15,286	15,119	14,280	11,382	14,670	13,735	16,011	165,346
USL Gross MI													
Total MI	14,484	13,576	12,672	12,800	14,700	16,099	15,588	14,920	11,570	15,200	14,218	17,008	174,280
TTN Net MI													
Total MI	2,432	2,432	2,432	2,432	2,432	2,432	2,432	2,432	2,432	2,432	2,432	2,432	2,432
TTN Gross MI													
Total MI	2,535	2,535	2,535	2,535	2,535	2,535	2,535	2,535	2,535	2,535	2,535	2,535	2,535
Total MI Required	13,052	11,207	10,744	10,669	12,264	13,664	13,187	12,485	9,138	12,665	11,783	14,576	162,811

Table-6

Total monthly power requirements for Ubonbo Sugar estate in kilowatt hours (kWh)

USL Irrigation	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	Total
Total kW Irrigation	2,672.103	2,287.216	2,155.777	2,173.915	2,546.515	3,011.691	3,106.306	2,828.264	2,699.435	3,905.309	3,354.085	3,752.931	34,513.547
USL Bulk Water Supply													
Total kW	756,000	1,082,000	1,594,000	1,601,500	1,541,500	1,581,500	1,370,500	1,192,000	1,221,000	1,111,000	1,260,000	1,336,000	13,924,000
TTN Irrigation													
Total kW	480,000	399,625	324,556	364,589	499,651	450,056	473,873	344,807	135,677	581,876	547,854	653,303	5,861,016
TTN Bulk Water Supply													
Total kW	552,500	557,425	557,420	557,420	557,420	557,420	557,420	557,420	557,420	557,420	557,420	557,420	10,960,120
Total kW Required	4,460.591	4,301.261	4,617.083	4,722.745	5,292.246	5,763.668	6,086.359	5,598.731	5,438.512	6,689.945	5,701.579	6,002.564	64,659.283

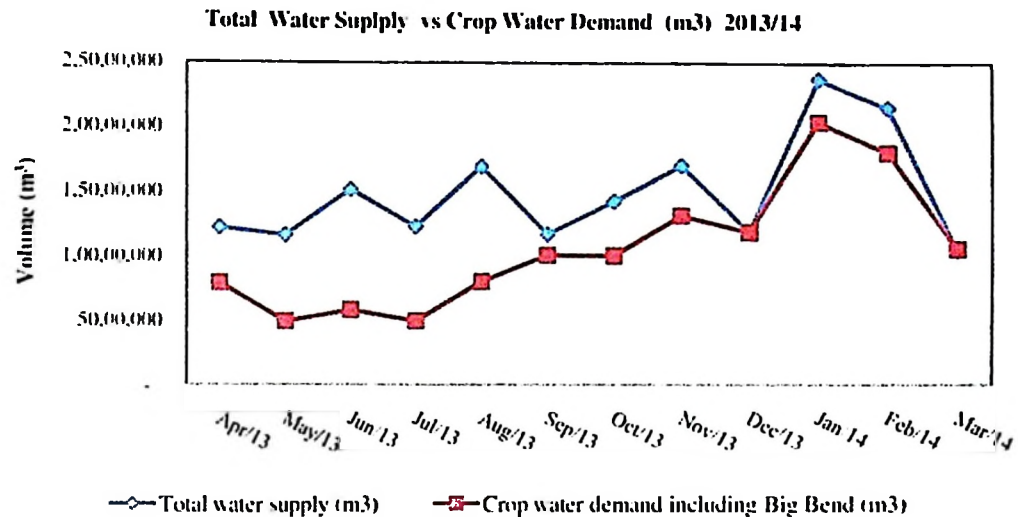


Figure-2

Actual water supply and demand curve for sugarcane at Uombo Sugar estate

Conclusion

Existing water and power budgeting systems have demonstrated some deficiencies in capturing and consolidating all relevant parameters needed to accurately define water and electricity demand in the estate. This has led to inaccuracies on budgets which induces pressure on the resources use and subsequent stimulation of water stress and yield losses on sugarcane. Consequently, a new and improved model needs to be adopted for efficient water and power budgeting at Uombo for effective and sustainable supply of irrigation water.

Recommendations: i. Accurately define parameters of major importance and develop a new water and power budget from first principles. ii. Install water measuring devices to quantify water used for other uses from the bulk water system. iii. Investigate agricultural power reticulation system within the estate to specifically determine actual power consumed by irrigation.

Acknowledgement

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PAPER FOUR

2.4. Performance of Centre Pivot Sprinkler Irrigation System and its Effect on Crop Yield at Ubombo Sugar Estate

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Abstract

The objective was to evaluate the performance of centre pivot sprinkler irrigation system and its effect on sugarcane yield at Ubombo Sugar estate to enable proposition of system configurations and management that will optimise water use and sugarcane yields. The process constituted analysis of weather parameters, design parameters, water application and uniformities, hydraulic measurements of pressure and discharge at various points in the system, system operating speed and sprinkler packages, irrigation water quality, soil physico-chemical properties, soil infiltration, soil compaction and sugarcane yields for four centre pivots (EEL09, NKA21, CAS02 and SMB). Results demonstrate that centre pivots were accurately designed and installed as they adequately supplied water to meet sugarcane demand of 7.5mm/day. Performance indicators show that centre pivots were performing relatively well as uniformity coefficients (CU and DU) for the systems were within acceptable standards above the base values of 85% for CU and 75% for DU. Application efficiencies (AELQ and PELQ) were only achieved by CAS02 and SMB as they were above the minimum of 90%. Poor infiltration as a result of compaction and clogging of sprinklers for EEL09, and lower than design pressure at pivot point for NKA21 were responsible for the sub standard application efficiencies. Soils were inherently sandy textured with a mixture of shallow and deep profiles. The physico-chemical properties indicate that soils were ideal for sugarcane growth except for shallow profiles which limited sugarcane yields due to the combined effect of low water holding capacity, reduced infiltration and hence runoff as a result of compaction by mechanical harvesting. Quality of irrigation water was within acceptable levels and had no negative impacts crop and soil. Yields were a major factor indicating the performance of the system and only EEL09 achieved low yields of 71 t/ha against 147 t/ha for CAS02, 124.8 t/ha for NKA21 and 106 t/ha for SMB. This is evidence of the performance and potential of centre pivot irrigation system. Factors affecting performance were pressure variations, clogging of sprinklers, rutting of un-gravelled tracks, shallow soils, compaction, reduced infiltration and game encroaching cane fields. Constant pressure checks, flushing of sprinklers, gravelled tracks or installing back booms, chiselling and ripping as well as fencing fields can improve system performance and sugarcane yields at Ubombo.

Keywords: Centre pivot, evaluation, irrigation, performance, sugarcane, Ubombo.

Introduction

The performance of irrigation systems is of concern in many areas of the world and has attracted the attention of researchers, planners and managers of irrigation systems in recent years¹. Irrigation system performance plays a significant role in crop performance, water use efficiency, cost of production and income generation². Although mainly used by large scale growers, centre pivot sprinkler irrigation system has also proved suitable for small scale growers in organized associations in Swaziland due to water scarcity. Recent analyses show that centre pivots are both economically and financially viable under the current pricing system in Swaziland³. A parallel observation has also been confirmed for sugarcane irrigation under Australian conditions⁴. The suitability of centre pivot irrigation systems in Swaziland has prompted for the rapid adoption and utilization of the system at Ubombo Sugar estate. At present, about 106 centre pivot

systems are physically on the ground with a semi solid set sprinkler system in the outfall of the pivots in an attempt to improve water use efficiency, reduce labour and energy costs as well as increased in sugarcane yields and profits. The impetus on centre pivot irrigation advancement is still on owing to anticipated strategic future developments of the estate and this will eventually result into a massive increase in the percentage of the system in the estate. However, no evaluation of the performance of the system has been conducted since their introduction in the estate to establish their performance standards, influence on sugarcane yields and major factors affecting system performance. Evidence indicates that research has only been undertaken on furrow and conventional sprinkler irrigation systems where results show that there were no design parameters available for system design and poor performance is often attributed to poor management of irrigation systems. Among other factors, there is a limitation in using efficiency as the only measure of

irrigation system performance because it does not show the uniformity of distribution or the percentage of the area that was adequately irrigated⁵. Ultimately, irrigation research in Swaziland has been largely focused on feasibility studies aimed at developing national irrigation schemes with less emphasis on irrigation system performance. The transition of commercial and smallholder farmers to centre pivot sprinkler irrigation necessitates extensive research on the performance of the system in order to attain greater irrigation efficiency, high water productivity and ultimate improvements on sugarcane yields.

Despite the impetus on centre pivot irrigation development, problems of the system has been observed at field level and includes uneven sugarcane growth, significant reduction in sugarcane yields, runoff and rutting of wheel tracks which often results in mechanical breakdowns and subsequent irrigation downtime. Evaluation of the centre pivot sprinkler irrigation system performance at Ubombo was therefore crucial to establish knowledge base on performance in order to justify improvements on system configurations and management, hence the purpose of this study. Evaluations included analysis of meteorological data to determine crop and irrigation water requirements, design parameters, measurements of pressure and discharge at various points in the system, pump flow rates, its operating speed, tyre pressures, water applications and inspection of sprinkler packages to determine system performance parameters and adequacy of irrigation water supply. Analysis of irrigation water quality, soil physic-chemical properties, soil infiltration, soil compaction and sugarcane yields also constituted parameters which provided basis for identification of the main factors affecting centre pivot irrigation system performance and the resultant sugarcane yields to enable proposition of pertinent system adjustments and management.

Material and Methods

Description of study area: Ubombo Sugar estate is situated in Big Bend in the south - east of Swaziland on longitude 32°52' east and latitude 26°45' south with an average altitude of 106 m above mean sea level⁶. The estate has a net planted area of about 11, 200 ha under sugarcane for sugar production. It is divided both spatially and administratively into three areas; North, Central and South and each varies according to the number and size of sections contained. Meteorological data is obtained from three weather stations each located in one of the areas. The rainfall regime is unimodal with mean annual rainfall of about 600 mm which normally occurs during summer between October and March. Mean annual temperature is 21°C and peaks to 39°C in summer. Water supply for irrigation is from the Great Usutu River through a main gravity canal approximately 39 km long which then subdivides into two primary canals to command the different areas⁷. Both canals are kept at about 80% of maximum capacity throughout the entire growing season. Ubombo Sugar

estate is essentially the downstream user with the largest demand in the consortium after two other commercial irrigation schemes. Major balancing dams, the Van Eck and Sivunga Dam with net storage capacities of $10.4 \times 10^6 \text{ m}^3$ and $6.9 \times 10^6 \text{ m}^3$ respectively along with night storages of various capacities strategically placed effectively command the entire estate. Filling of Van Eck Dam and a couple of night storages is achieved by pumping through a number of pumping plants from the primary canals while the Sivunga Dam and other reservoirs are primarily supplied through gravity owing to their spatial location. Irrigation systems comprise 106 centre pivot machines with average size of 50 ha, semi solid set in the outfall of the pivots, conventional sprinkler and furrow irrigation to some extent.

Sampling of centre pivot irrigation systems: Out of 106 centre pivots that were operational, four centre pivot systems (EEL09, NKA21, CAS02 and SMB) were purposively selected for the study (figure-1). The criteria was to have a sample of centre pivots which were to be harvested at the beginning of the harvesting season, spatial representation of the net area under centre pivot irrigation, a composition of systems harvested both manually and mechanically as well as the different age categories among centre pivot machines.

Field measurements of centre pivot irrigation systems: Parameters determined included sugarcane reference evapotranspiration (ET_o) using Instat software, sugarcane water and irrigation water requirements, system performance indicators, adequacy of irrigation water supply, net application rate, system operating pressure, travel speed and revolution time, spray nozzle sprinkler set and spacing, sprinkler discharge and pressure, tyre pressure, soil physic-chemical characteristics, soil infiltration, soil compaction, irrigation water quality and sugarcane yields. Design specifications for each of the centre pivots were solicited for purposes of checking the systems adequacy with regards to irrigation water supply and physical configurations on the ground. The system operating pressure, tyre pressure, travel speed, system flow rates, sprinkler nozzle discharge and pressure were measured on each centre pivot system. The effective radii of the systems were measured together with pump flow rates, pump operating pressures as well as centre pressures at pivot points. The spray nozzle sprinkler set was studied by physical observation and information from the manufacturer in the design specifications. 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 a measuring wheel under the sprinklers. Observations were done to identify if variation of spray nozzle sprinkler spacing along the lateral existed. The analysed results were then compared with the manufacturer's design specifications.

The physical and chemical characteristics of soils under each centre pivot were studied through laboratory analysis of samples taken for all pivots. Samples were taken using core ring samplers and soil auger at sampling intensity of one sample per 16 ha at relative depths of 30 cm intervals for 90 cm. This methodology made it possible for one sample per quadrant of each centre pivot owing to the size of the centre pivots. Samples were analysed by Mhlume Agriculture laboratory in compliance with international soil analysis standards. A double ring infiltrometer was used to measure intake rate of soils for each of the pivots to study the basic infiltration rates of the soils. Compaction for the soils was measured using an automated P5 Hand Penetrometer to assess its influence on infiltration, water storage, root penetration and sugarcane yields for each of the manually and mechanically harvested centre pivot systems. Soil compaction maps showing the trends of compaction for the centre pivots were developed using ArcGIS software through geospatial interpolation of measurement points captured using a handheld Juno SB GPS. The quality of irrigation water was measured by taking water samples from the fertigation fittings located at the pivot point of each centre pivot and the source of irrigation water for each pivot either canal or night storage dam. Water samples were analysed by Swaziland Water Services Corporation (SWSC) laboratory. Sugarcane yields were obtained from the weighbridge and Canepro information system to assess the influence of the centre pivot irrigation system, soils and water on yields. Mill cane tonnes per hectare and sucrose percentage were used as indices for assessing the influence of irrigation system, soils and water on sugarcane yields.

Results and Discussion

Tables 1 – 3 present results of the determination of sugarcane water and irrigation requirements at Ubombo Sugar estate. The output from Instat software gives a maximum ETo of approximately 6 mm/day at peak demand (figure-2). Annual crop water requirement (ETc) was 1167 mm with 461 mm of effective rainfall (TABLE-3). The irrigation requirement for sugarcane is 7 ML/ha which must be applied effectively over the entire period of the growing season. Irrigation systems were found satisfactory in applying the target amount as they ranged between 6.5 and 7.1 ML/ha. Design net system capacity used by Ubombo Sugar is 7.5 mm/day and the gross application rate depends on irrigation system efficiency. Centre pivots normally apply a gross amount of 8.8 mm/day and during each irrigation event, the normal irrigation practice is to apply 25mm/day⁸. For purposes of evaluation, a minimum of 16 mm/day was used and it was compliant with the base value of 15 mm/day⁹. Tables 4-5 presents system capacities, irrigation depth (D), centre pivot speed, revolution time (T) at each evaluation for all four centre pivots. Figure-3 shows the water distribution profile for all four centre pivots against a target amount. EEL09, CAS02 and SMB performed better in terms of satisfying a target depth of water although the distribution was very poor for CAS02 due to sprinkler

blockage. NKA21 did not meet the target depth but it was excellent in terms of water distribution. This was attributed to lower than design operating pressure on the pump which affected the centre pressure required at the pivot point as adequate pressure is normally achieved when both pumps delivering (other supplying NKA20) in the same pipeline are in operation for this pivot. The system flow rate was measured and found satisfactory in relation to the wetted area as 48.9 l/s was obtained in the delivery pipeline of the pump dedicated for NKA21 (table-6 and figure-6). Using a hydro model of 1.0 l/s/ha derived from the gross application of 8.8 mm/day, the flow was adequate to irrigate a net area of 45.6 ha for NKA21 and this was evident for all systems (table 6). The evaluation results reveal that centre pivots were performing relatively well as parameters of CU and DU for three systems were within acceptable standards. CUs for EEL09, NKA21 and SMB were 89.7%, 94.6% and 88.7% respectively and concur with the standard of 85.0% (table-7)¹⁰. CAS02 did not meet the acceptable standards with a CU of 80.5%. The DU for all systems was within recommended standards with EEL09, NKA21, CAS02 and SMB having 89.2%, 95.7%, 77.2% and 89.6% respectively. Centre pivot irrigation system DU should be at least 75%¹¹. However, on the other hand the recommended PELQ and AELQ were only met by CAS02 and SMB with 93.3%, 98.2% and 94.4%, 90.8% respectively (table-7). EEL09 and NKA21 did not meet the recommended performance standards which states that spray nozzle sprinkler centre pivot PELQ and AELQ should be at least 90%¹². The results implies that the systems were adequate in meeting sugarcane water requirements and the uniformity coefficients and efficiencies were generally acceptable except for the lower than expected application efficiencies of EEL09 and NKA21 which was attributed to clogging of sprinklers, compaction and poor infiltration for EEL09 and slightly lower than design operating pressure at the pivot point for NKA21.

