SUITABILITY OF CENTRE PIVOT IRRIGATION FOR SUGARCANE PRODUCTION IN SWAZILAND

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Abstract

Centre pivot irrigation is on the increase in Swaziland, with approximately 6% of the sugar industry (3500 hectares) already using this method. The main reasons for the rapid adoption of the centre pivot system are low cost per hectare, low labour and energy requirements, ease of operation, high application and distribution efficiencies and the prospect of increasing or maintaining yields while using less water. Although used mainly by large-scale growers, centre pivot irrigation has also proved suitable for small-scale farmers in organised associations. At present, two small-scale projects have 300 ha of sugarcane under centre pivot irrigation.

This paper outlines technical, agronomic, economic, managerial and environmental factors that determine the suitability of the centre pivot system for sugarcane. The paper concludes that centre pivot irrigation has the potential to increase productivity through more uniform water application (coefficient of uniformity >85%), efficient water application (application efficiency >80%) and low-pressure requirements (operating pressure <400 kPa). However, to realise these benefits a systematic process of matching the system to a given site is required, complemented by good management of the system after installation. The main constraints identified include application rates that exceed the infiltration capacity of most soils in Swaziland, and the limitations imposed by the need to irrigate out-fall areas on existing rectangular fields. Centre pivot irrigation requires relatively flat land that is free of obstacles and, to maximise irrigation efficiency and cost effectiveness, fields should be limited in size to between 40 and 70 hectares.

Keywords: sugarcane, irrigation, centre pivot, performance, economics, risk analysis, Swaziland

Introduction

The imminent introduction of a new Water Act in Swaziland, rising input costs and increasing scarcity of water have underscored the need to improve water use efficiency. In combination, these factors have made centre pivot irrigation attractive to sugarcane growers in Swaziland, and resulted in a rapid adoption of this method. This paper is part of an on-going research effort to develop guidelines and identify best practices for the different methods of irrigation used in Swaziland. The objectives of the paper are (i) to provide a framework for identifying the main factors that determine suitability of centre pivot systems in sugarcane, (ii) to use empirical data to show how centre pivot irrigation can be optimised and (iii) to contribute to the growing knowledge base on centre pivot irrigation in sugarcane. The intention is to assist growers considering investing in centre pivot systems and those who want to evaluate the suitability of existing systems.

An optimum centre pivot system is defined as one that can be managed to achieve maximum sucrose yield while conserving water, energy and labour, and protecting the environment. Centre pivots have made it possible to efficiently irrigate marginal soils where dragline systems are not adaptable and areas where the topography precludes the use of furrow irrigation. Advantages of centre pivots over furrow and dragline systems include easily varied application amounts and uniform water application, even under relatively windy conditions. Application efficiencies greater than 80% can easily be achieved depending on slope of land, scheduling practices, system design and wind conditions (Keller and Bliesner, 1990). Large areas can be irrigated at relatively low costs for electricity and labour. Nutrients can be applied with the irrigation water (fertigation), and the system does not require the land levelling operations necessary for efficient furrow irrigation (Qureshi *et al.*, 2002). Initially it may appear that pivot machines are so complete and automatic that there is little to be done by irrigation engineers. However, to optimise performance of these automatic systems, special consideration should be given to selecting the most suitable machine for a given site. Failure to follow a systematic approach often results in systems that do not maximise profit and water use efficiency.

Framework for assessing suitability

A centre pivot irrigation system is a durable fixed asset that requires significant capital outlay by the grower. A thorough evaluation of the suitability of the system to the site is therefore required. This is particularly important, given the capital intensive nature and technical sophistication of centre pivot systems. Bisschoff (1991) developed a framework outlining, in order of importance, the factors that determine suitability of a centre pivot system from a grower's point of view (Table 1).

Table 1. Factors affecting suitability of pivots

What growers look for
Financial factors
Managerial factors
Environmental concerns
Design aspects
Production potential
Return on investment
Other (experience, availability of spares, etc)

According to Bisschoff (1991), the factors in Table 1 represent the expectations of the grower. A suitable system would therefore be one that delivers quantifiable benefits in these categories.

