THE EFFECT OF DIFFERENT FURROW IRRIGATION REGIMES ON INFILTRATION AND SUGARCANE (*Saccharum officinarum* L.) YIELD AT UBOMBO SWAZILAND

by

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ABSTRACT

In surface irrigation, the soil serves as a medium for infiltration and for conveying water from the upstream to the downstream end of a field. Soil infiltration characteristics are therefore extremely important for surface irrigation design and management. In this study, the infiltration characteristics of the Sibaya (Si) soil type (Glenrosa, in the South African soil classification system) was determined by a volume balance method using a two-point approach technique. The infiltration model adopted was that of Kostiakov. The purpose of the study was to examine the effect of different irrigation scheduling on infiltration characteristics, and on irrigation performance. A trial was conducted on a field with predominately Rondspring and Sibaya soils from 1999 to 2001. The five irrigation treatments were the Ubombo method, Penman-Monteith (PM) derived irrigation scheduling factors of 1.25, 1.00 and 0.75, and alternate row irrigation using Ubombo scheduling and 1.00 x PM on plant and first ratoon cane, respectively. Treatments were arranged in a randomised complete block design with five replication. The Ubombo scheduling method had the highest number of irrigation events followed by the 1.25 x PM, whilst the 0.75x PM had the least. The infiltration variables indicated that, for the Ubombo and 1.25 x PM treatments, irrigation often occurred when the soil water content was still less than 50% depleted plant available water (DPAW). This was in agreement with the tensiometer and neutron probe data. The tensiometer readings ranged from –55 to –75 kPa, -50 to -65 kPa, and –8 to –12 kPa at 0.15 m, 0.30 m, 0.45 m soil depth respectively. Likewise, 0.75 x PM was irrigated when the soil water content was greater than 50% (DPAW). Tensiometer readings would nearly always read above –80 kPa at both 0.15 m and 0.30 m, and above –75 kPa at 0.45 m. Further examination of the tensiometer and neutron probe data suggested that irrigation scheduling determined the preferential depth of water uptake by the crop. Frequent irrigation resulted in the crop depleting soil water predominately at the 0.15-0.30 m soil depth and hardly any at 0.45 m and below, particularly when the crop was young. There were no significant differences in yield among any of the treatments in the plant or ratoon crops. The plant crop consistently recorded higher yields than the first ratoon in all the treatments. Ubombo scheduling recorded the highest sugarcane yield in both seasons at 84 tha^{-1} for the plant and 82 tha^{-1} for the first ratoon cane. The 0.75 x PM had the lowest yield (78.3 tha^{-1}) in the plant crop as well as in the first ratoon (74 tha^{-1}). The volume balance approach provided a reliable and convenient way of assessing surface irrigation systems to identify alternatives that may be effective in improving the system performance, and in assessing different irrigation schedules. Sound management which comes about by selecting the most efficient stream size, length of field, and set time, and also a suitable irrigation schedule for that soil type depends on detailed knowledge of the infiltration rate of a particular soil. Information on infiltration constitutes the basis for establishing the necessary design, evaluation criteria and operational management system in irrigation.

DECLARATION

I, Njabulo Welcome Mazibuko hereby declare that all the work in this thesis is a result of my own investigations, except for the assistance that has been acknowledged. It is submitted for the degree of Master of Science, University of Natal, and has not been submitted previously for any degree or diploma to any other university.

Signed : N.W. Mazibuko

I, Peter Lorimer Greenfield supervised the above candidate in the conduct of his dissertation study.

Signed: P.L. Greenfield

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER 1

INTRODUCTION

Sugarcane has been continuously grown for nearly 50 years commencing in 1957 at Big-Bend, Swaziland, on the estate now known as Ubombo Sugar. Because of the nature of the climate, irrigation is a prerequisite for successful sugarcane production in this region, and all the sugarcane in the area has been produced under irrigation.

The irrigation of sugarcane has been, and is still under continuous change to match the ever-changing technical and the increasingly complex economics of sugarcane production. At the early stages of the development of the estate, probably because water was not a limiting factor and other associate advantages of surface irrigation, the farm was wholly irrigated by surface methods. Few years later, in 1961, the first overheard irrigation (portable pipes) was installed mainly because of the prevailing belief that higher yields would be realised from sprinkler rather than surface irrigation. Ten years later, in 1971 to 1972, there was an extensive conversion from surface to sprinkler irrigation systems. Centre pivots were introduced in 1993, a period when there was extensive expansion of fields under sugarcane, and almost all the expansion was put down under center pivots. The expansion coincided with one of the worst drought periods in the history of sugarcane production in the country, and some of the fields are accordingly called "droughts". Currently, about 47%, 38%, and 15% of the estate is irrigated by portable sprinkler, surface irrigation, and centre pivot irrigation systems, respectively.

Notwithstanding the introduction of various overhead irrigation systems in Ubombo Sugar, surface irrigation has remained the dominant method of irrigation and it is likely to be so for the foreseeable future, even though there are some intentions of converting some surface irrigated fields to either center pivot or floppy sprinklers. The latter is not likely to take place rapidly due to capital investment requirements. As the conversion is not likely to be immediate, and given that surface irrigation is still a dominant method on the estate, proper management of surface irrigation is crucial in the growing of sugarcane on this estate. However, of all the systems, surface irrigation presents the most daunting challenge to management. Management of surface irrigation is a complex phenomenon (Clemmens, 1981). The issue gets more complicated with furrow irrigation as compared with border or basin irrigation. The simplicity of directing irrigation water into furrows contrasts with the complexity of the study of furrow flow hydraulics and intake phenomena, both of which are complicated by the geometry of the furrow, furrow cross section, and by the occurrence of unsteady, non-uniform flow (Fangmeir & Ramsey, 1978).

In its broadest sense, surface irrigation is defined as the process of applying water at a point or edge of a field, and allowing the forces of gravity and hydrostatic pressure to spread the flow across and down the field (Heermann, Wallender & Bos, 1990). By the very nature of surface irrigation, the function of the soil is two-fold; a medium for infiltration, as well as a conduit to convey water across the field. This, in effect, is a distinct feature of surface irrigation systems, in that infiltration, not the system hardware, essentially determines the system's application rate and strongly influences water distribution (Walker & Skogerboe, 1987 ; Fonteh & Podmore, 1993). This, in turn, makes infiltration rate the most crucial factor affecting surface irrigation. Consequently the determination of infiltration characteristics is important in the design, evaluation and development of flood irrigation operational management systems. However, the determination of soil infiltration characteristics is one of the most difficult soil properties to measure (Walker & Skogerboe, 1987; Austin & Prendergast, 1997).

Walker & Skogerboe (1987) listed some of the inherent advantages of surface irrigation: minimum capital investments, low maintenance costs, and low energy requirements. Yet, in spite of these and other advantages, the efficiency of surface irrigation systems is typically low. The major problem associated with surface irrigation is non-uniformity of water application, leading to over-irrigation in some places and under-application in others. Low irrigation efficiency is usually associated with high spatial and temporal variation of soil properties (Baustista & Wallender, 1985). It is also associated with soil variability and intake opportunity time (Tarboton & Wallender, 1985).

Characterisation of the infiltration properties of the major flood irrigated soil types at Ubombo Sugar Company under different irrigation regimes should enhance the efficiency and profitability of sugarcane production on the estate. In order to achieve this, one needs to characterize the infiltration rates into the soil over seasons and rations, which forms the overall objective of the study.