Sprinklers for NKA21, CAS02 and SMB were applying water slightly above the design application rates. A desk review of the design specifications for sprinkler packages indicated matching configurations from the inspections in the field except for cases where sprinklers were removed near the pivot points or at the towers to avoid wetting wheel tracks or irrigation of bare land at the pivot point (figure-5). The relatively high application rates were a result of nozzle wear and replacements are essential. The design application rates for the systems were exceeded by actual application rates particularly towards the end of the lateral (figure-4). In contrast, EEL09 had no specifications for sprinklers on the design specifications hence no benchmark for assessing performance of the sprinklers (figure 3). Furthermore, there was no soil infiltration data on the design reports where the sprinkler packages could have been determined for the pivots. Predisposing factors for higher application rates included among others, the sprinkler operating pressure which for some sprinklers were found operating beyond the threshold of 100 to 140 kPa. Parallel observation was also made on the tyres

where the recommended operating pressure of 100 kPa was not achieved for some systems as they recorded pressures of up to 200 kPa. Generally, this does not only affect the rims and gearboxes but also the distribution uniformity of water application along the centre pivot lateral.

Soil properties are among factors responsible for sugarcane yield in the fields. Fields EEL09, NKA21, CAS02 and SMB were sandy textured soils of up to 53% sand in the profile (Table-8). The amount of silt was slightly higher than clay content in all soils. The sandy texture could not affect sugarcane growth as it enhanced soil infiltration and drainage¹⁴. The inherent nature of the soils implies frequent and light irrigation to avoid percolation losses and subsequent induction of water stress to the crop. Only CAS02 had deep soils with high water storage capacity as evidenced by higher proportion of silt and clay (table-8). Chemical properties of the soils indicate that there is no salinity and sodium hazard as EC values were less than 0.7 dS/m and SAR less than 2¹⁵. Soil pH was slightly acid although it proved neutral for the irrigation water with slightly higher SAR values (Tables -9 and 10). Compaction measurements demonstrated that EEL09 was more compact than the other pivots as the major driver was mechanical harvesting (table-11). The compaction trend among the fields had an effect on infiltration rates of soils in the pivots. EEL09, a sandy textured soil was found to be behaving more like a clay soil with a basic infiltration rate of 6 mm/h in one of the quadrants while the other less compact fields had infiltration rates greater than 70 mm/h (table-12). This is typical evidence of the effect of compaction on water entry into the soil and hence runoff and subsequent induction of water stress to sugarcane. Table-13 presents yields for each of the centre pivots as influenced by the performance of the centre pivot system, soil and water characteristics as well management aspects. EEL09 recorded low yields of 71 t/ha as opposed to 147 t/ha and 124.8 t/ha for CAS02 and NKA21. The low yields were attributed to shallow soils with low water holding capacities (table-8), compaction due to mechanical harvesting, reduced soil infiltration and encroachment of

sugarcane by wild animals. The slightly higher application rates of worn out sprinklers implies that water is generally not infiltrating the soil but rather generating runoff which ultimately reduces the application efficiency of the system. Wear and eventually crashing of the mechanical centre pivot structure is often attributed to wheels driving on deep un-gravelled tracks and this induces irrigation downtime.

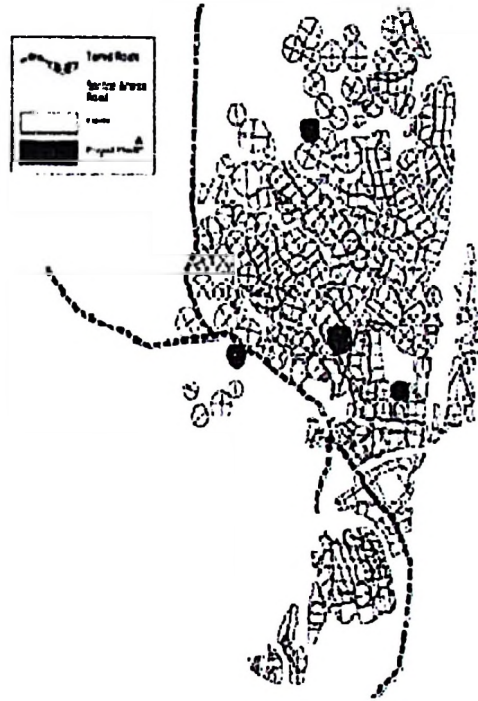


Figure-1
Layout of Uhombo Sugar estate and centre pivots studied

Table-1
Average weather parameters from 1991-2013 for Ngogo Meteorological station

	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Max °C	29.4	27.8	25.8	25.7	27.5	29.4	29.2	30.9	32.0	32.6	32.5	31.4
Min °C	16.9	12.5	8.5	8.4	11.2	15.1	17.6	19.4	20.6	21.3	21.2	20.1
RH Max %	88.8	91.6	91.8	90.3	85.0	78.4	74.4	75.5	77.5	82.0	83.2	85.2
RH Min %	53.1	48.7	46.2	44.0	41.8	45.0	53.4	54.5	55.9	58.0	56.2	56.2
Radiation (MJ/Kg)	16.5	13.7	12.1	12.9	15.5	17.9	18.6	20.7	21.7	23.0	22.1	19.5
Wind Speed (km/day)	63.4	53.9	53.1	64.7	88.8	111.3	112.8	109.5	101.1	92.0	86.4	74.6
Rainfall (mm)	43.2	16.9	11.5	9.9	17.4	23.9	60.5	97.3	104.7	99.9	84.3	70.7

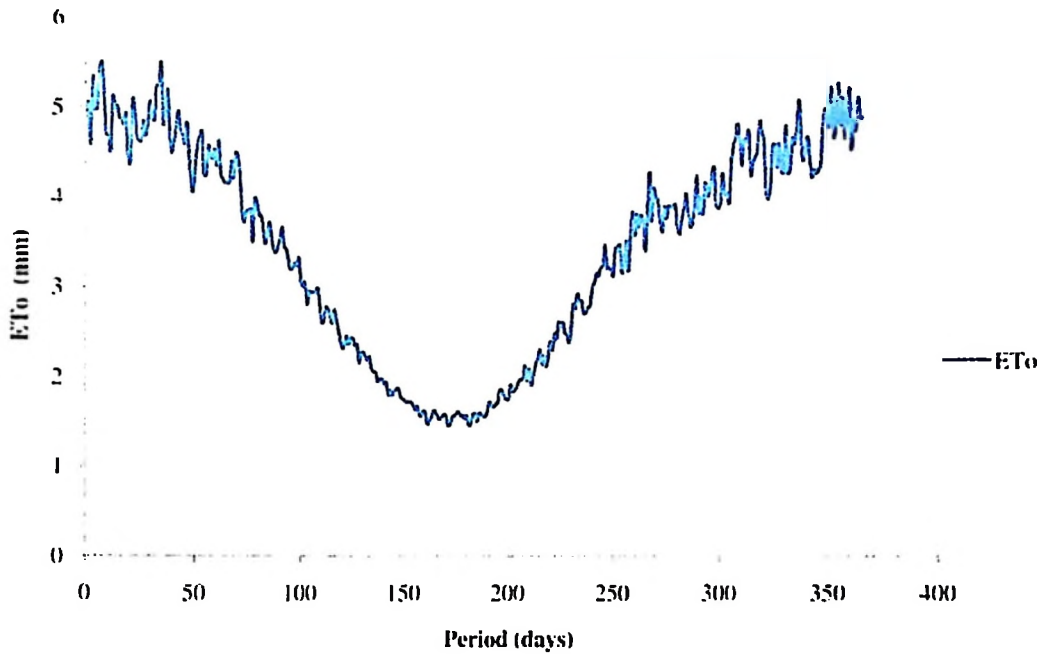


Figure-2
Reference evapotranspiration (ETo) for Big Bend

Table-2
Canopy factors (ETcane / ETo) for cane harvested in different months in Swaziland

Harvest	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Apr	0.4	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May		0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0	1.0
Jun			0.4	0.4	0.4	0.5	0.8	1.0	1.0	1.0	1.0	1.0
Jul				0.4	0.4	0.4	0.7	1.0	1.0	1.0	1.0	1.0
Aug					0.4	0.4	0.6	0.9	1.0	1.0	1.0	1.0
Sept						0.4	0.4	0.7	1.0	1.0	1.0	1.0
Oct							0.4	0.4	0.8	1.0	1.0	1.0
Nov								0.4	0.5	0.8	1.0	1.0
Dec									0.4	0.5	0.8	1.0

Source: Swaziland Sugar Association (1995)¹²

Table-3
Sugarcane water and irrigation requirements in Big Bend

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
ETo	156	134	158	91	69	53	63	90	116	128	141	107	1306
c/f	1.0	1.0	1.0	0.4	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	
ETc	156	134	158	36	28	32	50	81	116	128	141	107	1167
R	99.9	84.3	70.7	43.2	16.9	11.5	9.9	17.4	23.9	60.5	97.3	104.7	640
Re	80	67	42	26	10	7	6	10	14	36	78	84	461
IRR	76	67	116	11	18	25	44	70	102	91	63	23	706

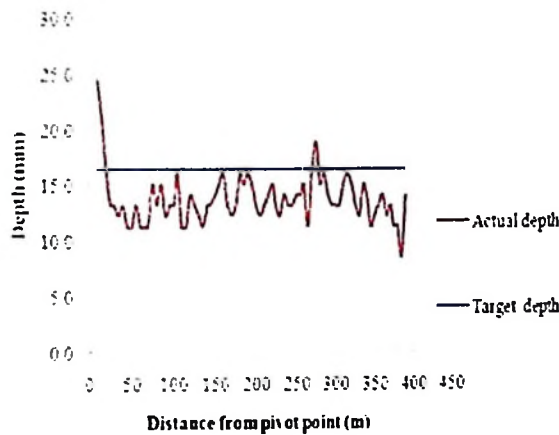
ETo = reference evapotranspiration (mm/month), c/f = canopy factor, ETc = cane evapotranspiration (mm/month), R = rainfall (mm), Re = effective rainfall (mm), IRR = irrigation requirement (mm)

Table-4
Performance parameters for centre pivots EEL09, NKA21, CAS02 and SMB

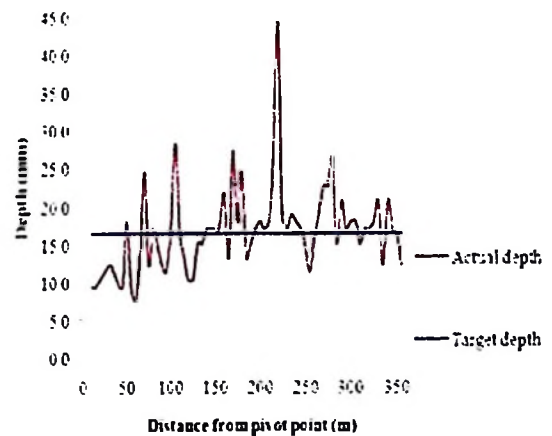
Centre pivot	Wetted area (ha)	Time per rev. (hrs)	CP speed (mm/min)	Pressure (Bar)
EEL09	49.1	42.8	935.0	3.1
NKA21	45.6	42.3	973.3	3.3
CAS02	36.5	34.9	973.3	1.4
SMB	70.4	46.3	1013.3	3.0

Table-5
System capacities and net crop water demand for centre pivots EEL09, NKA21, CAS02 and SMB

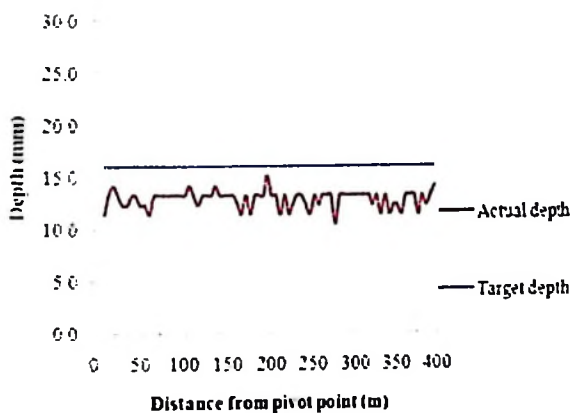
Centre pivot	Design flow rate (m ³ /h)	Actual flow rate (m ³ /h)	Flow rate (l/s)	Flow rate (ML/day)	Crop demand (mm/day)
EEL09	191.9	178.6	49.6	4.3	7.5
NKA21	200.0	176.0	48.9	4.2	7.5
CAS02	130.0	133.6	37.1	3.2	7.5
SMB	253.1	257.0	71.4	6.2	7.5



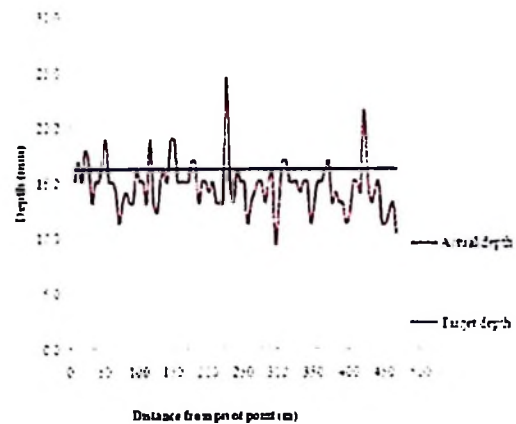
(a) EEL09 water application



(c) CAS02 water application



(b) NKA21 water application



(d) SMB water application

Figure-3
Water distribution profile along the lateral radii of EEL09, NKA21, CAS02 and SMB centre pivots

Table-6
Crop water requirement and adequacy of water supply for centre pivots EEL09, NKA21, CAS02 and SMB

Parameter		EEL09	NKA21	CAS02	SMB
		(49.1 ha)	(46.5 ha)	(36.5 ha)	(70.4) ha
ETo (mm/day)	6.0	6.0	6.0	6.0	6.0
Kc (sugarcane)	1.25	1.25	1.25	1.25	1.25
Net application (mm/day)	7.5	7.5	7.5	7.5	7.5
Gross application (mm/day)	8.8	8.8	8.8	8.8	8.8
Equivalent flow rate (l/s/ha)	1.0	49.6	48.9	37.1	71.4

Table-7
Performance indicators for centre pivots EEL09, NKA21, CAS02 and SMB

Centre pivot	CU (%)	DU (%)	PELQ (%)	AELQ (%)	Depth (mm/day)	Time (hrs)
EEL09	89.7	89.2	84.8	83.5	13.7	42.8
NKA21	94.6	95.7	81.3	80.0	12.8	42.3
CAS02	80.5	77.2	93.3	98.2	16.2	34.9
SMB	88.7	89.6	94.4	90.8	14.7	46.3

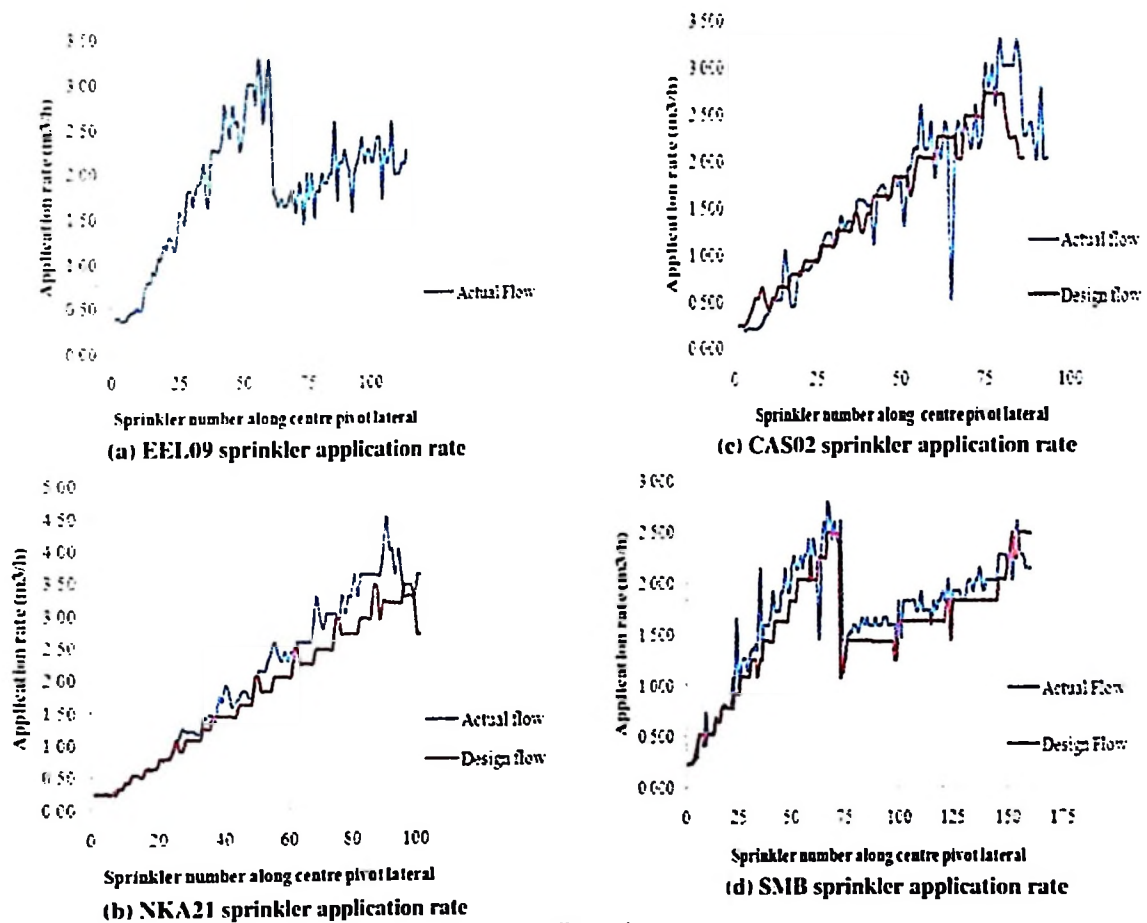


Figure-4
Sprinkler application rate along the lateral of EEL09, NKA21, CAS02 and SMB centre pivots