Design aspects

Measurement of soil infiltration rate

The first step in optimum centre pivot system design is to measure soil infiltration rate. Centre pivot systems apply water over short periods of time, with application rates that exceed the infiltration rates of most Swaziland soils, particularly towards the distal end of the pivot. Soil infiltration data provide a scientifically sound basis for the assessment of the interaction between pivot size, hydraulics, peak crop water use, depth of irrigation, application efficiency and economics.

A revolving sprinkler infiltrometer was used in the field to measure infiltration rates of soils to be irrigated by pivot (Reinders and Louw, 1985), with measurements being made in the areas to be irrigated by the last span and the pivot overhang. The infiltrometer simulates a center pivot in two ways: firstly, the small width that is wetted results in a high application rate and, secondly, it produces a sprinkling effect on the soil. Figure 1 shows a ‘time to ponding’ curve for a soil on a sugar estate in Swaziland, tested as part of a 219 ha centre pivot development project. Time to ponding is the time at which run-off starts on a particular soil. These tests were conducted under conditions that could be reasonably expected to represent a worst case scenario, i.e. after many years of irrigation and where soil had been compacted by harvest machinery after rainfall and other infield activities.

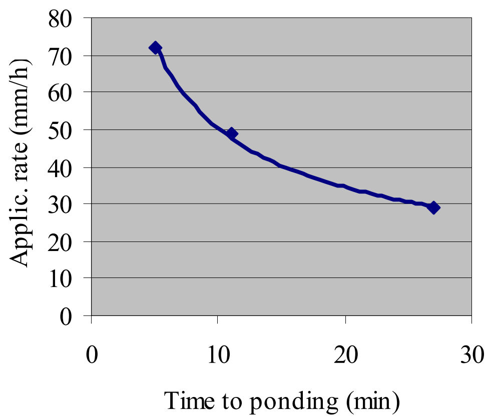

Figure 1. Time to ponding curve for an R-set soil in Swaziland.

In addition to being a design tool, the time to ponding curve is useful for determining operational parameters such as critical per cent timer setting and the depth of application that minimises run-off. For example, using Figure 1, the time to ponding and depth applied during that time can be determined for a pivot with a maximum average application rate of 50 mm/h, resulting in time to ponding of 11 minutes and a depth of application of 9 mm. Assuming no surface storage[1] it follows that, if a pivot is designed to apply 9 mm in 11 minutes, no run-off should occur. From this, the minimum pivot speed required to prevent run-off can be determined.

Pivot sizing

The maximum area that can be irrigated by a centre pivot system is limited by the infiltration capacity of the soil, because the rate of water application increases outward from the pivot to the last span. This is necessary because the area irrigated increases from the centre to the end. Consequently, the maximum area depends on the radius at which the application rate at the end of the pivot equals the infiltration rate plus any surface storage on that field. Using Figure 1 and the procedure developed by Reinders and Louw (1985), it was concluded that pivot size should be limited to 50 ha, or less where possible. Table 2 gives the sizes and peak application rates (PAR) of pivots that were installed following recommendations made after the infiltration tests. These pivots are labelled post-infiltration, whereas the sizes recommended by the manufacturer are labelled pre-infiltration. The results show that, by reducing the size of the pivot, peak application rates are reduced and minimise the potential for run-off during irrigation. Thus, the system can be managed to maximise application efficiency and irrigation uniformity.

[1] ‘Surface storage’ is the amount of water stored on the field in depressions and in the crop canopy before run-off occurs.

Table 2. Impact of infiltration rate on pivot size.