CHAPTER 2

REVIEW OF LITERATURE

2.1 The process of infiltration

Infiltration can be defined generally as the process of water entering the soil through the surface (Moore, Larson & Slack, 1980). Hillel (1980) similarly defined infiltration as a term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface.

Infiltration studies provide useful information that is vital in many agricultural and hydrological processes. Information on the rates at which water enters and moves through the soil is useful in connection with the selection of irrigation method, and in the improvement of saline alkali soils (Helalia, 1993). In the selection of irrigation method, for example, Kay (1993) reported that soils with low (0-10 mm/hour) or medium (10-30 mm/hour) infiltration rates are suitable for surface irrigation. Yet soils with a high infiltration rate (greater than 30 mm/hr) may only be suitable for sprinkler or trickle irrigation systems. On soils with a high infiltration rate, water is taken into the soil too quickly and it becomes difficult to apply water uniformly and efficiently with surface methods.

Infiltration studies are also important in that infiltration is one of the most dominant factors affecting irrigation performance, particularly surface irrigation systems. In surface irrigation systems, the soil serves a dual role of infiltration and water conveyance from the upstream to the downstream end of a field. Hence soil infiltration characteristics have a significant influence on the water advance and recession relationships, as well as the infiltrated depth. Therefore, an insight into the infiltration process and soil water regime for a furrow-irrigated system greatly aids in the development of an optimally managed irrigation scheme (Renault &

Wallender, 1992). Consequently, the determination of the water infiltration and its distribution along the furrow length with an inflow at a given time is an essential part of irrigation management. Also estimating the distribution of water between infiltration, surface storage, and runoff during irrigation is essential in calculating different irrigation efficiency and uniformity expressions.

Sound management which comes about by selecting the most efficient stream size, length of field, and set time, and also a suitable irrigation schedule for that soil type depends on detailed knowledge of the infiltration rate of a particular soil. In conclusion, information on infiltration constitutes the basis for establishing the necessary design, evaluation criteria and operational management system in irrigation.

2.2 Determination of soil infiltration characteristics

The core component of irrigation, particularly surface irrigation, is the determination and subsequent knowledge of soil infiltration characteristics. Infiltration characteristics of soils are amongst the most important parameters in the design, evaluation and management of furrow irrigation. Infiltration characteristics determine advance and recession times (Esfandari & Maheshwari, 1997), depth of infiltration and uniformity of water application during an irrigation event (Fonteh & Podmore, 1993).

Motivations for infiltration measurements vary widely, and the criteria those measurements must meet differ with the purpose (Amerman, 1983). For agricultural purposes, infiltration determinations are usually conducted for two reasons (Blair & Smerdon, 1988). The first is to estimate the infiltration value or relationship for a soil, field, or treatment. Investigators who have conducted such trials include (Holzapfel *et al.,* 1988). The second is to determine the amount of spatial or temporal variability in the infiltration rate. Studies of this nature include those conducted by Baustista &Wallender (1993) and Tarboton & Wallender (1989).

As noted earlier, to determine the efficiency of irrigation and develop improved design criteria for irrigation systems, movement and distribution of irrigation water is needed. Approaches to the techniques in the determination and analysis of infiltration are many and varied. This can be undertaken by employing direct or by indirect methods.

2.2.1 Direct determination of soil infiltration characteristics

Infiltration is a complex process and a single technique or equation often fails to represent all soil types and hydraulic conditions (Walker & Skogerboe, 1987) and objectives. Subsequently, many investigations have been conducted attempting either to measure directly, or estimate the coefficients appearing in the infiltration formulae used in surface irrigation models.

For purposes of classification, direct methods of determining soil infiltration characteristics are divided into two categories. The first of the approaches is to examine the hydraulic conditions of water under which it is subjected upon the trial run (Amerman, 1983; Walker & Skogerboe, 1987). This may be undertaken with ponded or flowing water conditions as reported by Davis & Fry (1960) and Amerman, (1983). Examples for ponded systems include the cylinder infiltrometer, basin infiltrometer techniques, and blocked furrow infiltrometer techniques, and those for the flowing methods would include the furrow infiltrometer and border infiltrometer techniques.

The second approach that has been used by workers such as Maheswari *et al.,* (1988) is to look at the scale or size of measurement of the techniques. This results in localized small area and large area techniques. The localised small area methods of infiltration measurement use a few square meters area of field, while the large area methods use the entire length of furrow. Using this classification, ring infiltrometers (Shockley, Phelan, Lawhon, Haise & Doonan, 1956), blocked furrow infiltrometers (Bondurant, 1957), bypass furrow infiltrometers (Shull, 1961), flowing infitrometers (Nance &Lambert, 1970), and flow-through infiltrometers

(Childs, Wallender & Hopmans, 1992) fall under the small area method whilst furrow infiltrometer and border infiltrometer techniques fall under the large area method.

Comparisons have been made by a number of researchers on the different techniques of determining soil infiltration characteristics. It has been observed, in general terms, that ponded water methods give lower infiltration rate values than flowing water methods (Elliot & Walker, 1987 ; Holzapfel *et al.,* 1988). Furrow infiltrometer (FI) blocked furrow infiltrometer (BFI) and border infiltrometer methods consistently gave higher values as compared to the other methods such as cylinder infiltrometer, which are one-dimensional (Figure 1).

There have been a number of reasons put forth to explain the dynamics of the methods. The first, and that seems to be significant, is that under flowing conditions, there is a hydrodynamic process that allows the infiltrating surface to be continuously modified, reducing the effect of soil particle deposition (Fangmeir & Ramsey, 1978; Holzapfel *et al.*, 1988). Additionally, there is a differential soil-wetting process that reduces air entrapment. Equations developed from each ponded infiltration test underestimated infiltration during the entire irrigation. Furrow irrigation involves a two-dimensional infiltration process; yet ponding techniques describe a one-dimensional infiltration process. Both particle deposition and air entrapment cause a partial surface sealing and reduce the rate of water intake, whereas, flowing water helps to maintain a higher infiltration rate in that no such surface sealing occurs in the furrow or border where water is flowing (Fangmeir & Ramsey, 1978).