Figure-5

Sprinkler package inspection and operating pressure measurement in one of the centre pivots while in operation

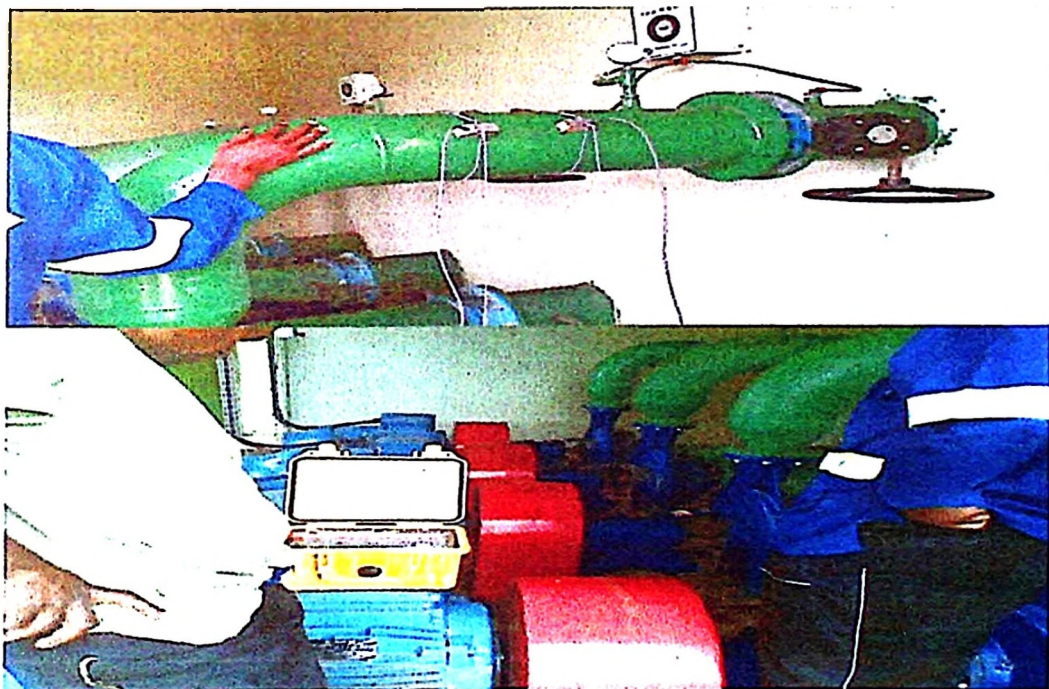


Figure-6

Pump flow rate measurement in the delivery pipeline of the pumps supplying NKA21 using a portable flow meter

Table-8
Soil physical properties for EEL09, NKA21, CAS02 and SMB centre pivots

Field	Organic Matter (%)	Bulk Density (g/cm ³)	Porosity (%)	Particle size Distribution (%)			
				Clay	Silt	Sand	Text. Class
EEL09	1.82	1.32	50.24	14.47	32.9	52.63	Sandy
NKA21	1.76	1.27	51.92	17.33	34.13	48.55	Sandy
CAS02	1.28	1.34	49.32	9.98	45.68	44.35	Silty sand
SMB	1.60	1.33	49.77	14.55	36.45	49.0	Sandy
		@ 100 kPa	@ 1500 kPa	RAM (mm/m)	% Moisture	Saturation (g)	
EEL09	274.67	271.99	269.64	35.2	30.99	287.66	
NKA21	265.1	261.57	257.96	44.44	23.09	277.7	
CAS02	261.26	256.8	253.43	60.0	33.74	267.53	
SMB	275.58	272.81	266.92	36.54	25.55	288.04	

Table-9
Soil chemical properties for EEL09, NKA21, CAS02 and SMB centre pivots

Field	pH	EC (mS/m)	SAR	T.S.C (Meq/L)	Na (Meq/L)
EEL09	6.33	0.3	1.09	3.48	1.17
NKA21	6.51	0.3	1.23	2.75	1.11
CAS02	7.21	0.4	2.18	4.50	2.29
SMB	6.75	0.3	1.42	2.94	1.24

Table-10
Irrigation water quality parameters for sources supplying EEL09, NKA21, CAS02 and SMB centre pivots

Field	pH		EC (mS/m)		SAR		TDS (mg/L)		TSS (mg/L)	
	CP	Dam/Canal	CP	Dam/Canal	CP	Dam/Canal	CP	Dam/Canal	CP	Dam/Canal
EEL09	7.5	7.7	0.3	0.2	5.4	6.3	93.3	75.4	26	30
NKA21	7.7	7.6	0.2	0.2	5.8	5.8	116.1	115.8	12	14
CAS02	7.6	7.7	0.3	0.2	7.9	5.1	142.5	107.2	0	40
SMB	7.8	7.9	0.1	0.1	4.8	5.4	51.4	51.0	140	146

Table-11
Average soil compaction values for EEL09, NKA21, CAS02 and SMB centre pivots

Test centre pivot	Area (ha)	Soil depth (cm)	A	B	C	D
			2500*	2500*	2500*	2500*
EEL09	49.1	0-15	1211	2471	1981	3678
		0-30	1523	3822	2538	3601
		0-60	2970	4100	4330	5223
NKA21	45.6	0-15	627	565	-	-
		0-30	877	1230	-	-
		0-60	1467	1832	-	-
CAS02	36.5	0-15	534	467	355	433
		0-30	805	704	658	662
		0-60	1064	942	1157	1280
SMB	70	0-90	1215	1098	1430	1657
		0-15	849	720	298	621
		0-30	1251	1007	869	1006
		0-60	2279	2644	1313	1852

A, B, C, D – centre pivot quadrants as function of pivot size, *Maximum penetration resistance ideal for sugarcane root growth

Table-12
Soil basic infiltration rates for EEL09, NKA21, CAS02 and SMB centre pivots

Centre pivot quadrants	EEL09	NKA21	CAS02	SMB
A	-	102	78	-
B	-	72	-	138
C	6	-	180	-
D	120	-	-	216

Table-13
Yields for EEL09, NKA21, CAS02 and SMB centre pivots

Yields	EEL09	NKA21	CAS02	SMB
TCH (t/ha)	71	124.8	147	106.2
Sucrose (%)	12.3	11.3	12.7	13.6

Conclusion

Centre pivots are performing relatively well and continue to be the system of choice at Uhombo Sugar estate. The appreciable performance conditions are attributed to accurate design and installation of the system, scheduled maintenance and management among other factors. Pressure variations, clogging of sprinklers, rutting of un-gravelled tracks are factors affecting the performance of the system and needs to be reviewed although performance indicators were found within acceptable standards. Major factors limiting centre pivot irrigation potential on sugarcane yields includes shallow soils with low water holding capacities, compaction, reduced infiltration and game encroaching sugarcane fields.

Recommendations: i. Constantly check system, sprinkler and tyre pressure and correct any deviations. ii. Flush centre pivot lateral and sprinklers to avoid sprinkler clogging. iii. Gravel wheel tracks or install back boom sprinklers along towers to prevent wheel ruts. iv. Chiselling every cut and ripping during

plough-out for mechanically harvested fields. v. Upscale research on effects of mechanical harvesting to develop management procedures. vi. Fence off fields at the vicinity of nature reserves to eliminate cane damage by wild animals.

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PAPER FIVE

**2.5. Measurements and Mapping of Soil Compaction for a Mechanized Centre
Pivot Irrigation System**

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Measurements and Mapping of Soil Compaction for a Mechanized Centre Pivot Irrigation System

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Abstract

The objective was to investigate the influence of centre pivot wheels on compaction of soils in the vicinity of the tracks, its spatial variability and soil compaction prospects for mechanical harvesting operations at Uhombo Sugar estate. Two centre pivots were selected for purposes of the study, SMB manually harvested and EEL09 being mechanically harvested. Measurements were taken using an automated P5 Hand Penetrometer on sampled points and a handheld Juno SB GPS was used to capture positions of each data point. Statistical analysis was performed on compaction values using SPSS, soil compaction maps produced using ArcGIS software and penetration trends using HPen32 software and geospatial interpolation technique. Significantly higher soil compaction values at 0 to 15 cm depth ($p < 0.01$) were associated with EEL09 centre pivot with an average of 3210 kPa compared to those of SMB at average of 1389 kPa. A parallel trend was observed at depth of 0 to 30 cm where significant differences in soil compaction between EEL09 (average of 4987 kPa) and SMB (average of 2209 kPa) centre pivots were recorded. Soil compaction mapping indicates that there is a general decline in soil compaction as one move away from the wheel tracks for both centre pivots. These observations are in agreement with the results obtained in a study conducted in a cracking clay soil where cone index measurements indicated that there was no lateral spread of compaction in the traffic lanes in a controlled traffic system. The trend on both pivots also indicates that compaction is spatially variable owing to the heterogeneity of soils within a centre pivot and the differences in harvesting systems. Higher compaction values were obtained for the mechanically harvested centre pivot (EEL09) and an increase in compaction for SMB was due to machinery traversing in-field when collecting manually harvested sugarcane. The current trend of soil compaction among the fields will generally affect soil infiltration, water storage capacity, irrigation systems performance and subsequent reduction in sugarcane yields.

Keywords: Centre pivot, compaction, harvesting, manual, mechanical, soil, sugarcane.

Introduction

Soil compaction is a serious concern for a majority of agricultural soils at global scale due to the evolution of conventional farming methods into mechanized operations. An increase in the frequency and type of machinery used for farm operations has led to the consolidation of soils in the field. Soil compaction research has revealed to have significant reduction in crop yields due to increased runoff and soil structure deterioration, hence water and soil quality degradation. In Pennsylvania in particular, a 10 percent yield reduction in wheat has been reported due to soil compaction problems¹. Compaction is therefore considered to be an issue that will likely to affect crop production and be of supreme importance in the subsequent years. Notwithstanding the problems associated with soil compaction, 47% of the sugarcane fields at Uhombo Sugar estate are now irrigated by mechanized centre pivot systems subsequent to innovations to convert poorly performing fields of furrow and dragline sprinkler systems and the number is set to rise as a result of the impetus for strategic future developments of the estate². In addition, a majority of these fields are increasingly being mechanically harvested by chopper

harvesters owing to the demand of biomass for cogeneration and high throughput capacity of the factory consequent to the expansion project. However, no efforts have been made to study and mitigate the effects of mechanizing these field operations to avoid land degradation and yield losses on sugarcane.

The consolidation of agricultural soils affects crop production by creating poor environment for root growth, reduction of water infiltration and increased runoff, hence soil erosion. Soil compaction caused by the passage of vehicles results in important economic and ecological consequences, such as poor crop productivity due to problems of crop establishment and root growth and excessive soil erosion due to reduced water infiltrability³. Wheel traffic from heavy machinery can compress soils to varying degrees throughout the plant root zone, often causing increased mechanical strength and decreased air and water permeability⁴. This condition can impede root elongation and significantly reduce crop growth and yield. The detrimental effects of soil compaction on crop performance have been reported to reduce crop growth potential, which included water infiltration, plant available water capacity, oxygen supply and de-nitrification⁵. Compacted

soil layers affect crops directly as plant roots encounter high physical resistance and indirectly by causing poor soil aeration, lowering the access of plants to soil water and increasing water logging⁶. In addition, an increase in the compactness of soil result in decreased root size, higher concentration of roots in the upper soil, lower rooting depth and a greater distance between the nearest roots⁷. Plant nutrient uptake and effectiveness of fertilization are also reduced by soil compaction. A similar study conducted in 2002 where Cone Index (CI) data was used to explain corn yield variation within a field, it was found that the mean CI throughout the top 76.2 cm soil profile was appropriate to explain yield variation⁸. It was also concluded that the maximum CI values at or above 1.4 MPa resulted in below average yields for 89% of the readings exceeding this limit. Another study conducted in 2006 to investigate the influence of soil compaction on sunflower production showed that plant height and leaf area were reduced by compaction due to deteriorated soil conditions for root growth⁹. The root biomass was lowered by 16 to 33% in compacted soil compared to non-compacted one. The study concluded that soil compaction was a major cause of the reduction of biomass accumulation in the plant root and the grain yield per plant.

In a mechanized centre pivot irrigation system, the centre pivot is repeatedly and continually driven on predetermined wheel tracks. Efforts have been previously made to improve traction along centre pivot wheel tracks through gravelling, use of dual drive wheels, installation of furrow busters, star tracks and back boom sprinklers. This prolonged movement on the predetermined tracks leads to the development of wheel ruts as a result of the repeated trafficking of the tower wheels over wet or moist soil¹⁰. Information of the lateral effect of centre pivot wheels on compaction of soil in the vicinity of the tracks is limited. Assessing and understanding the lateral effect of centre pivot wheels on soil penetration resistance is a crucial step towards appropriate application of the centre pivot irrigation technology within the estate. In addition, assessing the effect of mechanizing harvesting operations remains salient to make radical decisions towards soil management. Therefore, this study investigated the effect of centre pivot wheels on compaction of soil in the vicinity of the wheels, its spatial variability within the field and soil compaction prospects for mechanical harvesting operations to generate soil compaction maps which will form basis for sustainable management of soils to improve irrigation system performance and sugarcane yields in the estate.

Material and Methods

Experimental site: The experimental field work was performed at the end of the 2013/14 cropping season on two fields under centre pivot irrigation systems harvested manually and mechanically at Ubombo Sugar estate in the Lubombo region of Swaziland¹¹. The fields were located at Sangwaluma and Lukhalweni Sections (26°45'80"S, 31°56'26"E and 26°45'26"S, 31°53'53"E) with 70.4 and 49.1 ha respectively.

The crop was primarily sugarcane and soils were generally characterized as sandy loam. Field measurements were carried out immediately after mechanical and manual harvesting for each of the centre pivots.

Sampling and soil compaction measurements: Stratified random sampling technique was used for soil compaction data collection by randomly selecting three wheel tracks from the total number of tracks as determined by centre pivot size. Soil Penetration Resistance (PR) was used as an indicator of soil compaction¹². Measurements of soil compaction were taken using an automated P5 Hand Penetrometer from the sampled points when the soil was sufficiently brought to field capacity by soaking a column of water over all measurement points over night for pivots SMB and EEL09 (figure-1). The measurements were taken by gradually pushing a soil cone into the soil to measure the penetration resistance of the soil and pressure readings for each corresponding depth were stored in the data logger. The soil cone usually mimics a growing plant root as it penetrates the soil during elongation. A handheld Juno SB GPS was used to capture positions of each measurement point to enable generation of raster files for the production of soil compaction maps using geospatial interpolation tool for ArcGIS software ESRI Inc, 2010. Measurements were started on both sides of each track at a distance of 50 cm from the centre of the wheel track spreading out laterally by an incremental distance of 50 cm for 2 m and then by an incremental distance of 1 m up to 3 m to coincide with traffic lanes produced by chopper harvesters for the mechanically harvested centre pivot area. As a result, a total of 5 data points on each side of the track were acquired to make 10 measurements per wheel track and procedures were replicated on all four quadrants of the centre pivot irrigation system (figure-2). Data was downloaded from the data logger of the P5 Penetrometer and exported into Microsoft Excel for miscellaneous analysis. Graphs of penetration resistances were produced from the measurements for each data point using HPen32 software to study soil compaction for each specific site (figure-7 to 10). Interpolation technique was employed for purposes of predicting soil compaction trend for positions that lacked sampled points within the plots to enable superimposition of soil compaction trend (raster) for each centre pivot¹³.

Results and Discussion

Soil compaction analysis and mapping: Statistical analysis was performed to compare soil compaction values using one-way analysis of variance (ANOVA) from the Statistical Package of Social Sciences (SPSS) program, version 20 IBM Inc, 2011. Analysis was performed for soil depths 0 to 15 cm, 0 to 30 cm and 0 to 60 cm. For the depth of 0 to 15 cm, significantly higher soil compaction values ($p < 0.01$) were associated with EEL09 centre pivot with an average of 3210 kPa compared to those of SMB at average of 1389 kPa (Table-1). A parallel trend was observed at depth of 0 to 30 cm where significant difference in soil compaction between EEL09

coverage of 4987 kPa) and SMB (average of 2209 kPa) centre pivots were recorded. At 0 to 60 cm depth, average value for EEL09 was 5321 kPa and 3412 kPa for SMB centre pivot although measurements were limited by soil depth for EEL09. This was attributed to the fact that EEL09 was mechanically harvested by chopper hence high compaction values as opposed to SMB where compaction values were relatively lower. The higher values at SMB were induced by machinery removing cut cane particularly in the A and B quadrants of the pivot where the soils are relatively heavy and the fact that the portion was relatively wet during harvesting (figure-6). Geographical Information System (GIS) maps of soil compaction were developed using ArcGIS program ESRI Inc, 2010 for EEL09 and SMB centre pivots (figure-5 to 6). It is evident that high soil compaction values were obtained for EEL09 as opposed to SMB and the limiting factor among others being shallow soils of 50 to 60cm for EEL09. The trend in both pivots indicates that compaction is spatially variable owing to the heterogeneity of soils within the centre pivots and the differences in the machinery used for harvesting the two centre pivots (Figure-5 to 6). It is also imperative to be cognisant that actual penetration resistances towards root elongation and water absorption in the fields are generally higher than the values obtained owing to the normal irrigation practice of applying 25 mm per cycle which is lower than field capacities of the two centre pivots.