Pivot No.	Post-infiltration size (ha)	PAR (mm/h)	Pre-infiltration size (ha)	PAR (mm/h)
1	40	44	51	53
2	41	43	72	64
3	66	56	72	64
4	72	56	72	64

Design application to minimise run-off

Compared with conventional overhead irrigation, recommended centre pivot irrigation intervals are fairly short (3-4 days). As a guideline, a minimum application depth of 15-25 mm is recommended to minimise evaporation losses (Heermann *et al*., 1976). To minimise run-off, surface storage should be taken into account when determining the maximum application depth. Surface storage enables a higher application rate to be used for a time greater than the measured time to ponding without causing run-off.

System capacity, operating pressure and nozzle selection

The design or specification of a centre pivot system for a given site consists of selecting two primary variables: proper system capacity or flow rate to satisfy the water requirements of sugarcane, and an operating pressure based on the type of sprinkler package used. Design system capacity can be determined from the peak daily water requirement of sugarcane. Adequate system capacity reduces the risk of low yields and increases management flexibility. As the capacity decreases, the risk of yield reduction and year-to-year variability in yield increases, depending on amount of rainfall received and its timing and distribution. Thus, an analysis of rainfall probability patterns, soil moisture storage capacity and sugarcane water requirements is necessary for proper design. Simulated sugarcane water requirements using the CANEGRO model (McGlinchey, 1998), showed that a gross system capacity of 8 mm/day would be adequate over 80% of the season in Swaziland, assuming 85% application efficiency.

For centre pivot systems, the design of the mechanical structures and drive mechanisms, and the selection of nozzles is done by the manufacturers. Similarly, the manufacturers or their dealers determine operating pressure. The nozzle package is usually selected with the aid of a computer program that chooses sprinkler nozzles and heads that will provide uniform water application along the centre pivot lateral. Operating pressure is selected with energy saving as the primary objective, and ranges from 200 to 400 kPa depending on the topography and the length of the lateral. However, as the pressure is lowered, the application rate of the system will generally rise, increasing the possibility of run-off. Design parameters of pivots that were installed as part of the 219 ha project are given in Table 3.

Table 3. Design parameters for pivot.

Size (ha)	Radius (m)	Flow (m^3/h)	Peak (mm/day)	Pressure (kPa)
40	359	135	7.99	300
41	365	135	7.99	300
66	451	216	7.88	300
72	482	231	7.70	300

Economic and financial aspects

Centre pivot irrigation is suitable only if it is economically viable. Because of their capital intensive nature, profitability of centre pivot systems should be evaluated carefully. The projected decrease in sucrose prices and rising input costs emphasise the importance of evaluating the long-term economic and financial viability of centre pivot irrigation. Profitability is determined largely by physical resources, sucrose price, investment cost, operating and other input costs and attainable yields. These factors vary widely from farm to farm. Technical and design aspects such as size, capacity and static pump head have important economic implications. Basic pumping, piping and ancillary equipment, and the pivot structure itself, can be considered as fixed costs (Keller, 1984), and to receive the maximum benefit from these fixed costs, the pivot lateral should be designed to irrigate the maximum possible area, subject to soil limitations. However, the water application rate increases more or less linearly from the fixed to the moving end of the lateral and, if the lateral is too long, run-off will occur and reduce efficiency.

Figure 2 shows the impact of size on capital costs, in Emalangeni per hectare, for seven pivots installed in Swaziland in 1998. Although size reduces investment cost, it can significantly reduce irrigation efficiency and increasing running costs. This demonstrates that there is a trade-off between irrigation efficiency, economics and size. Excessively large pivots could also create environmental problems if run-off carried agro-chemicals from the irrigated field or caused soil erosion. The recommended procedure for economic evaluation of centre pivot is to construct a cost and benefit stream over the life cycle of the system, and calculate the net present value using discounted cash flow (DCF) analysis (Meiring and Oosthuizen, 1995). (A spreadsheet for conducting DCF analysis is available from Swaziland Sugar Association Technical Services.)