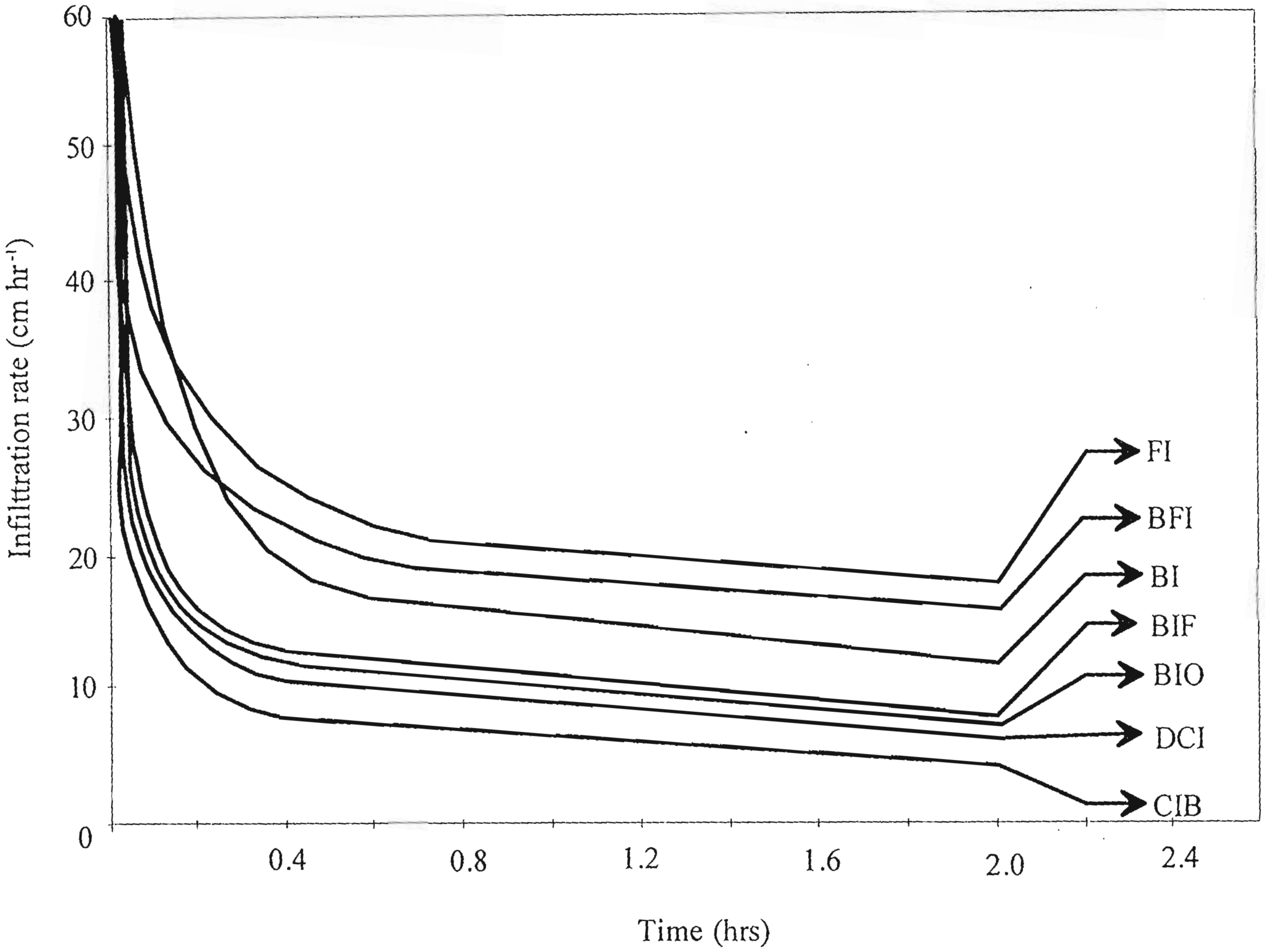


Figure 1 Mean infiltration rate versus time for seven infiltration methods: Furrow infiltrometer (FI), blocked furrow infiltrometer (BFI), border infiltrometer (BI), basin infiltrometer of 4 m^2 (BIF), basin infiltrometer of $1m^2$ (BIO), double cylinder infiltrometer (DCI), and cylinder infiltrometer with basin (CIB) (after Holzapfel *et al.*, 1988)

Secondly, when water is poured under conditions of infiltrometers such as ring infiltrometers, the resultant effect is that fine particles are dislodged from the surface and suspended in the water. When these particles settle down, they produce a layer of fine material that tends to reduce the infiltration rate and "seal" the ring (Holzapfel *et al.*,1988). Also, the act of driving the ring into the ground tends to compact the adjacent soil and cut off natural paths for air and water flow (macropores) thereby reducing the infiltration rate (Kincaid, 1980).

Small area methods such as the ring infiltrometers fail to indicate the typically dynamic field conditions (Walker & Skogerboe, 1987). They do not simulate infiltration under the geometric conditions of a furrow, or of any of the surface irrigation systems. Localised or stagnant methods such as ring infiltrometers or other such devices only provide relative values rather than a true estimate of the infiltration characteristics (Maheshwari *et al.*, 1988). For that reason, Kincaid (1980) recommends that water infiltration data that are to be used for evaluation, planning or management of surface irrigation systems should be obtained by flood or furrow-flow methods. Furthermore, static methods are not suitable for measurements on cracking soils, since a substantial volume of water will infiltrate laterally through interconnected cracks into the area outside the ring which may lead to overestimating infiltration rates (Bouma, 1984).

Apart from the dynamics, localized small area methods have additional limitations, mainly logistics. Small area methods generally involve a localized small area and, therefore, may not provide infiltration characteristics representative for the whole furrow. This can provide some misleading information if a relatively high level of accuracy is required. The problem can be circumvented with the use of more sampling units to account for the spatial variability of infiltration on the field. However, values can show high variance. This is often due to disturbance of the soil during the installation of the ring and various local factors such as the presence of stones, impermeable layers in the soil, roots and animal burrows (Esfandari & Maheswari, 1997).

Of all the methods and, not withstanding its shortcomings, the cylinder infiltrometer, is used extensively, particularly for soil characterization, mainly because of its simplicity and ease of operation (Withers & Vipond, 1980). Measurements of infiltration, employing localised small area methods do not only render them tedious and time consuming, but also prohibitively costly. Confronted with such limitations of localised techniques, indirect methods provide a meaningful alternative to the determination of soil infiltration parameters. The infiltration characteristics so obtained are more accurate and representative for the whole area considered (Maheswari *et al.*, 1988).

The large area methods are such that an equation describing water infiltration into the soil can be developed on advance water across the field, complemented with information on flow rates, slope roughness and geometry.

2.2.2 Estimation and characterization of furrow infiltration

Water moving over an infiltrating soil surface can be characterized using mathematical models incorporating one or both of mass and continuity/motion equations. The identification of parameters describing infiltration characteristics of a furrow using indirect methods is tied to a specified equation by the so-called inverse problem. The inverse theory is used either to determine the advance rate knowing all the other factors or to evaluate the infiltration function from the knowledge of the advance rate.

2.2.2.1 Infiltration models

As previously implied, the importance of determining, and possibly predicting soil infiltration characteristics for (i) temporal or spatial variation studies or (ii) as a function of a soil type or cultural management during an irrigation event cannot be overstated. The infiltration process has been the subject of numerous mathematical investigations and, due to its complex nature, there is no single equation that seems to be applicable for all soil types and hydraulic conditions (Walker & Skogerboe, 1987). Consequently, infiltration has been represented by numerous functional forms ranging from theoretical to empirical models (Equations 1 to 4) and has been reviewed amongst many workers by Clemmens (1981,1983) for borders, and for furrow by Smerdon *et al.,* (1988). Each of the infiltration equations has specific advantages and applications, and conflicting reports in the literature on their applicability could indicate their specificity to some factors such as soil types and infiltration techniques.

The Kostiakov, modified Kostiakov, Horton and Philip equations have been the most widely used equations for infiltration studies ((Elliot & Eisenhauser 1983; De Tar 1989).

The Kostiakov equation (Kostiakov, 1932)

$$Z = kt^{a} \qquad \cdots 1$$

The modified Kostiakov equation (Austin & Prendergast, 1997)

$$Z = kt^{a} + ct \qquad \cdots 2$$

The Horton equation (Horton, 1940)

$$Z = F(1 - e^{-at}) + ct \qquad \cdots 3$$

The Philip equation (Philip, 1957)

$$Z = kt^{1/2} + ct \qquad \cdots 4$$

Where: Z is the cumulative depth of infiltration, t the time of infiltration opportunity, and *k, a, c*, and *F* are constants.