Soil compaction around pivot wheels: Soil compaction values for measurements obtained at the vicinity of the wheel tracks were converted into raster files using geospatial interpolation technique to generate soil compaction trend around the centre pivot wheel tracks of EEL09 and SMB centre pivots (Figure-3 and 4). The mapping indicates that there is a general decline in soil compaction as one move away from the track. The high compaction at a specific site towards the last data point of the mid track of EEL09 was a result of traffic lanes produced by chopper between the cane rows as trend highlighted a reduction in compaction away from the wheel track (Figure-3, 7 and 8).

The trend generated for SMB track indicates that compaction was higher near the centre of the track and decreased laterally away from the wheel track (Figure-4 and 9). These observations are in agreement with the results obtained in a study conducted in a cracking clay soil where cone index measurements indicated that there was no lateral spread of compaction in the traffic lanes in a controlled traffic system¹². Results of a study in a loamy soil due to traffic stated that the geometry of the severely compacted areas under wheel tracks was bulb-shaped and the area could be approximated by a half-ellipse¹³. Integration and consolidation of these findings indicate that regardless of soil type, traffic has no lateral effect on compaction of surrounding soils.

Soil compaction under mechanical harvesting: Figures – 3, 7 and 10 presents the influence of mechanical harvesting operations on soil compaction. The general compaction of the soil is significantly lower than compaction values obtained after mechanical harvesting by chopper and additionally by machinery collecting cane infield for the manually harvested centre pivot. For the same track at EEL09, there was a huge difference between compaction values obtained in portions not tempered by chopper at 3 m. Figure-7 indicates that the first two readings were very high in terms of compaction particularly because the chopper wheel had passed in that portion as opposed to the three other readings which were significantly lower. Evidence is shown in the raster displaying the trend of compaction around the tracks where one portion of the maps shows very high compaction values as it has been tempered by the chopper wheel (Figure-3). Figure-10 also proves to have high compaction for SMB pivot that the rest of the field as it has been measured on field sections traversed by machinery collecting cut cane. A major predisposing factor could have been the clayey soil type harvested at relatively wet conditions. However, it is imperative to note that compaction from this kind of machinery is still lower than that of chopper as shown in figure-7 and 10.



Figure-1

Measurement of soil compaction using P5 Hand Penetrometer after soaking soil near field capacity at each data point in the centre pivots

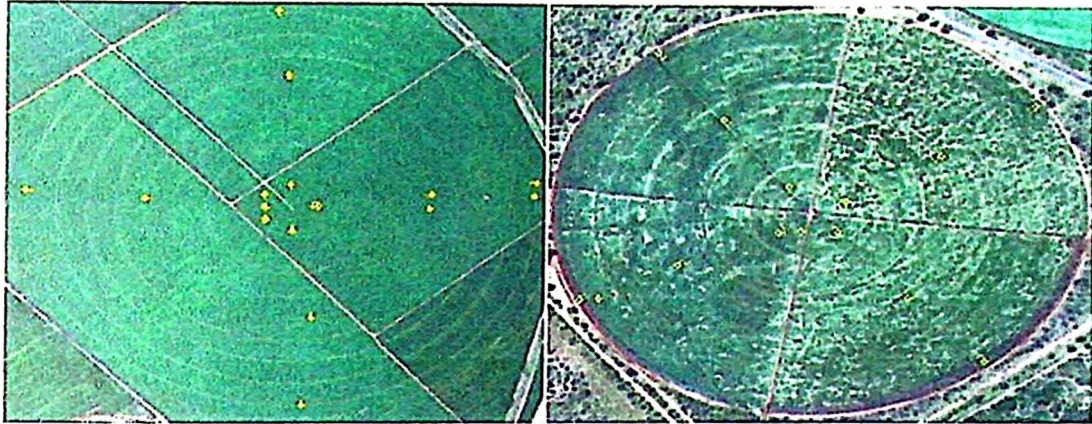


Figure-2

Measurement points superimposed on the aerial images of SMB and EEL09 centre pivots

Table-1
Average soil compaction (kPa) for all wheel tracks of SMB and EEL09 centre pivots

Test centre pivot	Area (ha)	Soil depth (cm)	First track	Mid track	Last track
SMB	70.4	0-15	2500 ^a	2500 ^a	2500 ^a
		0-30	2149	1720	298
		0-60	1251	1007	4369
EEL09	49.1	0-15	3279	2644	4313
		0-30	3678	2971	2981
		0-60	4601	4822	5538
		0-60	5223	5410	5330

Maximum penetration resistance ideal for sugarcane root growth

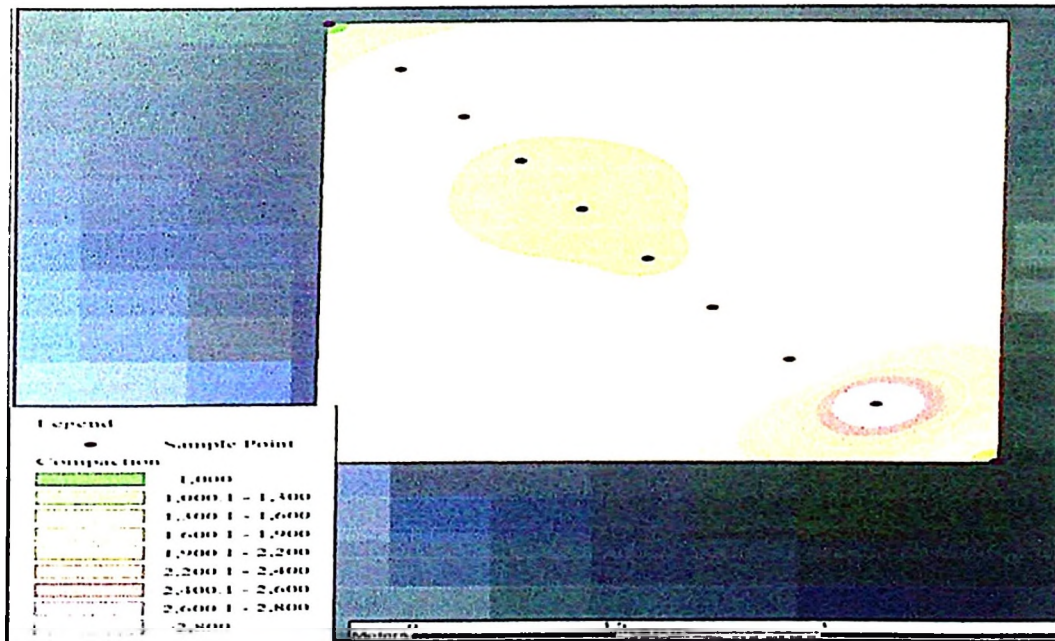


Figure-3

Soil compaction trend in the vicinity of the mid track of EEL09 centre pivot at 15 cm depth

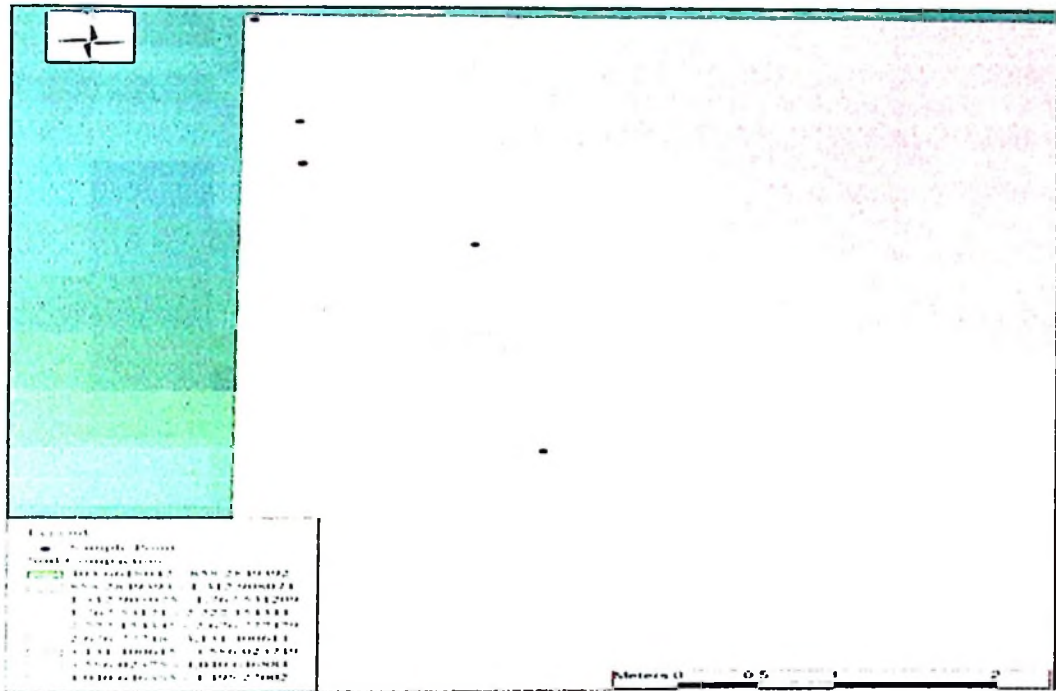


Figure-4
 Soil compaction trend in the vicinity of the first track of SMB centre pivot at 15 cm depth

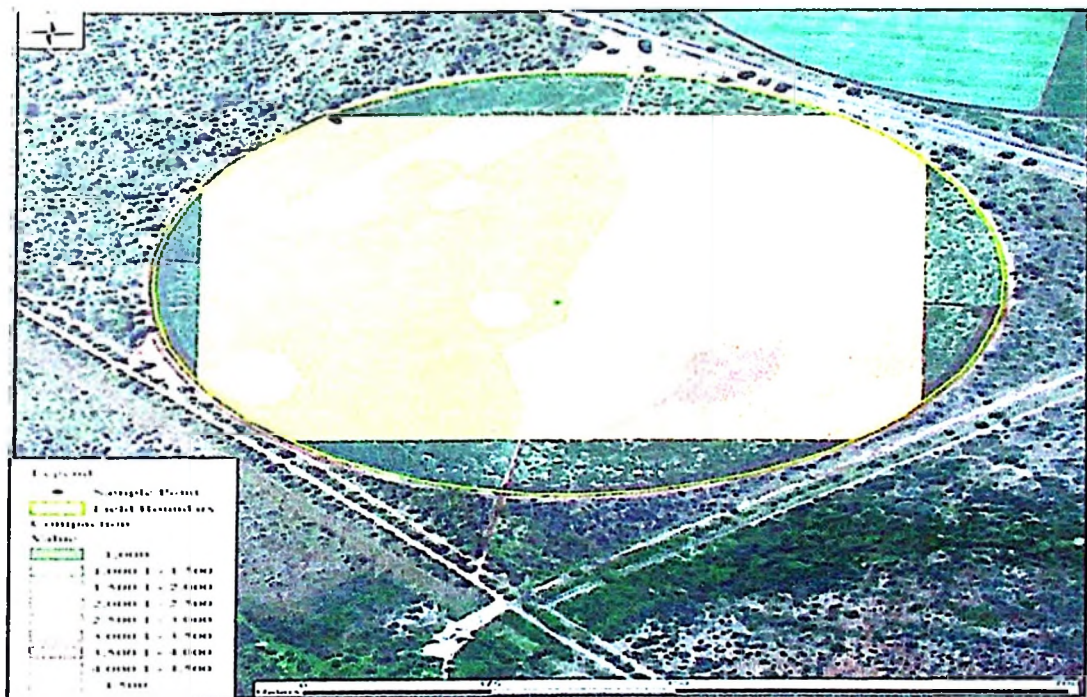


Figure-5
 General soil compaction trends interpolated from data points for the entire EEL09 centre pivot at 30 cm depth

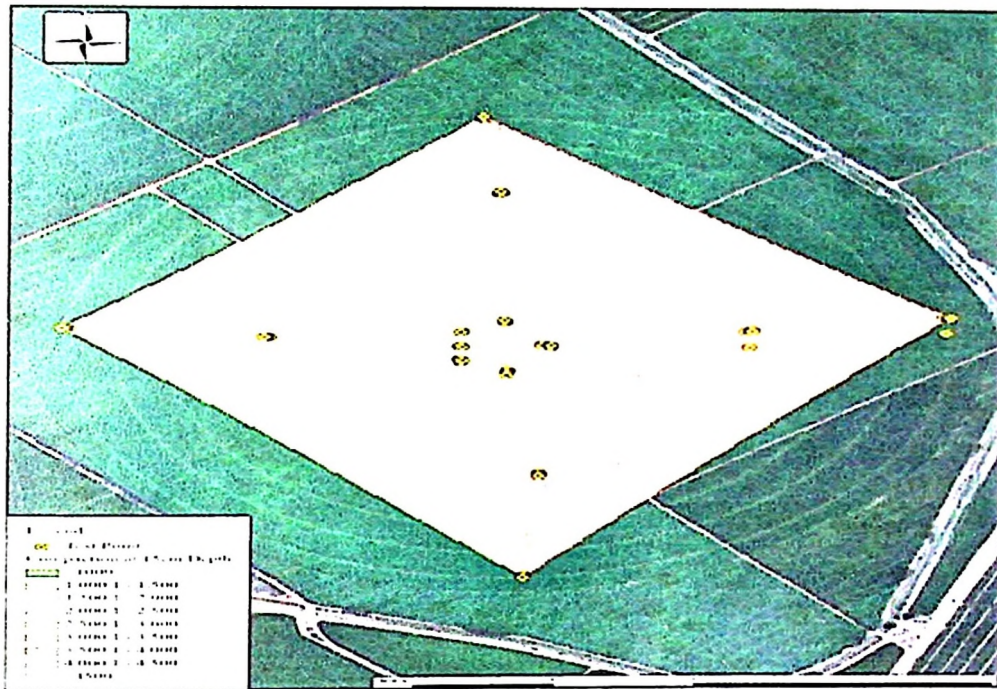


Figure-6
 General soil compaction trends interpolated from data points for the entire SMB centre pivot at 30 cm depth

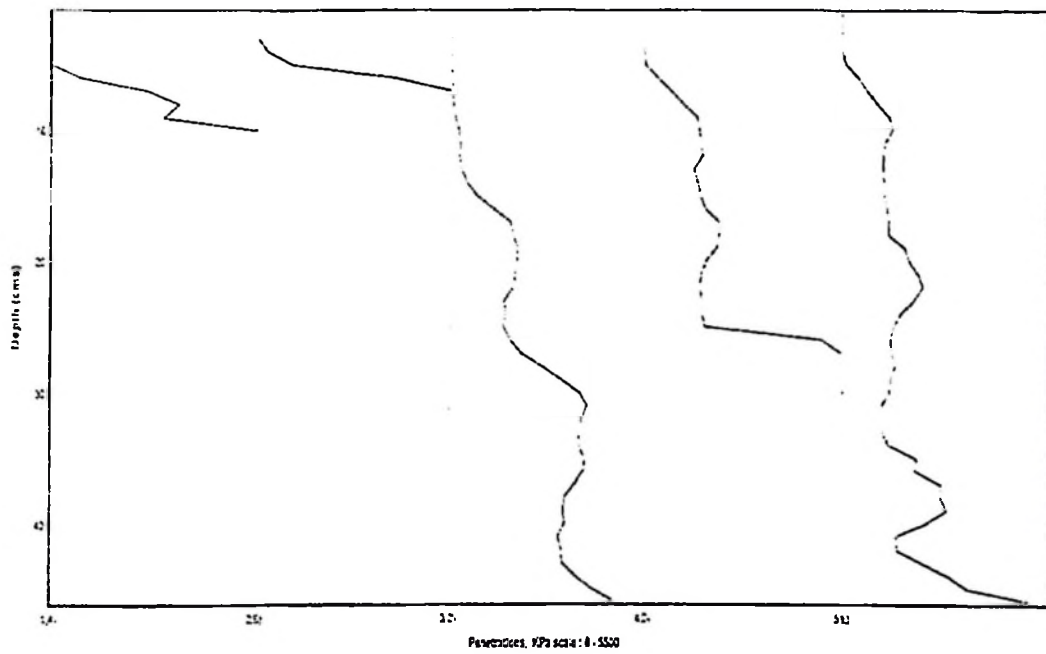


Figure-7
 Soil penetrations for EEL09 with portion where chopper wheel has passed during harvesting

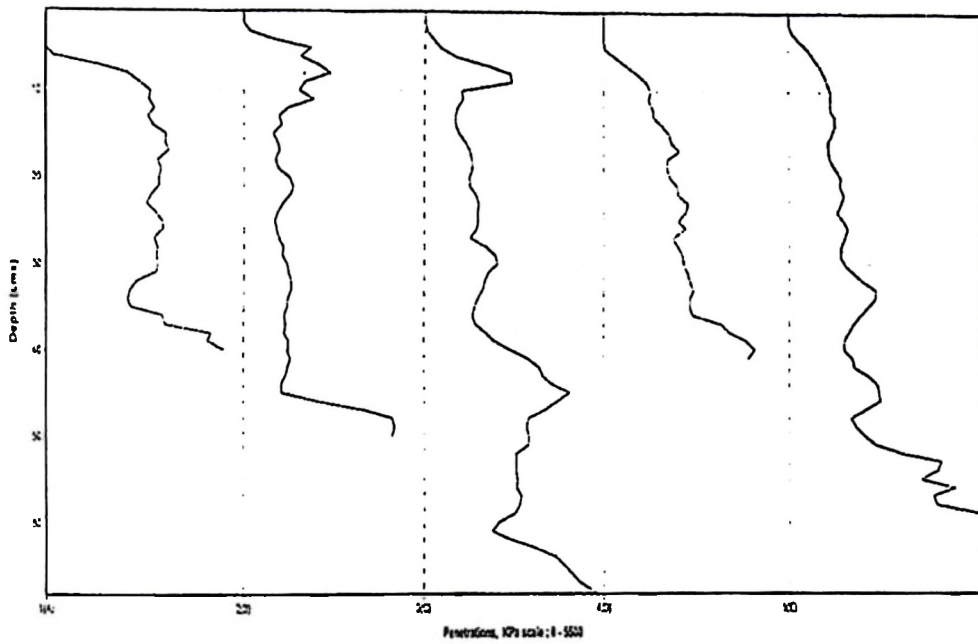


Figure-8
 Soil penetrations for EEL09 indication high compaction in the top 10 cm away from the wheel track