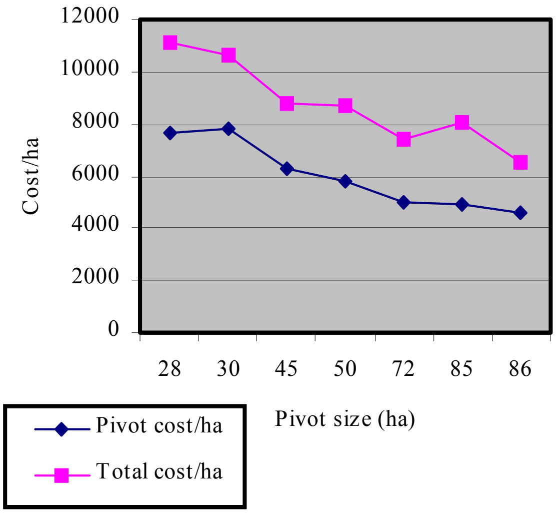

Figure 2. Relationship between cost (Emalangeni) per hectare and pivot size.

The analysis should include production costs, which can be obtained from the sugarcane budget and irrigation costs. Irrigation costs are made up of operating costs and fixed costs, and are influenced by design parameters. Profitability is very sensitive to sucrose price. Recent analyses show that centre pivots are both economically and financially viable under the current pricing system (Magwenzi, 2002). Qureshi *et al*. (2002) used DCF analysis to confirm the profitability of centre pivot systems in sugarcane under economic conditions in Australia.

Risk analysis

Production, financial and price risk

The most typical example of risk in sugarcane production is that associated with the weather. Cane and sucrose yields depend on random weather variables, thus yield becomes random as well. Another major source of risk is market price. In combination, production and price risk cause variation in centre pivot profitability. At present, the production of sugarcane does not carry significant downside price risk for the grower because of the preferential pricing system. Although the economic analysis may show that the system is viable, the financial feasibility (liquidity and sources of finance) should be evaluated to determine financial risks. The use of debt to finance a centre pivot irrigation system adds an additional source of risk: financial risk of potential equity loss. This is over and above the business risk represented in the economic analysis by production and price variability. The greater the proportion of debt relative to equity (all else being constant), the greater is the risk. This is because, regardless of financial performance, the debt providers must be paid the contractual interest payment.

Although irrigation decreases the risk of low yields, climate still has an important effect on cane and sucrose yields, and the eventual profits realised by growers. In Swaziland, climate accounts for 15-20% of the year-to-year variability in sugarcane yields (McGlinchey, 1999). Factors such as radiation and temperature play an important role in determining attainable yields. The ease with which centre pivot systems can be installed reduces risk associated with project implementation. This was demonstrated on a 100 ha small scale project in Swaziland, where the sugarcane crop was saved by the hurried installation of centre pivot systems on 70 ha following the failure of subsurface drip irrigation due to poor quality water. Once installed, centre pivot irrigation technology increases operational risk. Compared with other irrigation equipment, centre pivots have many moving parts, and electrical and electronic equipment, that can malfunction. Keller and Bliesner (1990) pointed out that, in sprinkler irrigation, the danger of system failure increases with technological complexity, expertise required for maintenance and availability of spare parts. Good planning, design and installation can help minimise the operational risk associated with centre pivot systems, with adequate system capacity being particularly important. Implementing a sound maintenance, performance monitoring and safety program reduces operational risk. Without detailed budgets showing net income, risk can be estimated from variability in sucrose or cane yield from which net income is derived. In calculating expected yield, each measured value is assumed to be equally probable. Variability is measured by the standard deviation of sucrose and cane yields.