The empirical, monomial power term of the Kostiakov equation (1), or its two -parameter variants (Equation 2) have been extensively used by many investigators mainly because of their algebraic simplicity (Elliot & Eisenhauser 1983; Smerdon *et al.*, 1988; De Tar 1989; Evans *et al.*, 1991). They are convenient in the sense that unlike the more theoretically based relationships such as those of Philip (1957), the Kostiakov relationships calculate infiltration depth explicitly as a function of time (Austin, 1997), and numerous data from field and laboratory infiltration tests are accurately represented by this equation (Clemmens 1981; Smerdon & Blair, 1988). However, this experimental model has an important limitation in that the required parameters are empirical in nature and do not directly represent the physical processes involved (Fonteh & Podmore, 1994 ; Zapata & Playan, 2000).

Horton (1940) developed a semi-empirical equation (3) incorporating an initial and a final infiltration rate. A physically based infiltration equation (4) was derived by Philip (1957) from the first two terms of the infinite series solution of the Richards equation. The Philip equation sets the exponent at 0.5 but is otherwise the equivalent of the extended Kostiakov equation (Evans *et al.*, 1990). Since the exponent (0.5) is fixed in the Philipequation, it is generally no more accurate than the extended Kostiakov equation.

Collis-George (1977) presented a linear infiltration equation in which cumulative infiltration was expressed as a constant plus the final infiltration rate by time. This model is particularly suitable for soils that exhibit shrinkage and cracking upon drying (Evans *et al*, 1990 ; Maheshwari & Jawardane, 1992; Austin, 1993). It has two inherent advantages; the parameters have physical interpretation, and variations in infiltration due to changes in antecedent soil moisture may be readily accounted for by the crack fill term.

2.2.2.2 Comparison of the models in relation to their ability to describe infiltration

It is worth noting that infiltration is a complex process and a single equation is not likely to be suitable for all soils and hydraulic conditions. This is because infiltration is dependent on a number of factors including soil properties, physical properties, initial soil water content, previous wetting history, permeability changes due to the surface water movement, and air entrapment (Walker & Skogerboe, 1987; Maheshwari & Kelly,1997). The infiltration characteristics are determined by interactions of several factors and any changes in one or more of these factors may cause infiltration characteristics to vary spatially and temporally (Maheshwari & Kelly, 1997). This makes the adequate determination of infiltration characteristics of a soil to be the greatest stumbling block by far in accurately describing or predicting the irrigation process in surface irrigation (Clemmens, 1983).

A considerable number of workers have attempted to compare different models, particularly comparing empirical against theoretical models. Amongst the researchers, there have been some seemingly contrasting reports on the applicability of the models. Philip (1957) found that experimental data fitted the Kostiakov equation well for commonly used irrigation times. However, Fangmeir & Ramsey (1978) found that the Kostiakov equation underestimates the infiltration during recession as compared with the Philip equation.

On the evaluation of infiltration measurements for border irrigation, Clemmens (1983) reported that the empirical equations matched field infiltration better than the theoretically based equations. He also reported that theoretical formulas are of limited use, as they inadequately describe the changing conditions of the soil surface that tend to dominate infiltration in surface irrigation systems. These surface conditions often change substantially from one irrigation to the next. Such findings were consistent with those of Maheshwari *et al.*, (1988) who showed that the theoretical equations such as the Philip equation, unlike empirical equations, did not satisfactorily fit the field data from several sites, for both cracking and non-cracking soils.

The inability of the theoretical models in general, and the Philip equation (4) in particular, could be attributed to a number of factors. The Philip equation is based on the assumptions that the soil is homogenous and non-cracking and the initial water content is uniform (Philip, 1957). These assumptions are not often satisfied for field soils resulting in a poor fit of the equation to field data (Watson, 1959). Infiltration characteristics are affected by variation of soil texture, structure and initial water content in the profile, surface and subsurface cracking, soil swelling during wetting, air entrapment, root penetration and biological activities. One or a combination of these factors is usually present in field soils, but they are not accounted for in the model. The effect of these factors on infiltration is not fully accounted for in the derivation of theoretically-based equations (Maheshwari *et al.*, 1988). Probably because of these reasons, the Philip equation is unable to consistently and accurately predict infiltration. Additionally, because of its fixed exponent (0.5) in the sorptivity term the fit of the Philip equation is further deviated by spatial variation in infiltration characteristics along the length of the furrow. This can be shown by the modified Kostiakov equation, which although similar to the Philip equation, has a variable exponent a in the first term and fitted the data better (Clemmens 1981, 1984 Maheshwari *et al.*, 1988). The values of this exponent a are highly variable. In some instances, it can be very low compared with the fixed value (0.5) of the exponent in sorptivity term in the Philip equation, particularly in drier soils. In other cases, exponent a approaches unity, as in wet soils. Maheswari *et al.*, (1988) subsequently adjusted the Philip equation to improve the reliability by adding a third parameter, c, and it fitted the data better. The additional term can be regarded as the depth of initial infiltration (almost instantaneously) such as that required in filling cracks. These results serve to further confirm that the Philip equation's assumptions of homogenous and non-cracking soils are not satisfied under field conditions, particularly for cracking soils.

The findings of Maheshwari *et al.* (1988) are in agreement with the work of other investigators such as Ottoni & Warrick (1983) and Maheshwari & Kelly (1997), who reported a poor performance of the Philip equation for several soil types in border irrigation. In particular, they found that the sorptivity term is often negative for irrigation events, which is a physical impossibility. In conclusion, infiltration equations based on static water conditions such as the Philip equation are hardly expected to cope with cracked soils in which the water fills the cracks as in a simple bucket and the sorptivity takes over to redistribute it into the soil matrix.

2.2.2.2.1 Limitation of Kostiakov model

The Kostiakov equation (1) expresses infiltrated depth, *z*, as a power function of time. However, it has two major shortcomings; (i) the parameters have no physical interpretation and therefore can only be obtained from empirical data, and (ii) the infiltration rate computed with the equation tends to zero for long infiltration times. However, this is only valid for some soils, such as clayey soils, which have a very small value for saturated hydraulic conductivity (Maheshwari & Jawardane, 1992). This characteristic is highly pronounced in vertisols as they shrink upon drying and swell at wetting due to their high percentage of montmorillonitic clay. In other soils, it has been observed on long irrigation events that infiltration does not decline to zero, but to a positive minimum value, *c*, and as such a constant rate term was included in the so-called extended or modified Kostiakov equation (2) to correct the problem of zero final infiltration rate with increasing opportunity times. The constant infiltration rate *c* has a theoretical interpretation. It represents the saturated hydraulic conductivity of the soil or a restricting layer, and is approached as the hydrostatic forces begin to dominate over capillary forces and the filling of the soil pores. The infiltration rate of water into such soils follows a power function at the initial stages of infiltration, and then begins to deviate and approach a constant value (Renault & Wallender, 1992). It is in such instances, at large opportunity times, where the original Kostiakov model under-predicts infiltration.

There are generally two approaches adopted under such circumstances to improve the reliability of the Kostiakov equation. The first option is to adopt a classical statistical methodology as done by Smerdon and Blair (1988). This methodology involved weighting the field data proportionately to the average opportunity time or advance distance to reduce the amount of under-prediction given by the Kostiakov equation. Alternatively, one can make use of an infiltration equation that incorporates both the time dependent and the basic or steady state infiltration rate terms (Singh & He 1988). Notably, the inclusion of the coefficient in the modified Kostiakov equation allows a better fit of observed infiltration data at large opportunity times at the sacrifice of poorer fitting of data at small opportunity times. Hartley (1992) reported that the modified Kostiakov infiltration function is more physically valid and applicable to a wider range of soils. Still, such soils can also be modelled using the Horton infiltration equation; this is because the asymptotic nature or behaviour of the Horton equation (3) is well pronounced in heavy clay soils and as such it adequately characterizes infiltration (Renault & Wallender, 1992). It has an additional advantage that it provides a basis for legitimate comparisons of infiltration as it is physically based.