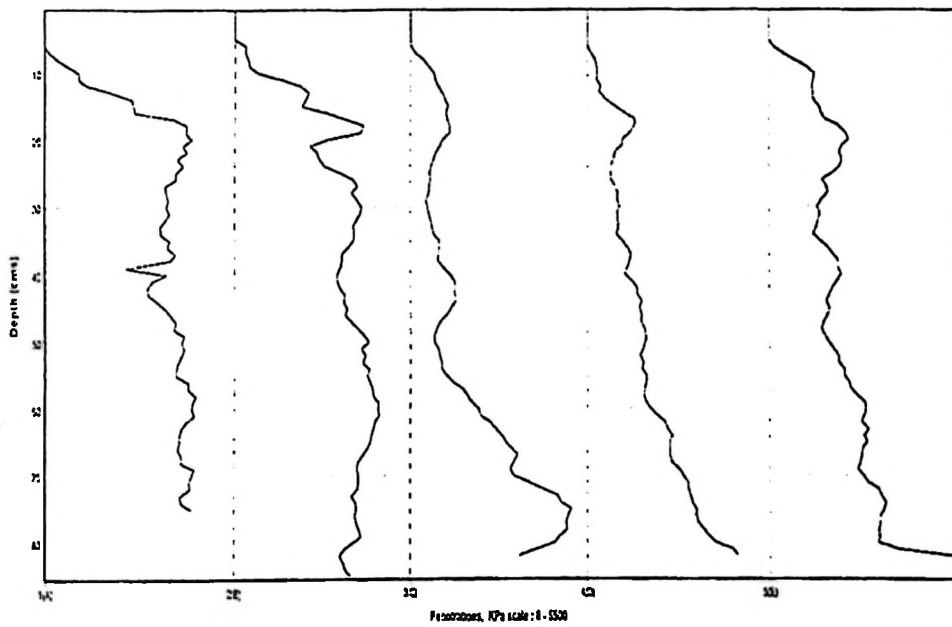


Figure-9
 Soil penetrations for SMB showing compaction away from the centre of the wheel track

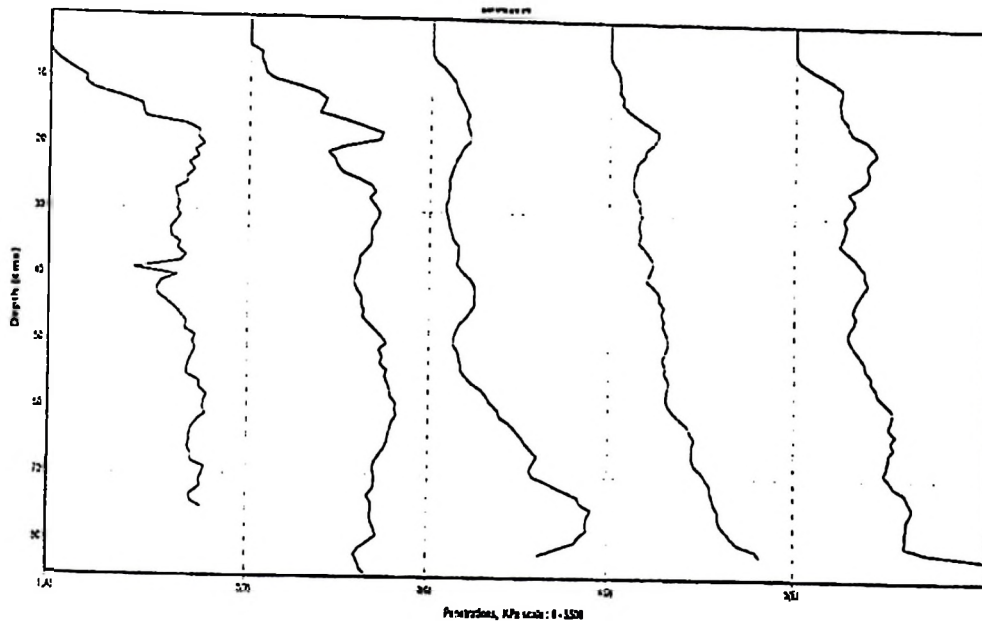


Figure-10
Soil penetrations for SMB showing compaction by machinery removing cut cane

Conclusion

There is no lateral effect of centre pivot wheels on compaction of soils in the vicinity of the tracks. Soil compaction is generally aggravated by mechanical harvesting and timing of operations as compaction values were higher for EEL09 which is chopper harvested. A remarkable increase in soil compaction for SMB centre pivot was also observed due to machinery traversing when collecting manually harvested sugarcane and the moist soil conditions during harvesting particularly the portions covered by heavy soils with high moisture retention. Actual penetration resistances towards root elongation are higher than the values obtained as fields are not irrigated to field capacity. The current trend of soil compaction among the fields will generally affect soil infiltration, water storage capacity, irrigation systems performance and subsequent reduction in sugarcane yields.

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CHAPTER THREE

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1. Conclusions

The following are conclusions from the study:

- i) Centre pivots are relatively performing well and continue to be the system of choice at Ubombo Sugar Estate in spite of lower application efficiencies for some of the units.
- ii) Pressure variations at pivot points and tyres, clogged sprinklers and low infiltration rates of soils due to compaction are the main factors affecting system performance.
- iii) Uniformities of water application tend to decline with an increase in centre pivot speed whereas application efficiency tends to increase with speed, a trend that appears to be unique for the current study as opposed to results reported elsewhere.
- iv) Irrigation water and power supply are limited by existing budgets which do not reflect legitimate estate water and power demand. This results in inadequacy of irrigation water supply, induction of water stress to the crop and subsequent reduction in sugarcane yields.
- v) Although soils and water are suitable for sugarcane production using centre pivot irrigation system, soil compaction as a result of mechanical harvesting causes significant reduction in soil infiltration rate, water storage capacity and ultimate

runoff from the fields. This generally underscores the potential of centre pivot irrigation system.

3.2. Recommendations

Based on the findings, the following are the recommendations of the study:

- i) Regular pressure checks, flushing of centre pivot lateral and sprinklers, gravelling of wheel tracks or installation of back boom sprinklers should be undertaken to improve centre pivot irrigation system performance.
- ii) Development and adoption of a new water and power budgeting model from first principles is essential to improve irrigation water supply. This will prevent crop water stress and subsequent reductions in yield.
- iii) Further research is crucial on the effects of mechanical harvesting on compaction of soils to develop operating procedures and mitigation strategies to avoid yield losses and soil deterioration.
- iv) Fencing fields near nature reserve to prevent wild animals from feeding and destroying sugarcane will improve yields (e.g EEL09).

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APPENDICIES

Appendix 1: Meteorological data used for the determination of crop water requirements

STATION: NNGOGO WEATHER STATION, LOCATON: BIG BEND

CO-ORDINATES: X 26° 46' 43'', Y 31° 56' 11'', Z 107 m

MEAN MONTHLY WEATHER SUMMARY, JANUARY 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
32.8	21.4	80.6	57.0	23.0	7.1	102.2	4.2
31.6	21.4	80.2	61.5	20.7	5.7	100.8	0.6
33.1	21.1	82.4	55.9	24.3	7.9	123.0	2.2
31.7	21.0	78.9	56.2	22.8	7.0	104.3	0.5
32.0	21.0	80.0	56.9	23.4	7.4	87.7	1.3
34.0	20.7	79.2	55.4	25.3	8.5	89.9	5.4
35.0	21.5	79.7	51.7	24.6	8.1	101.5	2.0
33.3	21.9	76.9	53.4	22.6	6.9	108.2	1.9
32.0	21.1	78.8	56.7	21.0	5.9	105.0	2.9
31.7	21.2	80.2	58.1	21.0	6.0	109.5	15.3
31.0	20.2	81.5	57.8	21.0	5.9	91.3	1.7
32.7	20.1	80.1	52.9	23.3	7.3	118.1	0.3
32.8	21.2	77.0	53.1	22.0	6.6	112.2	2.8
32.8	21.7	80.4	55.2	22.7	7.0	98.1	2.4
32.6	21.5	78.4	56.2	22.2	6.8	90.7	3.7
33.2	21.6	81.6	55.9	21.5	6.3	113.1	7.1
31.8	22.0	81.9	58.0	21.5	6.3	115.0	4.5
32.7	21.5	77.3	57.2	22.5	6.9	90.5	5.7
32.0	21.5	81.0	57.5	19.6	5.2	94.9	1.6
31.5	21.1	82.5	57.1	20.1	5.5	79.7	2.0
32.8	20.8	79.0	54.4	23.7	7.7	90.5	2.3
33.4	21.4	81.6	55.4	22.8	7.2	85.9	1.2
32.8	22.0	79.3	59.3	20.9	6.1	97.2	3.4
32.5	21.8	85.5	60.8	21.1	6.2	95.5	3.0
32.1	21.5	81.4	60.3	21.2	6.2	93.5	3.4
32.0	21.3	83.8	60.4	22.9	7.3	89.6	4.5
31.4	21.3	85.1	59.5	21.8	6.6	104.7	4.1
32.0	20.8	79.9	56.3	22.2	6.9	102.4	1.7
32.3	21.3	78.2	54.4	23.4	7.7	102.3	0.5
33.0	20.9	80.8	56.2	22.5	7.1	92.7	6.4
32.5	21.1	83.4	59.0	23.0	7.5	81.7	1.1

MEAN MONTHLY WEATHER SUMMARY, FEBRUARY 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
33.0	21.6	80.1	54.3	24.6	8.5	86.8	0.8
33.4	21.3	82.3	55.4	24.7	8.5	91.6	0.2
34.5	21.2	81.1	50.8	25.5	9.1	95.2	6.4
32.1	21.6	81.2	57.8	22.5	7.3	89.7	2.6
33.0	21.8	83.5	56.2	23.2	7.7	88.7	3.9
33.4	21.2	80.6	52.5	24.3	8.4	92.3	5.3
32.2	21.3	82.7	54.6	21.5	6.7	98.5	3.2
31.7	20.9	81.7	58.7	20.9	6.4	93.8	2.1
31.4	20.8	83.1	60.9	22.1	7.1	93.0	4.6
32.1	20.3	80.9	59.1	23.2	7.8	79.5	3.4
33.1	20.1	83.5	53.9	23.7	8.1	90.2	6.7
32.7	20.7	85.7	58.1	22.9	7.7	77.8	1.0
32.5	21.3	83.5	56.2	22.0	7.2	85.6	1.5
32.0	21.6	82.5	58.2	21.6	7.0	85.2	0.8
33.2	21.6	80.9	53.5	22.5	7.6	85.3	3.4
31.7	21.6	82.0	57.9	20.5	6.4	101.6	1.4
30.9	21.0	85.0	59.1	19.8	5.9	87.1	2.2
30.7	20.8	85.4	60.8	19.4	5.7	77.7	6.6
32.7	21.0	86.5	57.5	20.8	6.6	78.3	3.9
32.7	21.4	86.7	54.7	21.7	7.2	75.4	0.8
32.8	21.4	82.0	54.5	22.2	7.6	77.2	0.7
33.2	21.4	81.6	55.0	22.0	7.5	93.5	1.0
31.8	21.3	86.2	58.6	19.8	6.3	97.5	2.2
31.4	21.2	86.1	57.5	20.4	6.5	73.9	1.3
33.0	20.8	85.2	54.9	21.8	7.5	83.0	3.9
32.6	21.6	85.9	57.4	20.9	7.0	87.9	0.8
32.1	21.3	79.7	53.3	21.2	7.2	72.2	0.9
32.8	20.7	84.3	53.4	21.8	7.7	79.9	12.7

MEAN MONTHLY WEATHER SUMMARY, MARCH 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
32.0	20.8	83.5	59.1	21.2	7.3	75.0	6.3
32.7	20.6	85.6	55.3	22.4	8.1	90.4	2.6
31.8	20.8	82.2	55.1	19.9	6.6	96.4	4.1
31.6	20.6	85.2	56.1	20.1	6.8	89.9	1.6
31.1	20.5	84.1	56.9	20.1	6.8	87.1	1.3
31.5	20.4	83.1	56.0	20.3	7.0	79.1	1.1
31.8	20.5	85.3	54.6	20.4	7.1	70.5	4.4
32.1	19.9	84.5	53.3	21.8	8.0	82.1	0.5
32.1	20.7	83.8	54.1	20.2	7.1	84.1	2.9
32.8	20.9	83.4	52.5	22.0	8.3	77.1	0.7
33.1	20.4	84.5	48.8	21.5	8.0	83.4	1.5
32.2	19.9	83.9	52.2	20.2	7.2	96.1	2.1
30.2	20.2	83.5	57.7	18.6	6.2	85.2	0.1
30.5	19.9	82.7	57.2	18.4	6.1	69.7	1.0
31.2	19.6	87.6	56.1	19.1	6.6	78.1	2.5
31.1	19.6	87.2	56.7	19.3	6.9	72.3	2.6
31.2	19.7	85.0	57.3	19.5	7.0	71.3	8.0
29.7	19.5	84.7	63.8	17.9	6.0	66.0	1.7
31.8	19.2	85.5	52.2	20.2	7.6	74.8	0.3
32.1	19.8	84.7	54.7	19.9	7.5	65.6	1.3
31.5	19.9	88.2	55.6	19.3	7.2	63.5	1.9
32.4	19.0	88.1	54.0	19.3	7.2	64.6	0.9
31.8	20.2	83.4	54.8	18.2	6.5	66.0	7.2
30.5	20.1	87.7	58.9	17.7	6.2	62.0	4.3
31.0	19.8	88.2	60.1	18.4	6.8	61.6	0.8
31.7	19.8	85.0	55.5	18.8	7.2	70.8	0.6
31.0	20.0	83.5	58.6	17.8	6.5	70.5	0.6
30.3	20.1	85.8	59.4	17.4	6.3	69.7	1.9
30.3	20.1	86.8	60.5	17.4	6.4	61.8	2.2
30.9	19.5	86.0	59.0	17.9	6.7	61.8	2.7
30.6	19.4	87.3	56.8	18.4	7.2	66.0	1.0

MEAN MONTHLY WEATHER SUMMARY, APRIL 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
30.8	19.1	87.7	51.8	19.6	8.1	63.7	0.7
30.9	18.8	87.0	52.5	17.9	6.7	71.5	1.3
30.5	18.7	88.3	54.9	17.9	7.1	75.1	2.1
29.7	18.5	86.7	54.1	17.3	6.7	75.5	2.1
30.0	17.7	89.1	56.0	17.4	6.8	59.6	5.8
30.4	18.1	89.3	54.2	17.3	6.7	60.5	1.4
29.7	17.4	87.4	51.3	17.8	7.3	70.0	0.3
29.6	17.2	87.0	51.0	17.7	7.3	70.0	0.3
31.1	17.1	88.2	49.7	18.1	7.6	68.2	0.6
28.8	17.7	83.9	54.2	15.9	6.1	82.9	3.2
28.9	16.8	86.4	52.1	16.9	6.9	59.7	0.3
29.6	16.7	88.7	54.0	17.3	7.3	59.1	3.4
28.5	16.6	89.1	54.2	15.9	6.4	54.6	1.3
29.1	16.3	88.5	50.2	16.9	7.1	58.4	0.1
29.9	16.7	90.9	52.6	16.8	7.1	52.1	0.9
29.6	16.6	90.3	58.8	16.7	7.2	67.1	0.5
30.0	16.6	88.4	53.9	16.8	7.3	56.5	0.1
30.6	16.8	90.2	50.5	16.8	7.4	62.0	1.9
29.6	17.4	90.4	53.3	15.8	6.7	56.5	1.0
28.7	17.3	87.7	56.3	14.2	5.5	62.8	5.9
28.3	16.9	88.9	55.1	14.7	6.0	67.0	1.1
29.3	16.3	89.2	50.9	15.9	7.0	64.0	2.5
29.0	16.3	88.3	53.4	16.0	7.2	63.5	1.1
28.6	15.6	90.8	51.9	16.0	7.3	57.2	0.7
28.8	15.3	90.2	53.9	15.6	7.0	54.7	0.0
28.9	16.1	88.7	49.0	16.3	7.7	62.8	0.8
29.3	15.9	92.1	51.0	15.4	7.0	63.0	0.3
28.0	15.8	90.3	53.7	14.8	6.6	67.5	2.2
27.3	14.7	89.5	53.5	14.9	6.7	55.0	0.8
27.3	14.7	90.9	55.7	14.0	6.1	60.7	0.7