Expected yields

Given the variability in weather, rainfall, soils, irrigation uniformity, management and agronomic practices, the actual yield attainable under centre pivot irrigation is unpredictable. The term 'expected yield' is used to indicate the uncertainty in attainable yield. Commercial sugarcane and sucrose yields under centre pivot irrigation in Swaziland have been fairly stable. Tables 4 and 5 show cane yield in tons cane per hectare (tch) and tons sucrose per hectare (tsh) for Estates A and B. Estate A, which has a total of 1189 ha under centre pivot irrigation, simultaneously developed pivot and furrow systems on virgin soils. The furrow system is used to irrigate the out-fall areas. Estate B has 452 ha under centre pivot irrigation, installed to replace aging dragline sprinkler systems, and uses floppy sprinklers and subsurface drip irrigation in the fall-out areas. Because attained yield is uncertain, its variability from year to year is an important aspect of economic analysis. The dispersion of cane and sucrose yield can be measured by the standard deviation (Meiring and Oosthuizen, 1995). The greater the variability in cane and sucrose yield, the higher the standard deviation (STD). The coefficient of variation (CV) gives a measure of risk per unit of yield. The smaller the CV, the lower the risk.

Variability of yield is important because it affects cash flows and net income. The standard deviations show that the yield variations from year to year are reasonable and, given that climate accounts for 15-20% of yield variation in Swaziland, the production risk is acceptable. The lower STD and CV for dragline and furrow systems on Estate B could be attributed to high rainfall in the years that were analysed, and the fact that the systems are on some of the estate's best soils.

Table 4. Cane and sucrose yields for Estate A under centre pivot and furrow irrigation in Swaziland.

Ratoon	Centre pivot		Furrow	
	Cane (tch)	Sucrose (tsh)	Cane (tch)	Sucrose (tsh)
Plant	111	13	121	15
1	132	17	124	18
2	109	14	107	13
3	118	16	111	18
4	122	17	110	14
5	99	12	97	12
6	96	13	101	12
Mean	112	15	110	14
STD (tch/tsh)	13	2	10	2
CV%	11	14	9	17

Table 5. Cane and sucrose yields for Estate B under furrow, dragline and pivot irrigation in Swaziland.

Year	Furrow		Dragline		Pivot	
	Cane (tch)	Sucrose (tsh)	Cane (tch)	Sucrose (tsh)	Cane (tch)	Sucrose (tsh)
1997	123	17	123	17	134	18
1998	111	15	110	15	126	18
1999	113	16	116	16	123	18
2000	110	16	109	15	107	14
2001	117	16	110	15	132	19
2002	112	17	115	17	~	~
Mean	114	16	114	16	126	18
STD (tch/tsh)	4	1	5	1	15	3
CV%	4	4	4	5	12	14

Commercial yields as reported by the estates do not always provide a reliable measure of comparison because they are influenced by several factors. However, they integrate physical, management and climatic factors, as they influence large commercial operations and indicate the yield levels that can be reasonably expected. The yield figures are not intended to compare centre pivots, dragline and furrow systems, because soils, harvest times and management are different. There are intended to show the methodology that could be used for this kind of analysis and to give an indication of yield variability under centre pivot systems. An important point to note is that centre pivot systems achieve comparable or better yields despite being on the poorer soils on most estates. Furthermore, these yields are achieved using less water and labour and, when compared with dragline, less energy.

System performance

Given the demands being placed on growers to manage water resources efficiently, they can no longer afford to accept manufacturers' claims regarding irrigation systems without quantitative information on actual performance after installation. Optimum system performance can be viewed as the consistent achievement of high application efficiency, adequacy and uniformity at each irrigation event. This ideal can be achieved with properly managed centre pivot systems.

Uniformity of application

The impact of uniformly applied water on sugarcane yield has been well researched (Solomon, 1984). Irrigation uniformity is closely related to crop yields through the agronomic effects of under- or over-irrigation. Field tests conducted on commercial estates by the Swaziland Sugar Association Technical Services showed that centre pivot systems can significantly increase application uniformity. Seventeen centre pivot systems were evaluated to determine whether they were operating at an acceptable uniformity. Christiansen's coefficient of uniformity (CU) was used to measure uniformity of water application (Anon, 2001). CU is a measure of evenness of water application throughout the field, and ranges from 72 to 92%. Of the 17 pivots, 41% achieved a CU of at least 90%, meeting the criterion for new systems or existing systems that are well maintained. Fifty three per cent achieved a CU of at least 83%, which is classified as acceptable performance. Only one pivot showed a CU of 76%, which is below the 80% considered the minimum acceptable uniformity. Solomon (1990) showed that, with a CU of 80% or better, 97-100% of maximum sugarcane yield could be achieved.