Considering the foregoing, it appears that the simple and widely used Kostiakov equation is sufficiently accurate for general use in solving surface irrigation problems, particularly if the aforementioned weighting procedure is used to determine the coefficients. The use of the extended Kostiakov may be indicated by field data in specific situations. As noted earlier, infiltration characteristics of a soil are influenced by various factors. There have been attempts to relate soil conditions and characteristics to some infiltration parameters such as antecedent soil water and relating soil swelling and cracking behaviour (Maheshwari *et al.*, 1988; Malihol *et al.*, 1999).

2.2.3 Effect of antecedent soil water on infiltration

Soil water content prior to an irrigation event has long been recognised to have a significant bearing on the infiltration rate of water into the soil (Davis and Fry, 1960). The effect of the initial soil water content is reflected in the values of the constants of the adapted infiltration models; Kostiakov equation and extended Kostiakov or Horton equation (Maheswari & Jawardane, 1988). For the Kostiakov and the extended Kostiakov functions, the values of infiltration parameters a and k increase and decrease in magnitude, respectively, as the soil water content increases. The infiltration rate decrease is due principally to a decreasing matric potential gradient, which is one of the driving forces in the infiltration equation on an initially dry soil. Matric potential gradient is the dominant force in infiltration, particularly for a furrow irrigation system, where the infiltration is essentially bi-dimensional with lateral and vertical components. There is strong or significant correlation between cumulative infiltration and wetted perimeter (Fangmeir & Ramsey 1978), unless soil cracks dominate the infiltration process (Samani *et al.*, 1985, Strelkolf & Souza, 1984).

Infiltration from a furrow occurs within and around the wetted perimeter, which means that a significant portion of the total infiltration moves laterally through the sides rather than vertically downward (Strelkolf & Souza, 1984). The sorptivity component of infiltration is particularly significant in the early stages of infiltration on an initially dry soil. Horizontal or lateral infiltration rate is determined by the suction gradient in the soil, while vertical infiltration is determined by both suction and gravitational gradients but predominately the latter component (Fonteh & Podmore, 1993). For example, a dry fine textured soil conducts water laterally and vertically at about the same rate because the suction gradient is much greater than the gravitational force. In the case of dry medium-textured soils, infiltration is initially equal in all directions because of high suction gradients, but as infiltration continues, the gravitational force predominates. For most of the time therefore, the vertical infiltration rate is higher than the lateral rate for medium texture soils (Fonteh & Podmore,1993). There are marked variations between the infiltration parameters on a soil with different initial water contents irrespective of the methodology used to determine the infiltration parameters (Table 1).

Table 1 Variation in values of parameters *a, k,* and *c* for the Kostiakov and modified Kostiakov equations in soils of different water content using different infiltration methods: furrow infiltrometer (FI), blocked furrow infiltrometer (BFI), border infiltrometer (BI), basin infiltrometer of 4 m^2 (BIF), basin infiltrometer of 1m^2 (BIO), double cylinder infiltrometer (DCI) and cylinder infiltrometer with a basin (CIB) (after Holzapfel *et al.*, 1988).

		Infiltration model				
Soil water status	Infiltration Method	Kostiakov		Modified Kostiakov		
		k (cm/hr^{1+a})	a	*k* (cm/hr^{1+a})	*a*	*c*
Dry	BI	14.13	0.441	9.24	0.694	4.9
	FI	23.08	0.246	12.79	0.442	10.9
	BFI	12.97	0.371	4.14	0.885	8.2
	BIF	10.90	0.360	6.96	0.464	4.0
	BIO	11.65	0.335	8.34	0.464	3.4
	DCI	7.03	0.486	4.94	0.571	2.2
	CIB	11.34	0.381	7.88	0.463	3.6
Medium	BI	12.52	0.410	7.47	0.667	4.9
	FI	17.02	0.269	5.79	0.662	10.9
	BFI	15.70	0.238	7.32	0.469	8.2
	BIF	8.70	0.328	4.78	0.462	4.0
	BIO	8.10	0.349	4.87	0.457	3.4
	DCI	7.83	0.380	5.70	0.454	2.2
	CIB	6.53	0.467	3.05	0.671	3.6
Wet	BI	7.72	0.306	2.69	0.696	4.9
	FI	16.66	0.290	3.02	0.654	10.9
	BFI	14.53	0.305	8.08	0.714	8.2
	BIF	4.93	0.276	1.02	0.631	4.0
	BIO	4.32	0.282	0.97	0.567	3.4
	DCI	4.32	0.487	2.26	0.652	2.2
	CIB	4.34	0.374	1.13	0.792	3.6

Variation in the values of soil infiltration parameters *k* and *a* depends on the soil water content before irrigation (Hume, 1993; Esfandiari & Maheshwari,1997), and for cracking soils, on the extent of cracking on the surface and in the profile (Maheshwari, 1994). High values of *k* and low values of *a* reflect that most of the infiltration takes place during the first few minutes. The value of *a* can vary significantly from one irrigation to another. If the infiltration is governed by soil water suction and hydraulic conductivity as in the case with uniform soil profiles, the exponent *a* in the Kostiakov equation should have a value of about 0.5 (Hartley, 1992).

2.2.4 Relating soil swelling and cracking behaviours to infiltration

Typically, during irrigation on cracked soils, when the waterfront arrives at a point, a large volume of water generally flows into the cracks and a relatively small proportion of it is absorbed at their surfaces. Until the soil swells and cracks are closed, the infiltration continues mainly through cracks and it absorbs three dimensionally into the soil profile. The water also moves laterally, away from the place of ponding if there are interconnected cracks into the area. Once the soil is saturated and cracks have closed, the soil attains a constant infiltration rate which is dependant mainly upon the saturated hydraulic conductivity of the restricting layer (Collis-George, 1977).

The generalised response (Figure 2) is typical with soils found in sites that are subject to a cycle of swelling and cracking during the periods of consecutive irrigation. The cracking at the surface can go deep into the soil profile, resulting in substantial infiltration during initial ponding, and as the irrigation progresses, the swelling affects long term infiltration by the closure of cracks and changes in the size of soil pores.

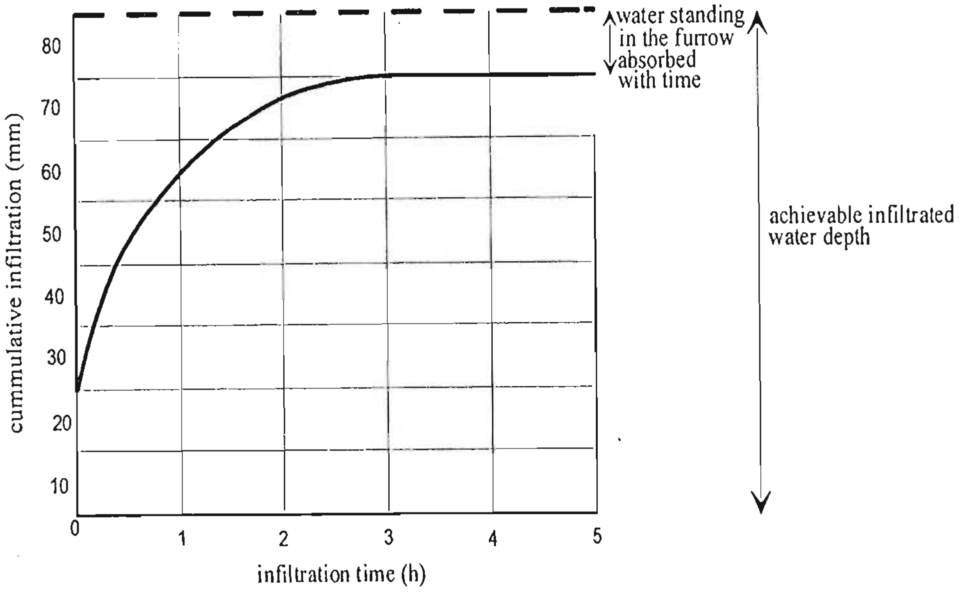


Figure 2 Generalised infiltration characteristics of a vertisol flood irrigation (after Smedema, 1984).