MEAN MONTHLY WEATHER SUMMARY, MAY 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
28.1	14.6	89.2	54.4	14.7	6.7	52.6	0.4
28.9	14.5	89.7	52.6	15.1	7.2	57.9	1.0
28.4	14.6	91.3	53.4	14.4	6.6	59.7	0.5
29.5	14.6	90.7	50.0	14.9	7.1	55.7	0.6
28.5	15.4	89.4	52.1	14.8	7.1	61.2	0.8
28.8	14.4	88.1	49.9	14.7	7.1	53.5	0.0
28.8	14.1	90.2	48.3	15.0	7.4	54.5	0.5
27.7	14.1	92.7	55.1	13.9	6.6	47.9	1.2
28.8	13.6	92.2	47.6	14.3	7.0	56.2	0.1
28.2	13.8	89.4	48.7	14.4	7.1	60.9	0.4
28.2	13.5	90.7	48.3	14.7	7.5	51.3	0.4
27.8	12.6	93.1	48.8	14.3	7.2	62.9	1.4
27.9	12.7	91.6	48.8	14.2	7.2	72.7	4.2
27.7	12.7	91.0	50.0	13.5	6.6	59.2	0.4
27.9	13.4	92.2	50.8	13.4	6.6	52.8	0.0
27.4	13.7	92.0	51.9	13.4	6.6	54.4	1.3
27.7	12.8	92.7	49.0	13.0	6.3	45.1	1.2
27.6	12.4	94.5	51.4	13.8	7.1	44.0	0.4
28.0	11.8	94.8	46.6	13.9	7.2	44.4	0.0
28.0	12.3	92.0	49.2	12.8	6.4	49.4	0.3
27.5	13.0	91.4	47.6	13.1	6.7	49.2	0.1
26.5	11.7	92.4	49.2	12.4	6.1	47.6	0.1
27.5	10.9	93.8	45.6	13.3	6.9	45.5	0.0
27.3	10.4	92.0	46.5	12.9	6.7	45.4	0.0
27.0	11.0	92.0	47.5	12.9	6.7	53.3	0.5
27.8	10.4	92.6	43.3	13.2	7.0	53.5	0.5
27.3	9.7	92.0	41.8	13.5	7.3	58.4	0.0
25.8	10.0	91.4	49.4	12.3	6.3	69.5	0.5
26.1	10.1	91.6	44.1	12.9	6.9	52.9	0.0
26.7	8.7	91.9	44.0	13.0	7.0	53.8	0.1
26.9	9.6	91.7	44.3	12.9	7.0	46.0	0.0

MEAN MONTHLY WEATHER SUMMARY, JUNE 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
26.6	9.7	90.5	46.6	12.4	6.6	57.2	1.0
26.4	10.2	91.2	46.0	12.5	6.7	54.9	0.0
26.4	9.5	89.3	45.9	11.9	6.1	58.8	0.3
26.0	9.4	92.1	45.0	12.4	6.7	47.5	0.5
26.0	9.0	92.3	45.7	12.4	6.7	60.0	0.1
25.9	8.9	92.2	47.6	11.9	6.3	50.7	0.8
25.8	8.2	95.2	45.1	12.5	6.8	43.5	0.0
26.4	8.9	90.6	46.5	12.1	6.5	53.8	0.2
25.4	8.8	90.7	47.0	11.8	6.3	58.4	0.1
24.9	8.4	93.5	52.6	11.5	6.0	46.3	0.2
25.6	8.3	93.0	47.5	12.2	6.7	45.1	0.2
26.2	8.4	92.6	45.7	12.0	6.5	46.9	1.0
26.5	8.7	92.8	45.1	12.5	7.0	54.1	0.7
26.2	8.4	90.3	39.7	12.4	7.0	50.9	0.1
26.1	7.2	92.2	44.2	12.3	6.9	53.5	0.2
26.0	7.4	92.9	44.1	12.1	6.7	49.7	0.3
25.8	7.8	91.0	43.2	12.4	7.0	50.5	0.2
25.7	8.3	92.5	47.9	11.8	6.4	64.1	0.9
25.2	10.0	89.3	50.6	11.4	6.0	58.2	0.2
24.7	8.9	92.9	49.1	11.1	5.7	48.8	1.2
25.4	8.6	93.5	48.4	11.7	6.3	42.9	0.0
26.3	8.2	93.4	48.1	12.4	7.0	48.4	0.2
26.4	8.5	93.1	44.3	12.5	7.1	46.3	0.1
26.0	8.3	92.9	42.9	12.1	6.7	59.1	0.2
26.2	7.7	90.6	43.7	12.1	6.7	62.8	0.0
25.6	7.7	88.6	43.8	12.0	6.6	57.1	0.0
26.1	7.3	90.1	41.0	11.9	6.5	57.8	0.8
25.3	7.7	89.8	46.2	11.4	6.0	60.4	0.4
25.2	7.9	90.4	50.0	12.4	6.9	58.6	0.4
24.5	8.3	93.8	51.9	11.6	6.1	47.1	1.3

MEAN MONTHLY WEATHER SUMMARY, JULY 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
24.5	8.9	92.6	51.6	10.9	5.5	58.8	0.0
25.4	8.0	92.9	48.3	12.2	6.7	61.2	0.1
25.7	8.0	90.1	45.9	12.2	6.7	57.1	0.0
24.5	8.1	93.1	51.8	11.9	6.3	51.2	0.1
24.4	8.5	88.5	49.4	11.6	6.0	68.0	0.1
24.3	7.7	90.1	46.6	12.0	6.4	64.3	1.0
24.6	7.7	91.5	47.3	11.6	6.0	63.4	0.5
25.4	7.6	92.1	45.0	12.3	6.7	49.7	0.0
25.8	7.2	91.6	42.4	12.8	7.1	53.0	0.0
26.5	7.1	92.4	38.7	13.1	7.4	63.0	0.1
25.2	8.1	91.5	43.4	12.1	6.3	67.7	0.1
24.9	8.6	90.6	47.3	12.5	6.7	61.0	0.2
24.8	8.9	91.7	44.4	12.5	6.7	64.2	0.1
26.0	7.6	93.6	42.3	13.2	7.3	59.4	0.0
26.5	8.0	89.3	39.1	13.7	7.7	68.4	0.1
25.4	8.3	87.2	42.2	13.1	7.0	77.1	0.0
25.8	7.3	87.5	40.7	12.7	6.7	71.3	0.6
25.1	8.2	89.1	46.4	12.7	6.6	66.0	1.9
25.6	7.8	90.2	43.8	13.7	7.5	52.1	0.1
26.4	7.7	91.0	38.7	14.3	8.0	67.6	0.0
26.7	7.8	89.9	39.0	13.2	6.9	62.1	0.0
26.7	8.2	89.8	39.9	13.7	7.3	56.9	0.1
26.3	8.8	91.2	42.1	12.8	6.4	72.2	0.2
26.6	9.1	88.6	41.6	13.3	6.8	71.2	0.1
26.3	9.3	92.4	43.9	13.3	6.8	78.7	0.9
26.7	9.8	88.8	41.6	13.3	6.8	69.1	1.0
27.4	9.4	84.5	40.0	13.9	7.2	78.8	0.8
25.8	9.7	90.5	45.5	13.5	6.8	67.5	0.4
25.9	10.0	88.1	44.0	13.8	7.0	82.4	0.0
25.1	9.7	88.2	48.2	13.0	6.2	66.4	0.1
26.6	9.1	89.6	42.4	14.7	7.7	56.8	1.2

MEAN MONTHLY WEATHER SUMMARY, AUGUST 1991- 2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
27.3	9.9	87.9	41.0	14.3	7.2	67.2	2.4
26.6	8.8	89.5	41.0	14.6	7.4	87.9	2.2
27.1	10.0	84.6	40.2	14.5	7.3	88.0	0.0
26.0	11.0	87.3	45.4	13.1	6.0	84.9	1.2
26.1	11.2	84.0	46.1	13.4	6.2	91.4	3.2
25.5	10.7	87.8	46.7	13.6	6.2	74.7	0.8
26.6	10.0	90.3	39.3	14.8	7.2	71.4	0.3
27.4	10.0	86.8	39.2	15.4	7.7	81.8	0.1
26.5	10.0	89.2	40.2	14.8	7.1	79.1	0.6
26.9	10.0	88.2	39.2	15.5	7.7	97.4	0.3
26.3	10.6	84.5	41.4	15.1	7.2	88.6	0.1
27.5	10.5	83.9	38.2	16.3	8.1	91.2	0.0
28.5	9.5	86.8	36.3	16.3	8.1	80.9	0.0
29.0	9.8	85.0	35.7	16.0	7.7	83.7	0.8
27.3	10.6	84.6	42.1	15.1	6.9	86.2	1.3
26.2	10.8	87.1	47.0	15.8	7.4	84.8	0.6
26.4	10.6	85.3	45.4	15.0	6.6	71.5	0.0
27.3	11.2	86.5	45.8	15.4	6.9	83.5	0.0
28.3	11.9	84.6	43.1	16.4	7.6	100.5	0.2
27.7	12.5	84.5	42.2	15.8	7.1	97.5	1.0
28.3	11.5	86.7	40.2	17.3	8.2	104.7	0.0
28.4	11.7	82.0	42.9	16.5	7.5	93.8	0.1
27.9	12.8	86.4	43.5	16.0	7.0	105.2	0.3
27.5	12.3	78.6	46.2	15.0	6.2	93.1	0.9
26.6	12.7	79.6	44.3	15.3	6.3	90.1	0.6
27.3	12.4	82.5	43.5	15.6	6.5	93.7	0.0
27.4	13.0	79.4	42.5	15.1	6.0	92.2	0.0
28.2	12.5	82.6	40.2	17.2	7.5	91.9	0.0
29.8	12.3	82.8	38.2	16.7	7.1	94.0	0.1
29.5	13.0	84.4	40.5	17.2	7.4	104.0	0.0
29.8	13.7	81.8	40.0	16.5	6.8	97.8	0.2

MEAN MONTHLY WEATHER SUMMARY, SEPTEMBER 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
29.4	12.9	81.1	38.1	18.1	7.9	89.4	0.3
30.1	13.4	82.7	40.0	17.1	7.1	104.9	0.9
30.4	13.9	81.8	35.9	17.9	7.7	113.1	0.1
29.2	14.9	80.7	45.6	17.1	7.0	93.9	0.1
29.6	13.9	84.0	43.5	16.8	6.7	106.4	1.7
28.7	14.1	77.9	44.8	16.4	6.3	105.1	1.6
28.0	14.3	82.2	46.4	16.8	6.5	96.8	3.5
29.9	13.7	82.3	39.4	18.1	7.4	106.0	0.2
30.4	15.0	76.2	42.1	17.0	6.5	99.5	0.9
30.4	15.3	80.0	44.7	17.5	6.8	106.3	1.1
27.5	14.7	81.5	48.5	16.5	6.0	104.9	0.7
28.2	13.4	81.1	48.2	17.3	6.5	110.2	1.0
29.2	14.2	78.1	45.9	17.2	6.4	134.7	1.4
26.5	15.9	78.0	51.1	16.1	5.5	108.3	0.7
29.2	14.6	79.0	40.9	18.7	7.3	95.2	0.8
30.6	14.4	78.2	40.4	19.7	8.0	114.1	0.4
29.5	15.5	78.7	45.0	17.8	6.5	110.7	0.4
29.8	16.0	75.7	43.6	17.7	6.4	137.7	0.2
28.8	15.5	75.1	43.1	18.1	6.6	114.8	1.0
29.3	15.7	73.5	43.5	18.7	7.0	116.7	1.9
29.3	14.4	75.9	43.0	18.7	6.9	121.3	0.6
28.3	16.1	74.4	54.4	16.6	5.4	110.0	1.0
30.4	15.6	79.0	45.8	18.9	7.0	101.9	0.1
32.3	16.6	76.0	46.1	20.4	7.9	131.1	0.0
29.8	17.1	78.8	50.2	18.5	6.6	104.6	0.1
31.2	16.9	79.9	45.6	19.7	7.3	125.0	0.5
30.7	17.3	76.0	43.4	18.3	6.3	127.4	0.8
29.6	17.2	71.9	49.1	17.9	6.0	138.5	0.6
27.7	16.0	73.7	50.8	18.3	6.2	122.5	0.6
28.8	15.4	77.1	51.6	18.9	6.5	87.4	1.1

MEAN MONTHLY WEATHER SUMMARY, OCTOBER 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
29.6	16.1	76.9	49.7	19.5	6.8	109.0	1.6
29.5	16.3	75.0	53.1	18.1	5.9	118.6	1.4
29.6	16.8	73.9	50.5	19.0	6.4	108.8	2.7
29.7	16.8	72.9	49.6	18.9	6.3	105.0	1.4
29.9	17.5	73.5	47.8	18.5	6.0	102.6	1.0
29.5	16.6	78.3	52.4	19.1	6.3	122.0	1.4
28.6	17.3	74.3	54.0	16.9	4.9	121.8	0.9
27.5	17.2	73.5	55.3	16.8	4.7	118.3	1.6
28.0	17.2	77.2	54.5	18.1	5.5	116.8	1.3
28.7	17.0	76.4	54.4	18.8	6.0	117.8	1.4
30.3	16.9	73.6	45.9	19.4	6.3	100.2	2.4
29.8	17.7	73.8	52.6	17.9	5.3	108.9	2.0
28.4	17.3	75.3	55.8	17.5	5.0	106.9	2.9
28.7	17.0	76.0	56.0	17.9	5.2	103.5	1.9
29.1	17.6	75.1	54.8	18.3	5.4	118.9	2.9
29.9	17.1	69.2	52.3	19.8	6.3	124.6	1.1
28.4	17.6	77.1	52.6	18.3	5.3	106.0	1.0
28.4	17.3	76.1	54.6	19.6	6.1	112.3	0.6
28.7	18.0	74.8	54.6	17.7	4.9	111.3	0.7
29.5	17.3	72.2	48.2	19.8	6.2	107.4	3.3
29.2	18.0	73.6	55.6	19.1	5.7	106.4	1.6
30.2	18.0	74.3	51.8	19.1	5.7	101.6	2.2
30.7	18.1	72.8	49.4	19.3	5.8	117.3	2.5
30.9	18.5	73.4	52.3	19.3	5.7	132.5	2.7
29.5	18.7	74.3	57.4	17.7	4.7	119.5	3.9
27.9	18.3	75.8	57.8	18.1	4.9	121.3	2.2
28.6	18.2	73.9	55.2	18.6	5.2	103.8	1.4
30.3	18.5	75.8	52.8	19.6	5.8	121.4	2.5
28.8	19.2	73.9	58.0	18.5	5.0	118.3	3.7
29.4	18.4	77.0	55.8	19.0	5.4	108.6	2.9
28.9	18.1	77.1	61.5	19.0	5.4	105.7	1.6

MEAN MONTHLY WEATHER SUMMARY, NOVEMBER 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
30.0	17.6	77.4	51.0	21.4	6.8	103.7	3.0
31.4	17.9	78.4	52.6	22.1	7.2	104.4	2.8
31.2	19.1	73.7	51.1	21.8	7.0	112.5	0.8
32.4	19.3	69.8	46.6	21.3	6.6	120.2	1.4
31.6	19.1	71.7	51.2	20.4	6.0	125.0	1.6
30.1	19.0	75.5	56.3	20.0	5.8	123.4	3.5
30.6	18.7	73.5	49.5	21.8	6.9	111.5	2.1
31.5	19.1	71.8	49.1	21.3	6.6	104.1	1.7
32.2	19.8	69.0	51.3	21.2	6.5	110.1	3.9
30.9	19.3	75.5	53.9	19.5	5.4	98.8	2.2
31.0	19.9	77.4	55.7	20.4	5.9	96.6	3.7
31.9	19.8	76.6	54.6	20.3	5.9	101.5	7.6
31.7	20.0	78.9	55.2	20.8	6.1	105.6	4.0
31.5	19.7	74.9	53.9	22.7	7.3	110.7	4.2
31.7	19.6	75.5	53.2	21.9	6.8	107.3	4.7
31.4	20.0	77.0	56.3	21.1	6.3	114.1	4.4
30.2	20.4	73.4	59.0	17.9	4.3	105.0	5.2
29.3	19.1	78.8	59.5	18.4	4.6	107.9	6.7
30.0	19.3	82.8	56.8	19.4	5.2	99.2	2.5
32.2	20.2	76.2	55.5	20.7	6.0	106.3	1.8
32.5	20.8	77.0	58.2	20.0	5.5	126.4	1.8
30.3	19.5	73.5	56.4	19.9	5.4	101.6	3.7
30.9	19.7	76.5	58.0	21.5	6.4	109.2	3.0
30.3	19.7	75.3	59.3	19.2	5.0	121.0	3.3
29.7	19.5	78.4	60.5	20.0	5.5	109.4	3.3
31.0	19.2	72.5	48.9	22.0	6.7	111.7	3.8
29.3	19.8	76.8	59.4	19.8	5.3	109.6	1.1
29.8	19.6	75.8	53.7	19.5	5.1	111.6	3.5
30.0	18.7	75.5	55.5	22.1	6.7	115.8	2.5
31.4	19.1	75.8	53.7	21.4	6.2	99.6	3.6