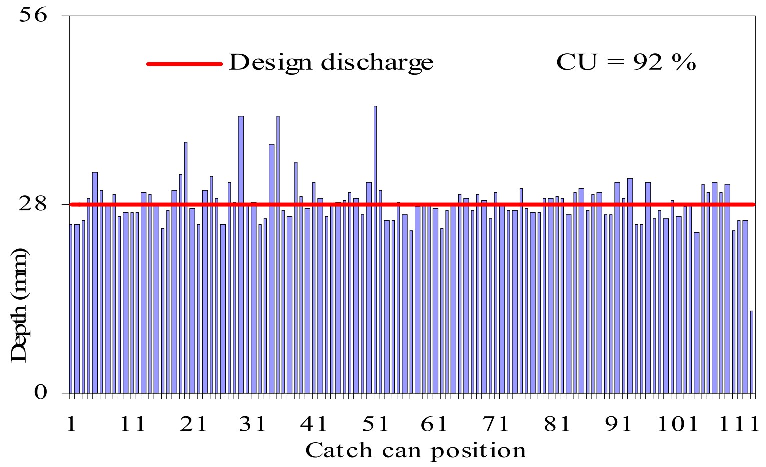

Figure 3. Application profile for a pivot system on a commercial estate in Swaziland, showing a CU of 92%.

Figure 3 shows the application profile of the pivot that had the highest CU (92%). This profile can be viewed as the benchmark performance to expect from a well maintained or new pivot. It is important to note that good uniformity of application will only be achieved with a system that has been carefully matched to the site, and is well managed and maintained.

Application efficiency

Water application efficiency is very important in system selection and design, and in irrigation management. The ability of an irrigation system to apply water uniformly and efficiently is a major factor in the agronomic and economic viability of a sugarcane enterprise. Just how efficient are centre pivot systems under commercial conditions? Salazar *et al*. (1996) concluded that seasonal application efficiencies of 80-90% are achievable with centre pivot systems if scheduling is accurate. Estimates of application efficiency from uniformity data collected in Swaziland using the method developed by Keller and Bliesner (1990) showed potential application efficiencies ranging from 72-88%.

The primary losses associated with centre pivot irrigation (other than those due to over-watering) are direct evaporation from wet soil surfaces, wind drift and evaporation losses from the spray, system drainage and leaks. Evaporation from the soil surface will depend on irrigation frequency and scheduling before full canopy. Some of the water 'lost' to wind drift and spray evaporation is not actually lost, since it substitutes for crop transpiration. Net losses in this case may be as low as 2-3% (Solomon, 1988). Van der Ryst (1995) concluded that under centre pivot irrigation, spray and evaporation losses should seldom exceed 10% if irrigation is carried out day and night. Losses estimated from field tests in Swaziland have ranged from 4-8%. When assessing suitability it is important to establish how modern centre pivot technology minimises spray and wind drift losses. According to Keller and Bliesner (1990), modern centre pivots minimise wind drift losses through close spacing of sprinklers, and nozzle technology that produces large droplets that cannot easily be blown by the wind.

Managerial aspects

The way the centre pivot system is managed after installation will determine the magnitude of yield attained and its variability. Maximum profit is probably the most popular objective, primarily because maximum yield does not necessarily provide maximum profit when there is an increase in operating costs. However, due to the current preferential pricing system enjoyed by Swaziland growers, profits are likely to be maximised near the maximum yield level. Given the projected decrease in sucrose price, this objective will become even more important in the future. Once an investment in a centre pivot system has been made, the quality or level of management will determine whether profits will be maximised, and the variability in profits from year to year. Good management therefore plays a critical role in optimising performance and minimising financial risks. A weakness in current centre pivot management practices is that key inputs such as energy and water are not precisely measured and documented, and the productivity per unit of water or energy can thus not be determined accurately. Centre pivot management should focus on optimum scheduling of irrigation events and proper system maintenance, integrated with other crop husbandry operations to maximise sucrose yield.