2.2.5 Reasons for a low water intake rate with time

Physical processes either at the soil surface after irrigation or in soils with a high initial water content and thus lower hydraulic conductivity may induce the decrease in water intake rate. Subsequently, soil deposition can result in a thin low conductivity depositional layer at the soil surface (Sergeren & Trout 1991), thereby decreasing infiltration. Most likely, the depositional layer developed during irrigation causes the decrease in infiltration. Spatial and temporal infiltration variability may result from soil aggregate breakdown. Wetting and flooding can induce soil structural changes (Collis- George, 1977; Zerihun *et al.,* 1997) and as a result the infiltration properties may vary from one irrigation event to the next even at similar conditions of water content.

Soil capillarity decreases right from the first irrigation event to the next during the same season. At the same time soil compaction and cracking magnitude increase in heavy clay soils.

2.2.6 Relationship between the water advance rate exponent and infiltration exponents

Hanson *et al.,* (1993) reported that there is a strong though negative relationship between the water advance rate in a furrow and the infiltration exponents of the Kostiakov equation. As the advance exponent is increased, the infiltration exponent tends to decrease. Further infiltration exponents tend to become negative as the advance exponents approached unity (Hanson *et al.,* 1993). When the advance exponent approaches unity, the infiltration models used fail to reasonably describe actual infiltration, and under such circumstances, the volume balance method generally underestimates cumulative infiltration substantially. This is particularly the case for the Kostiakov rather than the modified Kostiakov function, because the latter has an inclusion of the steady state infiltration rate.

There are other instances where advance exponents can approach unity: (i) where very low steady state infiltration rates exist and (ii) under the combinations of relatively short runs. It is also possible for the infiltration exponents to exceed unity particularly for advance exponents less than about 0.4. This behaviour could occur where the water advance along the lower part of the field was much lower than expected, perhaps due to a slope decrease along the field run resulting in a decreasing furrow flow rate. Thus, the calculated infiltration over unit length for the second advance time would greatly exceed that of the first.

From the principle of volume balance, the linear advance of a waterfront for a constant inflow rate is only possible when the volume of water infiltrated is constant along the length of a field. Therefore, a linear fit both for the advance distance and a linear fit for the volume of water infiltrated, indicates that the infiltration at the site continued at a significant rate for a relatively long period.

Fitted infiltration data and the linearity of advance functions support the findings of De trek & Grismer (1987) which suggest that linear irrigation advance for constant inflow, is only possible when the depth of infiltration is constant along the field and associated with cracks, most of the infiltrating water does so in the high rate period, which also suggests that the size of an irrigation event is influenced by the soil water content and degree of cracking prior to irrigation.

In conclusion, it appears that the advance exponent might flag conditions where the volume balance models severely underestimate the cumulative infiltration.

2.3 Characterization of surface (overland) flow

A mathematical simulation of a surface irrigation system should provide precise estimate of its irrigation efficiency (Tabuado, 1995). This requires knowledge of the water movement both on the soil surface and through the soil surface. The former is accounted for by the inverse solution which represents the distribution of water temporarily stored on the surface of the furrow. The latter is accounted for by an equation describing the process of infiltration, and is quantified by empirical or semi–empirical equations as already reported in Chapter 2.2.2.21 (Equations 1 to 4).

As for the infiltration process, different approaches have been developed to characterise water flow along the furrow length during irrigation by different groups of workers. Mathematical models predicting of the advancing waterfront down a furrow length are available. These models are the numerical solutions of the partial differential equations of momentum (Equation 5) and continuity (Equation 6) in an open channel flow applied to the case of furrow irrigation systems. These are the hydrodynamic (Kincaid *et al* 1972; Katopodes & Strelkoff 1977), zero inertia (Elliot *et al* 1982), kinematic wave (Walker & Humphreys, 1983) and volume balance (Hall, 1956; Davis, 1961) models.

2.3.1 The hydrodynamic model

Hydrodynamic models use the most general form of the Saint–Venant equations, which are the nonlinear partial differential functions that characterise the unsteady, gradually varied flow of water in a furrow (Equation 5). They are the most accurate. However, they are the most complex and the most expensive in their requirements for data acquisition and execution. Kincaid *et al.,* (1972) pioneered work in this area by modelling the advance phase in border irrigation. Katopodes & Strelkolf (1977) presented a hydrodynamic model for border irrigation in which they included both the advance and recession phases. In general, the practical value of the models in the full hydrodynamic category is to serve as a standard by which less sophisticated models can be evaluated and calibrated (Katopodes & Strelkolf 1977).

$$\frac{1}{Ag}\frac{\partial Q}{\partial t}+\frac{Q}{A^2.g}\frac{\partial y}{\partial x}+\left(1-F_r^2\right)-S_o+S_f=0 \qquad \cdot\cdot 5$$

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}+\frac{\partial Z}{\partial t}=0 \qquad \cdot\cdot 6$$

Where: Q is the inflow rate (L^3T^{1}), A is the cross sectional area of flow (L^2), Z is the infiltrated volume per unit field length (L), Y is the depth of water flow (L) in the channel at the distance x from the field inlet, F_r is the Froude number, S_o is field slope, S_f is friction slope, T is a temporal coordinate (t), x is the spatial coordinate (L), and g is acceleration due to gravity.

2.3.2. The zero inertia model

Zero inertia models are based on the understanding that flow velocities encountered in surface irrigation are very small, and changes in velocity with respect to time and space are virtually nonexistent. According to Katopodes & Strelkolf (1977) and Elliot & Walker (1982) under most surface irrigation conditions, inertial terms in the Saint- Venant equations are negligible when compared to the force terms (head and friction). This condition is present when the Froude number is low: the model can be described mathematically as in equation 6.

$$\frac{\partial y}{\partial x}=S_o-s_f \qquad \ldots 7$$

Where S_o and S_f are as previously described for equation 5

2.3.3 The kinematic wave model

Kinematic wave models assume that flow in the irrigation channel is all at a fixed depth. The momentum equation is reduced to the well-known steady flow identity between bottom and friction slope. The assumption yields a unique area-discharge relationship describing the flow (Kincaid *et al.,* 1972). Walker & Humphreys (1983) solved the model using the deformable control volume method originally used by Strelkolf & Katapodes (1977) to solve the zero inertia model .

The fourth and last category encompasses the volume balance models, which are in a class on their own in that they completely neglect the equation of motion.