MEAN MONTHLY WEATHER SUMMARY, DECEMBER 1991-2013

Maximum Temperature (°C)	Minimum Temperature (°C)	RH Max (%)	RH Min (%)	Radiation (MJ/m ²)	Sunhours	Wind run (km/day)	Rain (mm)
31.4	18.9	75.2	52.0	22.3	6.8	94.9	3.4
33.4	19.4	74.8	49.3	22.7	7.0	120.7	3.5
32.0	20.7	72.2	55.3	20.4	5.6	118.2	1.2
30.6	20.5	77.2	60.1	20.1	5.4	107.9	4.5
31.2	19.6	77.3	53.6	20.9	5.9	101.5	0.8
31.5	20.3	78.8	53.6	21.2	6.1	112.4	3.6
31.4	20.1	75.8	60.2	20.5	5.6	93.0	3.9
31.2	20.4	81.1	59.8	19.2	4.8	99.2	2.3
30.9	20.2	81.5	61.7	19.9	5.4	101.7	5.2
30.5	20.6	80.8	59.4	19.3	5.0	107.1	3.1
30.5	20.2	81.3	59.6	19.7	5.1	112.6	4.1
29.6	19.6	78.0	61.1	20.8	5.8	97.8	8.0
31.8	19.5	78.1	55.4	23.5	7.4	85.9	1.7
32.9	19.7	79.5	53.8	23.0	7.1	112.2	3.1
32.1	20.9	76.0	55.7	21.7	6.3	104.8	1.8
31.9	20.5	78.2	58.4	22.4	6.8	94.3	3.5
33.4	21.0	76.8	51.3	23.6	7.5	110.0	7.4
31.3	20.5	73.6	53.4	20.9	5.8	107.7	1.5
31.7	20.7	75.5	52.5	22.1	6.5	94.8	1.4
33.5	20.8	73.3	52.2	23.7	7.6	112.1	5.9
31.9	19.8	80.3	54.5	22.8	7.0	90.9	1.7
33.3	20.1	74.5	50.4	23.1	7.1	108.3	2.0
33.1	21.8	73.8	57.5	20.4	5.5	97.4	4.2
33.5	22.0	80.3	56.6	22.2	6.6	96.7	2.7
33.0	21.3	74.4	54.4	23.3	7.3	118.1	1.5
32.3	21.4	78.2	57.6	20.4	5.5	93.2	7.1
31.7	21.0	81.2	58.2	23.0	7.1	90.0	1.8
32.7	21.3	81.5	59.3	22.2	6.6	80.2	6.2
33.3	21.8	76.1	52.2	23.1	7.2	96.4	4.5
32.5	21.4	77.4	56.5	22.8	7.0	80.5	1.9
33.2	21.3	79.0	56.5	22.3	6.7	95.2	1.3

**Appendix 2: Physical and chemical properties of soil samples obtained from EEL09,
NKA21, CAS02 and SMB centre pivots**



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Location: Sugar Estate
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Big Bend
Big Bend
431
Tel: Number (00268) 313 4121
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Run Number: 2013-000043
Client Ref Number: None
Report Number: RSW/001/2013
Inspector: ags@swaziland.sugarcrops.co.za
Date Sample Received: 16/01/2014
Date for print generated: 01/02/2014
Date of Report: 24/02/2014

Type of Analysis: N, P, K, Available Moisture Capacity

TEST CERTIFICATE

Sample Reference Number	Block	Field	Variety	Site	Depth	pH		Ca		Mg		K		Cl		Sulph		C
						Method Number Frog method	Method Number H2O	Method Number Ann. Arson	Method Number Ann. Arson	Method Number Ann. Arson	Method Number Ann. Arson	Method Number Recession	Method Number Recession	Method Number Recession	Method Number Recession			
1	0-30 CM	EEL 00A				14.99	8.21	5558	1719	133	30.75	17.45	45.83	2.01				
2	31-60 CM	EEL 00A				15.44	8.18	4625	2123	78	28.33	13.85	50.00	0.84				
3	0-30 CM	EEL 00B				20.10	8.18	4700	1961	129	43.65	18.95	37.60	1.68				
4	31-60 CM	EEL 00B				24.70	8.30	3364	1859	143	33.89	19.75	48.40	1.32				
5	31-60 CM	EEL 00B				21.01	8.50	4029	1203	130	33.43	19.75	48.40	0.95				
6	0-30 CM	EEL 00C				18.04	8.74	3515	1883	91	30.89	11.95	53.83	1.14				
7	31-60 CM	EEL 00C				199.56	8.59	2631	1732	84	36.79	11.95	72.73	0.70				
8	0-30 CM	EEL 00D				7.78	8.08	3001	1681	142	43.65	19.75	41.23	1.48				
9	31-60 CM	EEL 00D				103.31	8.29	3335	1233	51	34.80	8.60	74.60	0.45				
10	0-30 CM	SMB A				132.31	8.88	3668	1263	129	29.40	18.83	53.83	1.20				
11	31-60 CM	SMB A				33.88	8.98	4187	1334	90	33.60	14.70	51.70	0.83				
12	0-30 CM	SMB B				60.40	8.95	4783	2190	147	29.40	18.80	51.70	1.35				
13	31-60 CM	SMB B				120.33	7.08	3034	1111	80	25.20	18.80	50.00	0.60				
14	0-30 CM	SMB B1				40.40	8.74	2954	1162	128	33.60	18.80	49.60	1.44				
15	31-60 CM	SMB B1				9.52	8.60	3047	1128	118	39.90	12.60	47.50	0.87				
16	0-30 CM	SMB C				19.82	8.80	4668	1187	200	34.70	14.70	26.60	1.32				
17	31-60 CM	SMB C				7.82	8.68	3820	1183	187	30.40	12.60	37.60	0.90				
18	61-90 CM	SMB C				102.48	8.88	5008	1423	128	31.50	22.30	41.20	0.68				
19	0-30 CM	SMB D				22.24	8.48	2933	933	133	46.20	12.70	32.10	1.60				

The result obtained is only relevant to the laboratory sample as received by the laboratory. Opinions and interpretations of test results fall outside the scope of the laboratory.
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In-house regulations are available for verification
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Doc No: RSL/11/10
 P/11/10/25
 Eq: B01
 Eq: B01
 013
 Tel Number: (00268) 313 4000
 Fax Number: (00268) 313 1361

Doc Number: 2015-0441
 Lab Ref Number: None
 Report No: RSL/11/10/25/10
 Report to: Agricultural Laboratory
 Date Sample Received: 2015/04/01
 Date of Report: 2015/04/01

TEST CERTIFICATE

Sample Reference Number	Block	Tid	Variety	Site	Dept	P		Ca		Mg		K		Cl		Na		S	
						Method No	Result	Method No	Result	Method No	Result	Method No	Result	Method No	Result	Method No	Result	Method No	Result
20	31-03 CU	SUB D				9.34	941	208	860	136	136	33.50	12.00	34.90	3.75				
21	61-50 CU	SUB D				116.44	855	2835	774	98	98	33.50	5.40	54.00	3.75				
22	0-33 CU	SUB D				65.78	851	3119	126	154	2843	8.40	8.40	8.40	3.75				
23	31-03 CU	SUB D1				328.13	658	2377	974	58	58	33.50	8.40	78.70	3.75				
24	0-33 CU	LCO 2A				24.39	752	1247	1824	325	325	32.00	10.50	47.50	3.75				
25	31-03 CU	LCO 2A				9.63	755	7702	1002	315	315	30.43	12.80	37.00	3.75				
26	61-50 CU	LCO 2A				13.45	751	4350	1341	331	331	60.90	8.30	37.00	3.75				
27	91-120 CU	LCO 2A				13.00	748	5770	1354	297	297	45.20	8.30	47.50	3.75				
28	0-33 CU	LCO 2C				65.66	877	4851	1164	186	186	28.43	12.60	38.00	3.75				
29	31-03 CU	LCO 2C				37.95	865	4207	1365	373	373	48.13	13.50	48.00	3.75				
30	61-50 CU	LCO 2C				22.22	860	4548	1312	186	186	32.50	12.50	47.50	3.75				
31	91-120 CU	LCO 2C				9.29	881	6717	1584	186	186	32.43	12.50	39.00	3.75				
32	0-33 CU	SA 1003 1				145.18	752	2951	1222	759	759	32.43	14.70	38.00	3.75				
33	31-03 CU	SA 1003 2				126.85	741	4385	1305	82	82	31.00	14.70	64.00	3.75				
34	0-33 CU	SA 1003 2				31.68	738	3490	1412	36	36	35.25	14.70	47.80	3.75				
35	31-03 CU	SA 1003 1				28.33	720	3254	1278	123	123	33.90	14.70	45.00	3.75				
36	0-33 CU	NKA 21A				5.74	854	2556	1150	213	213	33.90	12.60	37.00	3.75				
37	31-03 CU	NKA 21A				8.14	844	2477	1331	181	181	27.50	13.60	33.00	3.75				
38	0-33 CU	NKA 21B				11.85	821	3241	1112	85	85	47.00	14.80	41.00	3.75				
39	31-03 CU	NKA 21B				32.84	822	2968	1245	90	90	33.90	14.80	43.00	3.75				
40	61-50 CU	NKA 21B				375.78	887	3237	1113	75	75	34.3	8.30	85.00	3.75				

The result obtained is only relevant to the laboratory as requested by the laboratory. It does not constitute a guarantee of the accuracy of the laboratory.
 The Test Report shall be kept as a file under approval of the laboratory.
 Electronic printouts are available for verification.
 2015-04-01 11:00:00
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Plant Number: 2013/0004
 Cane Ref Number: New
 Report No.: 102/10/101/001
 Registration: Agriculture, Swaziland
 Issue Number: 10/10/2014
 Date of Report: 26/10/2014

TEST RESULTS

Sample Reference Number	Block	Field	Variety	Site	Depth	P		K ₂ O		Mg		N		Ca		S	
						Method Number	Result	Method Number	Result	Method Number	Result	Method Number	Result	Method Number	Result	Method Number	Result
41	0-30 CM	90A_01_B1				5.64	883	2962	1189	253	1310	33.80	7.70	37.70	1.82		
42	31-60 CM	90A_01_B1				1.60	818	2733	1065	120	76.00	27.00	29.50	0.87			
43	61-90 CM	90A_01_B1				0.67	873	4081	1123	120	49.20	6.00	37.00	0.84			

P = Phosphorus, K = Potassium, Mg = Magnesium, N = Nitrogen, Ca = Calcium

TEST RESULTS

Sample Reference Number	Block	Field	Variety	Site	Depth	DM		IC		Mg		Ca		S	
						Method Number	Result	Method Number	Result	Method Number	Result	Method Number	Result	Method Number	Result
1	0-30 CM	EEL 09A				3.88	46.00	1.01	3.81	1.41	1.25	2.15	30.8	276.54	
2	31-60 CM	EEL 09A				1.44	28.00	1.05	1.18	1.48	1.05	1.65	45.0	242.01	
3	0-30 CM	EEL 09A				1.86	22.00	1.01	1.68	1.18	1.11	1.11	11.7	42.8	
4	31-60 CM	EEL 09A				2.27	44.00	0.94	1.28	1.64	1.54	4.44	20.7	279.20	
5	61-90 CM	EEL 09A				1.14	29.00	1.11	1.61	0.77	0.58	2.74	28.3	247.14	
6	0-30 CM	EEL 09C				1.90	49.00	1.32	1.88	1.14	1.17	1.66	28.2	247.20	
7	31-60 CM	EEL 09C				0.91	27.00	1.22	1.18	0.56	0.78	2.72	21.2	242.84	
8	0-30 CM	EEL 09A				2.82	26.00	1.04	1.22	1.52	1.28	4.81	35.0	241.94	
9	31-60 CM	EEL 09A				0.97	29.00	1.12	0.85	0.81	0.73	2.18	18.3	241.89	
10	0-30 CM	90A A				2.17	30.00	1.03	1.28	1.11	1.77	3.64	27.2	242.54	

The result obtained is only relevant to the laboratory which is accredited by the laboratory. It does not represent the full range of the laboratory.

The Test Report shall only be regarded as correct in full when approved by the laboratory.

Reference: 102/10/101/001

2013/0004 (1) - 102/10/101/001

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Report Number: 2111-000011
 Client Reference Number: 2111
 Report Number: 1100000011
 Report Date: 2011-01-01
 Date of Report: 24/01/2011

TEST CERTIFICATE

Sample Reference Number	Block	Fuel	Variety	Site	Depth	IC		SAR		Mg Mg/L	Ca Mg/L	Total Mg/L	Moist %	Ash %
						Method Number	Method Number	Method Number	Method Number					
11	31-120 CA	SMB A				102	28.00	121	112	0.73	3.81	2.82	27.1	263.45
12	0-33 CA	SMB B				232	41.00	122	143	1.35	3.32	4.20	18.9	244.45
13	31-120 CA	SMB B				138	42.00	137	155	1.18	3.41	4.12	18.7	263.45
14	0-33 CA	SMB B				248	24.00	155	128	0.93	3.92	2.88	27.8	223.63
15	31-120 CA	SMB B1				150	28.00	186	187	0.82	3.93	3.02	24.5	283.37
16	0-33 CA	SMB C				227	31.00	129	123	1.01	3.92	3.14	23.7	248.80
17	31-120 CA	SMB C				155	21.00	153	122	0.94	2.81	2.48	33.5	238.12
18	0-33 CA	SMB C				138	22.00	182	118	0.45	3.91	2.18	24.5	247.12
19	0-33 CA	SMB D				181	25.00	141	121	0.45	3.91	2.57	30.8	243.54
20	31-120 CA	SMB D				129	22.00	136	105	0.82	3.92	2.28	33.7	228.58
21	0-33 CA	SMB D				887	17.00	148	853	0.42	0.93	1.72	18.9	244.45
22	0-33 CA	SMB D1				237	28.00	146	124	0.74	0.87	2.65	20.7	247.13
23	31-120 CA	SMB D1				841	21.00	158	131	0.77	3.53	2.47	23.2	332.91
24	0-33 CA	UCO 2A				232	45.00	182	145	1.25	1.45	4.50	32.7	293.53
25	31-120 CA	UCO 2A				138	53.00	189	212	1.81	1.33	5.28	37.8	300.48
26	0-33 CA	UCO 2A				101	71.00	475	497	1.49	0.71	7.18	34.9	245.63
27	31-120 CA	UCO 2A				890	75.00	477	511	1.65	0.85	7.41	31.0	293.68
28	0-33 CA	UCO 2C				150	22.00	129	122	0.64	2.81	2.97	23.8	233.15
29	31-120 CA	UCO 2C				125	21.00	181	82	0.63	2.79	2.74	38.1	239.47
30	0-33 CA	UCO 2C				108	28.00	172	108	0.62	3.68	2.60	30.5	275.64
31	31-120 CA	UCO 2C				103	47.00	125	137	1.68	1.52	4.73	20.3	293.43

The result obtained is only valid on the laboratory sample as received by the laboratory. Opinions and interpretation of test results fall outside the scope of the laboratory.
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 Director, Agriculture Laboratory for Swaziland
 2011-01-01 11:00:00
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Block Number: 114-22A1
 Client Ref Number: None
 Report Number: 136362-0017
 Equipment: 136362-0017 - P1031107
 Date Issued to Receiver: 14/01/2018
 Date Issued to Analyser: 14/01/2018
 Date of Report: 28/01/2018

TEST CERTIFICATE

Sample Reference Number	Block	Field	Variety	Site	Depth	OH	IC	SAR	Na	Mg	Ca	T.C	Moss	Na
						%	meq/ton	meq/ton	meq/ton	meq/ton	meq/ton	meq/ton	meq/ton	meq/ton
						Method Number	Method Number	Method Number	Method Number	Method Number	Method Number	Method Number	Method Number	Method Number
						Wetley	Wetley	Wetley	Wetley	Wetley	Wetley	Wetley	Wetley	Wetley
						Calc.	Calc.	Calc.	Calc.	Calc.	Calc.	Calc.	Calc.	Calc.
37	0-33 C01	SA NO3 1				1.86	33.00	1.84	1.68	0.71	3.23	3.35	3.4	262.85
31	31-42 C01	SA NO3 2				0.50	29.00	1.64	1.25	0.56	0.87	2.36	25.8	261.83
34	0-33 C02	SA NO3 2				1.24	30.00	1.50	1.56	0.90	2.75	1.91	23.2	277.53
35	31-32 C02	SA NO3 1				0.99	48.00	2.30	2.56	1.29	1.11	4.98	20.1	279.54
36	0-33 C01	NKA 21A				2.84	31.00	1.27	1.20	1.87	2.56	3.31	27.2	267.75
37	31-42 C01	NKA 21B				2.12	28.00	1.07	1.02	0.81	2.92	2.79	19.7	261.87
38	0-33 C01	NKA 21B				2.04	28.00	1.19	1.12	0.93	1.80	2.59	23.1	264.22
39	31-32 C01	NKA 21B				1.34	24.00	1.34	1.11	0.85	0.72	2.48	23.3	264.22
40	61-90 C01	NKA 21B				0.37	38.00	1.15	1.24	1.11	1.21	3.98	21.3	276.89
41	0-33 C01	NKA 21 BT				2.78	28.00	1.81	1.22	0.72	3.12	2.66	23.3	268.02
42	31-42 C01	NKA 21 BT				1.82	19.00	1.76	0.82	0.52	0.54	1.90	25.7	262.84
43	61-92 C01	NKA 21 BT				1.18	22.00	1.09	0.83	0.74	0.71	2.30	20.3	270.47

OH = Organic Matter IC = Inorganic Carbon SAR = Sodium Adsorption Ratio Na = Sodium Mg = Magnesium Ca = Calcium T.C = Total Carbon Moss = Percentage Moisture Na = Sodium