Irrigation scheduling and crop husbandry

Irrigation scheduling includes optimising timing of application and applying the correct depth to maximise application efficiency. Best timing and application is that which gives maximum yield from a given number of irrigations after planting or ratooning (Mijelde *et al*., 1990). Cane yields have been shown to increase linearly with evapotranspiration (ET) until potential ET has been attained (Thompson, 1977).

Growers with centre pivots can apply light and frequent irrigation as needed to best fit sugarcane ET requirements. This is possible because there is little labour associated with each irrigation event. Applications can thus be scheduled without considering labour regimes or being tied to soil moisture holding capacity or content. The extent to which centre pivots facilitate irrigation decision making, control of water and energy inputs, and the potential to apply fertiliser and other chemicals through the irrigation system are important crop husbandry benefits.

Maintenance

Most manufacturers provide an operator's maintenance manual that should be followed. Each year after harvest, the centre pivot system should be thoroughly inspected for needed repairs and maintenance. Sprinklers should be examined and repaired or replaced if they are not operating satisfactorily. Any leaks in the lateral pipe should be repaired promptly. Sloping terrain and the development of deep ruts in the wheel tracks affect the lifespan of gearboxes and motors. Long hours of operation and friction may cause stress and accelerate deterioration. Regular servicing and monitoring of gearboxes, motors sensors, safety devices and other electrical components are required to make full use of their capabilities and maximise their lifespan.

Constraints

As with all irrigation systems, centre pivot has constraints that need to be taken into account when assessing suitability for a particular site:

- On many soils, application rates may exceed the infiltration rate.
- Irrigating the approximately 20% outfall areas adds considerably to system complexity and costs.
- Harvesting should be carefully planned to simplify drying off because water application rates cannot be varied other than within the sectors of the circle.
- Centre pivots require level land, free from obstacles such as trees, streams, rocky outcrops and power lines, and slopes of less than 10%.
- On most soils, centre pivot wheel tracks should be lined to minimise erosion.
- Where pockets of non-productive soils or rocky areas are inside the circle they cannot be isolated from the system.
- Field size should be limited to 40-70 ha for maximum efficiency.

Conclusion

Centre pivot systems are a suitable method of irrigating sugarcane, because they are able to meet the grower's need to irrigate large areas uniformly and efficiently with minimum labour and energy. Economic analyses have shown that centre pivot systems are viable under present economic conditions in Swaziland. However, to realise the benefits fully, a systematic process should be followed to match the pivot to the soil and topography. The system must be properly designed and installed, and a regular maintenance programme must be in place. Economic and risk analyses should be undertaken to achieve maximum profit using a systematic and frequent irrigation schedule.

To maximise application efficiency, amount applied per irrigation should be limited to a range of 15-30 mm, depending on soil type. Under climatic conditions in Swaziland a minimum gross system capacity of 8 mm/day will meet peak sugarcane water requirements 80% of the time. This capacity is recommended to minimise capital costs and peak application rates. System capacity lower than 8 mm/day increases risk of lower yields, whereas higher capacities result in capital investment that may be higher than necessary.

There is a trade-off between application efficiency and economics. The bigger the pivot, the cheaper it becomes. However, high application rates from big pivots increase run-off losses and reduce efficiency, and may create environmental problems if the run-off carries agro-chemicals from the field. Growers who want to maximise application efficiency should be prepared to invest in a higher number of smaller units ranging from 40-70 ha. Economic analyses should be done to ensure that technical efficiency is not pursued at the expense of economic efficiency. It is expected that the efficiency of the smaller pivots will pay dividends through lower running costs and more uniform application of water.

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