2.3.4 The volume balance model

The principles of the volume balance (VB) methods are only based on the conservation of mass equation (Equation 2) as originally established for border irrigation by Lewis & Milne (1938), and then later applied to furrow irrigation by other researchers. Studies using volume balance approaches that have been conducted include those by Philip & Farrell (1964); Chriastiasten *et al.,* (1966); Norum & Gray (1970); Fangmeir & Ramsey (1978); Reddell (1981); and Elliot & Eisenhauer (1983). Volume balance models have been used as the basis of a variety of infiltration parameter estimation techniques (Chriastiansen *et al.,* 1966; Smerdon, 1988; De Tar, 1989). This is probably because its comparison with field data on the rate of advance indicates that it simulates actual advance reasonably well (Walker & Skogerboe, 1987). Although these models are theoretically less accurate than the sophisticated numerical models, they are referenced to this day in classic textbooks as the basis of the design and evaluation procedures for use in surface irrigation systems (Walker & Skogerboe, 1987). These techniques are particularly simple and easy to use. This characteristic provides for a relatively easy approach to evaluating and managing a furrow irrigation system.

2.3.4.1 Variants of the volume balance model

There is no single volume balance approach; rather, there are a number of methodologies with various assumptions and data requirements. With the inherent empiricism associated with the volume balance model, there have been a number of assumptions relating furrow irrigation hydraulics, and as a result, there are divergent approaches to the solutions of the inverse problem. The approaches often differ depending on the assumed advance law, assumed surface storage, the infiltration function, the accounting for runoff (if any), and the method of integration (analytical or numerical). However in most cases, inflow is held constant (Benham *et al.*, 2000).

Most volume balance methods used to calculate infiltration parameters in surface irrigation are derived from advance phase data either with a power function (Chriastianseen *et al.*, 1966; Norum and Gray, 1972; Smerdon *et al.*, 1988; DeTar, 1989) or with exponential function (Burt *et al.*, 1982). There are other models that have been developed based on the depth of water on the channel (Esfandiari & Maheshwari, 1997)

The integrated volume balance (Equation 8) is used to indirectly measure the infiltration characteristics knowing the inflow, average storage, and the advance trajectory (Smerdon *et al.*, 1982).

$$Q_{in} t = A_o \, x(t) + \int_0^x Z(t - t_s) \, ds \qquad \cdot\cdot 8$$

Where: Q_{in} is the inflow per furrow, A_o is the average cross section area of the stream, flow , *x(t)* is the distance water has advanced along the field at time t (advance function or trajectory), t_s is the value of t when water has arrived at location s behind the advancing front, and Z is infiltration volume per unit length of furrow as a function of opportunity time $t - t_s$.

Many volume balance approaches have been developed each with different assumptions and data requirements (Walker & Skogerboe, 1987). Wilke & Smerdon (1965) Norum & Gray (1972) presented dimensionless graphs of solutions of volume balance and graphical methods that can be used to determine the Kostiakov coefficient k and exponent a from advance, flow rate, and surface storage data.

Christiansen *et al.,* (1966) presented a paper on the volume balance approach that used graphical or regression techniques for determining the infiltration parameters, and assumed that the advance equation could be described by a power function. The Chriastiansen *et al., (1966)* procedure involved plotting the advance data on log-log graph paper to obtain the coefficients of a power advance equation. Infiltrated amounts versus time during the water advance, estimated as the difference between volume of inflow and surface storage, are also plotted on log-log graph paper. Data from these plots are then used to calculate the coefficients of the Kostiakov infiltration equation. Ley (1978) modified Christiansen's approach using the Finabocci search method to find the optimal parameter values that not only match the furrow advance but also minimized the error between the predicted and measured run-off values.

Reddell (1981) determined the infiltration parameters with the assumption that the surface storage term in the volume balance equation is negligible. Elliot & Walker (1982) further simplified the estimation of the Kostiakov infiltration parameters from advance data. They developed an algebraic method using a volume balance model for furrow irrigation, popularly known as the "two-points" method. Data required for the method are advance measurements at two locations along the furrow length (preferably at mid field and the end), furrow flow rate, slope, field length, surface roughness, and furrow geometry. Renault & Wallender (1992) developed the advance linear velocity (ALIVE) method, solving the flow rate balance equation using the Laplace transformation.

Sherpard *et al.,* (1993) proposed a one-point method based on the volume balance approach for estimating soil infiltration parameters in the Philip infiltration equation. In the one point method, elapsed time for the waterfront to advance to a single observation point down the furrow, usually to the furrow end, is the only measurement required.

2.3.4.2 The Two-points method

Elliot & Walker (1982) concluded after various comparisons of different fitting methods that the best fit is achieved by a two point fitting of the equation, and that a power function gave the best fit to the time-distance relationship in a previously dry furrow. Their results were consistent with those of Blair (1982) who reported that the two -points method for determining advance equation coefficients was as accurate as regression methods based on the whole advance points, if the two advance distances were approximately in the middle and at end of the field. Burt *et al.,* (1982) also used advance time data for the middle and end of the field when they determined infiltration coefficients for the Kostiakov equation. The results from this approach are supported by infiltrometer data analysed by Blair (1982). Moreover, this author found the two point method solution of the Kostiakov equation to be as accurate as regression methods when the first infiltration value was measured at an infiltration opportunity time of between one and two hours and the second after four hours. Thus, if the advance times to the middle and end of the field are similar to the optimal times suggested by Blair (1982), the two-point method is probably sufficiently accurate for determining infiltration coefficients.

The advantages of a two-point method lie in the simplicity of its determination for the volume balance analysis. It is easily implemented with a hand held calculator, and it yields excellent results, unless the time interval between the two points is small. This implies that it might fail in very short lines, even where the advance function is quite linear (Blair,1982). Generally however, simplicity and accuracy of the two-point method makes it an attractive model for general application. The major drawback of the two-points approximation volume balance method is that the description of the advance phase is based on two measurements of advance. Thus if one or both of these advance measurements is atypical, or an outlier in the statistical sense, then this method may perform poorly (Walker & Busman, 1990). However, if it is suspected that two-measured advance–time data may be atypical, then several advance measurements should be made, and a smooth curve fitted to the data. This curve may then be used to determine two advance time data sets representative of the entire advance phase.

Smerdon *et al.,* (1988) and Blair *et al.,* (1988) evaluated seven "two points" methods. Volume balance models included the integral method as used by (Elliot & Walker, 1982), the numerical method (Burt *et al.,* 1982), and the Laplace model (Wilke & Smorden, 1965). It was reported that the methods performed comparably. They adopted the Kostiakov, the modified Kostiakov and the Soil Conservation Service (SCS, USDA) as infiltration models, and advance equations included the power as well as the SCS advance equations.

The techniques used in the various approaches are quite well established and are described in impeccable detail in various literatures. Therefore, the techniques will not be given detailed treatment here. However, some important aspects of the solution techniques as well as certain features unique to the models used in the study should be observed. This is limited to the two-points method (Walker & Skogerboe, 1987) and solution by optimisation (MyClymont & Smith, 1993).

2.3.4.3 Mathematical principles of the two points method

As already mentioned above, the advance trajectory of the waterfront along a furrow can be satisfactorily characterized with a power function.

$$x = pt^r \qquad \cdots 9$$

Where x is the distance the front has advanced in time t, and p and r are empirical fittings.