The result obtained is only relevant to the laboratory sample as received by the laboratory. Opinions and interpretations of these results are those of the laboratory.
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 2018-01-28 11:04:40-03:07
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Block Number: 23 (360000)
 Client Ref Number: None
 Report Number: LB 2014/0417
 Date of Sample Collection: 06/01/2014
 Date of Sample Analysis: 09/02/2014
 Date of Report: 20/02/2014

TEST CERTIFICATE

Sample Reference Number	Block	Field	Variety	Size	Depth	α-D LPS		β-D LPS		Brix g/100	Purity %	Brix mm
						Method Number	Method Number	Method Number	Method Number			
24	07-30 CM	UCO 2A				217 87	241 65	238 00	1.30	49.13	56.80	
25	11-60 CM	UCO 2A				248 40	268 20	262 56	1.37	47.40	57.43	
26	03-90 CM	UCO 2A				217 58	243 04	230 70	1.30	47.64	56.84	
27	01-120 CM	UCO 2A				245 43	265 87	258 28	1.32	51.81	55.80	
28	07-30 CM	UCO 2C				219 24	243 04	240 40	1.30	47.29	56.80	
29	31-60 CM	UCO 2C				244 52	262 50	258 80	1.36	48.87	57.95	
30	07-90 CM	UCO 2C				205 36	258 04	234 12	1.31	50.51	56.47	
31	07-120 CM	UCO 2C				244 24	262 50	258 01	1.37	47.25	56.81	
32	01-30 CM	SA N01 1				212 37	241 15	235 48	1.26	52.45	53.18	
33	11-60 CM	SA N03 2				245 18	261 55	262 35	1.35	49.22	56.01	
34	01-30 CM	SA N03 2				277 03	275 20	273 41	1.36	47.66	56.24	
35	31-60 CM	SA N03 1				246 66	262 49	263 65	1.32	50.65	55.27	
36	01-30 CM	NKA 21A				231 87	248 25	247 56	1.29	52.61	56.30	
37	31-60 CM	NKA 21A				272 82	272 62	268 30	1.29	51.46	56.73	
38	01-30 CM	NKA 21B				241 55	278 31	270 53	1.48	44.73	57.25	
39	31-60 CM	NKA 21B				272 81	275 30	273 68	1.26	52.29	47.63	
40	01-60 CM	NKA 21B				258 23	292 31	243 56	1.23	53.51	48.29	
41	01-30 CM	NKA 21 B1				263 43	261 66	257 54	1.28	50.31	44.46	
42	31-60 CM	NKA 21 B1				287 28	242 89	245 54	1.27	53.83	50.38	
43	01-90 CM	NKA 21 B1				289 42	250 00	248 85	1.21	50.87	47.60	

Brix = Brix Direct, RSM = Purity, Sucrose Moisture

Laboratory Manager

The results obtained are only relevant to the laboratory sample as received by the laboratory. Storage and interpretation of test results fall outside the scope of the laboratory. The Test Report shall not be reproduced or copied in full or item approved by the Laboratory.

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 2013-5-0-041 - LB/MS/02/0017

**Appendix 3: Irrigation water quality parameters for water obtained from sources
and fertigation fittings of EEL09, NKA21, CAS02 and SMB centre
pivots**

Parameter	Method	EEL09- Dam	EEL09 - Centre Pivot
Alkalinity	SO32	93.73	142.88
Chloride (mg/L)	AMC04.0	40	40
Conductivity (uS/cm)	SOP26	149.9	186.7
Fluoride (mg/L)	AMC02.0	0.26	0.12
Nitrate (mg/L)	AMC02.0	<0.2	<0.2
pH at 25degrees celcius	SOP26	7.677	7.504
Total Suspended Solids (mg/L)	SOP31	30	26
Total Dissolved Solids (mg/L)	SOP26	75.4	93.25
Sulphate (mg/L)	AMC02.0	5	<1
Calcium (Ca) (mg/L)	SOP32	7.99	11.8
Iron (Fe) (mg/L)	SOP32	1.567	5.765
Magnesium (Mg) (mg/L)	SOP32	5.886	8.010
Manganese (Mn) (mg/L)	SOP32	0.000	0.049
Sodium (Na) (mg/L)	SOP32	16.64	17.12
Aluminium (Al) (mg/L)	SOP32	1.745	2.033
Arsenic (AS) (mg/L)	SOP32	0.000	0.000
Cadmium (Cd) (mg/L)	SOP32	0.000	0.000
Chromium (Cr) (mg/L)	SOP32	0.000	0.000
Copper (Cu) (mg/L)	SOP32	0.000	0.000
Lead (Pb) (mg/L)	SOP32	0.000	0.000
Zinc (Zn) (mg/L)	SOP32	0.000	0.565
Boron (B) (mg/L)	SOP32	0.050	0.059
Cobalt (Co) (mg/L)	SOP32	0.000	0.000
Nickel (Ni) (mg/L)	SOP32	0.000	0.000
Berylium (Be) (mg/L)	SOP32	0.000	0.000
Molybdenum (Mo) (mg/L)	SOP32	0.000	0.000
Tin (Sn) (mg/L)	SOP32	0.000	0.000
Vanadium (V) (mg/L)	SOP32	0.000	0.000

Parameter	Method	NKA 17- Dam	NKA21 - Centre Pivot
Alkalinity	SO32	181.44	182.4
Chloride (mg/L)	AMC04.0	45	40
Conductivity (uS/cm)	SOP26	231.3	232.3
Fluoride (mg/L)	AMC02.0	0.24	0.27
Nitrate (mg/L)	AMC02.0	<0.2	5.3
pH at 25degrees celcius	SOP26	7.58	7.703
Total Suspended Solids (mg/L)	SOP31	14	12
Total Dissolved Solids (mg/L)	SOP26	115.8	116.1
Sulphate (mg/L)	AMC02.0	2	3
Calcium (Ca) (mg/L)	SOP32	13.98	13.71
Iron (Fe) (mg/L)	SOP32	0.697	0.726
Magnesium (Mg) (mg/L)	SOP32	10.55	10.18
Manganese (Mn) (mg/L)	SOP32	0.000	0.000
Sodium (Na) (mg/L)	SOP32	20.52	19.99
Aluminium (Al) (mg/L)	SOP32	0.716	0.721
Arsenic (AS) (mg/L)	SOP32	0.000	0.000
Cadmium (Cd) (mg/L)	SOP32	0.000	0.000
Chromium (Cr) (mg/L)	SOP32	0.000	0.000
Copper (Cu) (mg/L)	SOP32	0.000	0.000
Lead (Pb) (mg/L)	SOP32	0.000	0.000
Zinc (Zn) (mg/L)	SOP32	0.000	0.000
Boron (B) (mg/L)	SOP32	0.062	0.058
Cobalt (Co) (mg/L)	SOP32	0.000	0.000
Nickel (Ni) (mg/L)	SOP32	0.000	0.000
Beryllium (Be) (mg/L)	SOP32	0.000	0.000
Molybdenum (Mo) (mg/L)	SOP32	0.000	0.000
Tin (Sn) (mg/L)	SOP32	0.000	0.000
Vanadium (V) (mg/L)	SOP32	0.000	0.000

Parameter	Method	CAS02 - Canal	CAS02 - Centre Pivot
Alkalinity	SO32	157.83	208.19
Chloride (mg/L)	AMC04.0	35	35
Conductivity (uS/cm)	SOP26	214.2	285.1
Fluoride (mg/L)	AMC02.0	0	0.31
Nitrate (mg/L)	AMC02.0	<0.2	1.4
pH at 25degrees celcius	SOP26	7.712	7.56
Total Suspended Solids (mg/L)	SOP31	40	0
Total Dissolved Solids (mg/L)	SOP26	107.2	142.5
Sulphate (mg/L)	AMC02.0	7	8
Calcium (Ca) (mg/L)	SOP32	18.28	24.89
Iron (Fe) (mg/L)	SOP32	4.261	1.018
Magnesium (Mg) (mg/L)	SOP32	10.08	14.18
Manganese (Mn) (mg/L)	SOP32	0.009	0.000
Sodium (Na) (mg/L)	SOP32	15.43	22.44
Aluminium (Al) (mg/L)	SOP32	7.742	1.525
Arsenic (AS) (mg/L)	SOP32	0.000	0.000
Cadmium (Cd) (mg/L)	SOP32	0.000	0.376
Chromium (Cr) (mg/L)	SOP32	0.000	0.000
Copper (Cu) (mg/L)	SOP32	0.000	0.000
Lead (Pb) (mg/L)	SOP32	0.000	0.000
Zinc (Zn) (mg/L)	SOP32	0.000	1.373
Boron (B) (mg/L)	SOP32	0.073	0.055
Cobalt (Co) (mg/L)	SOP32	0.000	0.000
Nickel (Ni) (mg/L)	SOP32	0.000	0.000
Berylium (Be) (mg/L)	SOP32	0.000	0.000
Molybdenum (Mo) (mg/L)	SOP32	0.000	0.000
Tin (Sn) (mg/L)	SOP32	0.000	0.000
Vanadium (V) (mg/L)	SOP32	0.000	0.000

Parameter	Method	SMB - Canal	SMB - Centre Pivot
Alkalinity	SO32	63.49	68.43
Chloride (mg/L)	AMC04.0	35	35
Conductivity (uS/cm)	SOP26	100.8	104.4
Fluoride (mg/L)	AMC02.0	0	0
Nitrate (mg/L)	AMC02.0	<0.2	<0.2
pH at 25degrees celcius	SOP26	7.856	7.784
Total Suspended Solids (mg/L)	SOP31	146	140
Total Dissolved Solids (mg/L)	SOP26	50.82	51.43
Sulphate (mg/L)	AMC02.0	3	3
Calcium (Ca) (mg/L)	SOP32	6.812	6.975
Iron (Fe) (mg/L)	SOP32	9.709	9.949
Magnesium (Mg) (mg/L)	SOP32	4.664	4.523
Manganese (Mn) (mg/L)	SOP32	0.000	0.000
Sodium (Na) (mg/L)	SOP32	12.75	11.50
Aluminium (Al) (mg/L)	SOP32	16.490	17.040
Arsenic (AS) (mg/L)	SOP32	0.000	0.000
Cadmium (Cd) (mg/L)	SOP32	0.000	0.000
Chromium (Cr) (mg/L)	SOP32	0.000	0.000
Copper (Cu) (mg/L)	SOP32	0.000	0.000
Lead (Pb) (mg/L)	SOP32	0.000	0.000
Zinc (Zn) (mg/L)	SOP32	0.000	0.000
Boron (B) (mg/L)	SOP32	0.099	0.086
Cobalt (Co) (mg/L)	SOP32	0.000	0.000
Nickel (Ni) (mg/L)	SOP32	0.000	0.000
Beryllium (Be) (mg/L)	SOP32	0.000	0.000
Molybdenum (Mo) (mg/L)	SOP32	0.000	0.000
Tin (Sn) (mg/L)	SOP32	0.000	0.000
Vanadium (V) (mg/L)	SOP32	0.000	0.000

Appendix 4: Infiltration rates of the quadrants of EEL09, NKA21, CAS02 and SMB centre pivots
 Site Location: EEL09_C Soil type: Sandy loam Test date: 24/04/14
Soil infiltration test results

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/h r	Cumulative infiltration mm
			Before filling (mm)	After filling (mm)				
13:22	0	0	0	200				Start = 0
13:24	2	2	190	200	10	5	300	10
13:27	3	5	190	200	10	3.3	198	20
13:32	5	10	187	200	13	2.6	156	33
13:42	10	20	175	200	25	2.5	150	58
13:52	10	30	177	200	23	2.3	138	81
14:12	20	50	149	200	51	2.6	156	132
14:32	20	70	165	200	35	1.8	108	167
15:02	30	100	140	200	60	2	120	227
15:32	30	130	140	200	60	2	120	287

*Basic Infiltration Rate= 120.0 mm/h

Site Location: EEL09_D
Soil infiltration test results

Soil type: Sandy loam

Test date: 24/04/14

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/h r	Cumulative infiltration mm
			Before filling (mm)	After filling (mm)				
10:44	0	0	0	200				Start = 0
10:46	2	2	195	200	5	2.5	150	5
10:49	3	5	195	200	5	1.7	102	10
10:54	5	10	197	200	3	0.6	36	13
11:04	10	20	195	200	5	0.5	30	18
11:14	10	30	198	200	2	0.2	12	20
11:34	20	50	197	200	3	0.2	12	23
11:54	20	70	194	200	6	0.3	18	29
12:24	30	100	196	200	4	0.1	6	33
12:54	30	130	196	200	4	0.1	6	37

*Basic Infiltration Rate=6.0 mm/h

Test date: 06/05/14

Soil type: Sandy loam

Site Location: NKA21_A

Soil infiltration test results

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/hr	Cumulative infiltration mm
			Before filling (mm)	After filling (mm)				
10:19	0	0	0	200				Start = 0
10:21	2	2	173	200	27	13.5	810	27
10:24	3	5	187	200	13	4.3	258	40
10:29	5	10	176	200	24	4.8	288	64
10:39	10	20	167	200	33	3.3	198	97
10:49	10	30	172	200	28	2.8	168	125
11:09	20	50	146	200	54	2.7	162	179
11:29	20	70	156	200	44	2.2	132	223
11:59	30	100	145	200	55	1.8	108	278
12:29	30	130	149	200	51	1.7	102	329

*Basic Infiltration Rate = 102.0 mm/h

Test date: 06/05/14

Soil type: Sandy loam

Site Location: NKA21_B

Soil infiltration test results

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading (mm)		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/h r	Cumulative infiltration mm
			Before filling (mm)	After filling (mm)				
12:31	0	0	0	200				Start = 0
12:33	2	2	195	200	5	2.5	150	5
12:36	3	5	197	200	3	1	60	8
12:41	5	10	192	200	8	1.6	96	16
12:51	10	20	187	200	13	1.3	78	
13:01	10	30	188	200	12	1.2	72	29
13:21	20	50	175	200	25	1.3	78	41
13:41	20	70	176	200	24	1.2	72	66
14:11	30	100	165	200	35	1.2	72	90
14:41	30	130	165	200	35	1.2	72	125
								160

*Basic Infiltration Rate=72.0 mm/h

Test date: 13/05/14

Soil type: Sandy loam

Site Location: CAS02_A
Soil infiltration test results

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/hr	Cumulative infiltration mm
			Before filling (mm)	After filling (mm)				
13:31	0	0	0	200				Start = 0
13:33	2	2	180	200	20	10	600	20
13:36	3	5	188	200	12	4	240	32
13:41	5	10	190	200	10	2	120	42
13:51	10	20	184	200	16	1.6	96	58
14:01	20	30	185	200	15	1.5	90	73
14:21	20	50	169	200	31	1.6	96	104
14:41	30	70	168	200	32	1.6	96	136
15:11	30	100	160	200	40	1.3	78	176
15:41	30	130	161	200	39	1.3	78	215

*Basic Infiltration Rate=78.0 mm/h

Test date: 13/05/14

Soil type: Sandy loam

Site Location: CAS02_C

Soil infiltration test results

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/h r	Cumulative infiltration mm
			Before filling (mm)	After filling (mm)				
11:37	0	0	0	200				Start = 0
11:39	2	2	87	200	113	56.5	3390	113
11:42	3	5	100	200	100	33.3	1998	213
11:47	5	10	76	200	124	24.8	1488	337
11:57	10	20	25	200	175	17.5	1050	512
12:07	20	30	28	200	172	17.2	1032	684
12:27	20	50	94	200	106	5.3	318	790
12:47	30	70	125	200	75	3.8	228	865
13:17	30	100	110	200	90	3	180	955
13:47		130	110	200	90	3	180	1045

*Basic Infiltration Rate = 180.0 mm/h

Test date: 21/04/14

Soil type: Sandy loam

Site Location: SMB_B
Soil infiltration test results

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/h r	Cumulative infiltration mm
			Before filling (mm)	After filling (mm)				
11:12	0	0	0	200				Start = 0
11:14	2	2	185	200	15	7.5	450	15
11:17	3	5	185	200	15	5	300	30
11:22	5	10	181	200	19	3.8	228	49
11:32	10	20	167	200	33	3.3	198	82
11:42	10	30	170	200	30	3	180	112
12:02	20	50	149	200	51	2.6	156	163
12:22	20	70	154	200	46	2.3	138*	209
12:52	30	100	130	200	70	2.3	138*	279
13:22	30	130	129	200	71	2.3	138*	350

*Basic Infiltration Rate = 138 mm/h

Test date: 21/04/14

Soil type: Sandy loam

Site Location: SMB_D
Soil infiltration test results

Reading on the clock hr min	Time difference min	Cumulative time min	Water level reading (mm)		Infiltration mm	Infiltration rate mm/min	Infiltration rate mm/hr	Cumulative infiltration mm
			Before filling	After filling				
13:49	0	0	0	200				Start = 0
13:51	2	2	172	200	28	14	840	28
13:54	3	5	180	200	20	6.7	402	48
13:59	5	10	167	200	33	6.6	396	81
14:09	10	20	145	200	55	5.5	330	136
14:19	10	30	147	200	53	5.3	318	189
14:39	20	50	123	200	77	3.9	234	366
14:59	20	70	122	200	78	3.9	234	444
15:29	30	100	91	200	109	3.6	216*	553
15:59	30	130	92	200	108	3.6	216*	661

*Basic Infiltration Rate=216 mm/h

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