The power advance equation coefficient and exponent can be solved in one of two ways. One is to use the least squares method whereby one plots a line on a log-log plot of advance of time data or uses a "two point" method. In the other, the times for water to advance to the middle and end of the furrow are normally the two points used to calculate the multiplier and exponent in the Kostiakov infiltration equation.

$$r = \frac{\log\left(\frac{t_1}{t_2}\right)}{\log\left(\frac{L_1}{L_2}\right)} \qquad \cdots 10$$

and

$$p=\frac{t_1}{L_1^r}=\frac{t_2}{L_2^r} \qquad \cdots 11$$

Where: L_1 is the distance to half or closer to half the length of the furrow length, L_2 is approximately equal to the furrow length, and t_1 and t_2 are the corresponding advance times.

The infiltration models can be any suitable model, but for the purposes of the study, the infiltration function will take the Kostiakov-Lewis characteristic form of:

$$Z=kt^a+ct \qquad \cdots 12$$

Where: Z is infiltrated volume per unit length after infiltration opportunity time, t, c is the basic intake rate in units of volume per unit time period, and k and a are empirical fitting

$$Q_{in}t=A_o x(t)+\int_0^t Z(t-t_s)prt_s^{r-1}\,dt_s \qquad 13$$

parameters.

Based on the above assumptions, the volume balance equation is written for any one time as:

Further, the extended Kostiakov model (Equation 12) is substituted in equation 13 resulting equation 14.

$$Z(t-t_s)=K(t-t_s)^a+f_o(t-t_s) \qquad \cdots 14$$

Again further expansion and integration leads to the equation 15:

$$Q_{in}t=A_o x+\sigma_z k\, t^a x+\frac{f_o t}{1+r}x \qquad \cdots 15$$

The subsurface shape factor, σ_z defined in equation 16, where parameters r and a are as previously defined in equations 10 and 19 respectively.

$$\sigma_z = \frac{a+r-ra+1}{(1+a)(1+r)} \qquad \cdots 16$$

Where invoking the equation twice during advance (x_1, t_1), and (x_2, t_2) then fitting a curve to several points leads to the two points, Elliot & Walker (1982) derived the equations 17 and 18.

$$\frac{Q_{in} t_1}{x_1} = A_o x + \sigma_z k t_1^a x + \frac{f_o t_1}{1+r} x \qquad \cdots 17$$

$$\frac{Q_{in} t_2}{x_2} = A_o x + \sigma_z k t_2^a x + \frac{f_o t_2}{1+r} x \qquad \cdots 18$$

The exponent a and multiplier k of the Lewis cumulative infiltration in equation 12, are, respectively, given by

$$a = \frac{\log\left[\dfrac{\dfrac{Q_{in} t_1}{x_1} - A_o \dfrac{f_o t_1}{1+r}}{\dfrac{Q_{in} t_2}{x_2} - A_o \dfrac{f_o t_2}{1+r}}\right]}{\log\left[\dfrac{t_1}{t_2}\right]} \qquad \cdots 19$$

and

$$k = \frac{\left[\dfrac{Q_{in} t_1}{x_1} - A_o \dfrac{f_o t_1}{1+r}\right]}{\sigma_z t_1^a} \qquad \cdots 20$$

Where r and p are the exponent and the coefficient of the power function trajectory, respectively, in equations 9 and 10.

2.3.4.4 The advance–rate-linear velocity (ALIVE) method

The advance rate linear velocity (ALIVE) theory (Renault & Wallender, 1992) is based on a flow rate balance equation rather than distance. Renault and Wallender (1992) reported that the use of advance rate in the ALIVE approach provides more information on the behaviour of the irrigation water than models using advance distance. An exact analytical solution of the advance rate is derived when using a Horton infiltration function and consideration of three standard assumptions. In brief, the advance rate as a function of time is composed of two decreasing exponential terms. The advance rate as a function of distance, presents two linear decreasing phases (Figure 3). Four velocity parameters (maximum initial velocity V_m, maximum advance length for initial infiltration rate L_o, initial virtual velocity V_o, and maximum length watered (L_m) are identified on the velocity diagram. These parameters are then used to solve the inverse problem, identifying the infiltration parameters of Horton's law. The first one occurs during the early stages of irrigation, when the front is slowed dramatically by the high initial rate of infiltration along the wetted run. The initial velocity value V_m gives the front velocity without infiltration and can be derived from equation 21.

$$V_m = \frac{Q_{in}}{A} \qquad \cdots 21$$

The second linear decrease follows when the decrease of infiltration at the upstream end of the furrow starts to produce effects on the flow balance. The two lines intercept with the axis to give four parametres V_m, L_o, V_o, and L_o (Figure 3). Fitting the experimental data on the advance rate trajectory can be achieved analytically with a minimum of three advance points, or by curve fitting on the velocity diagram.

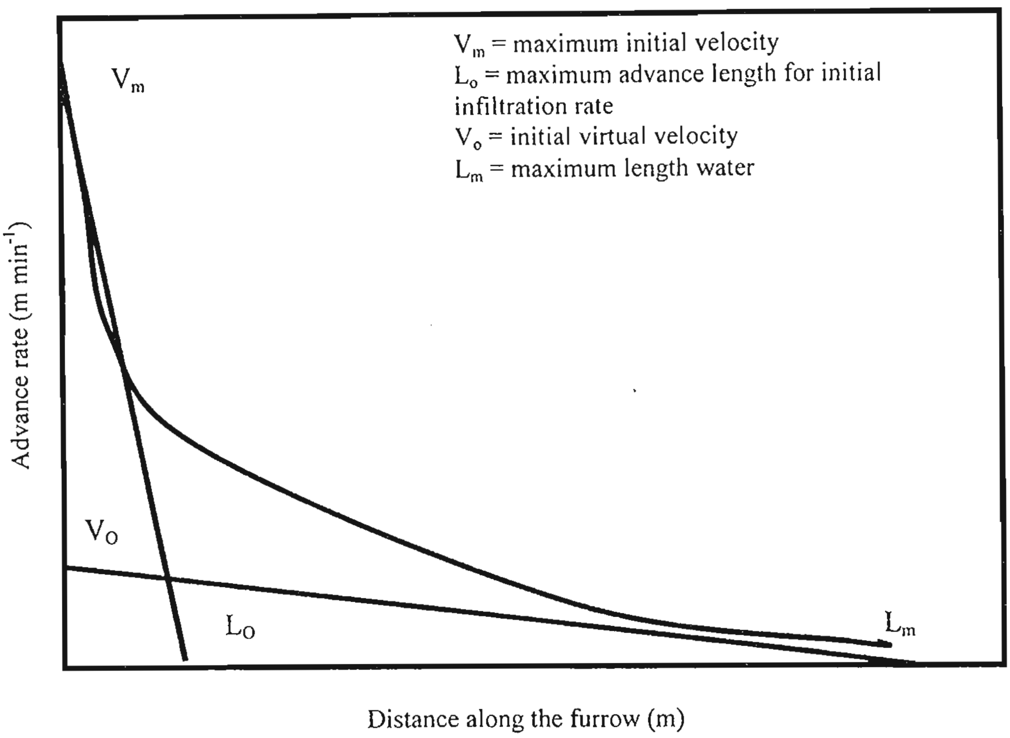


Figure 3 Velocity diagram showing first linear phase, rapid decline; and second linear phase, stabilized phase (after Renault & Wallender, 1992).

The Horton infiltration function is

$$Z(t) = (F - 1 - e^{\sigma\tau}) + Ct \qquad \cdots 22$$

Where: c is the steady state of the infiltration reached for large values of time (l/m),

F is rapid subsurface storage (L); and

θ is a positive parameter expressing the decrease in infiltration during the transient period (min^{-1}). The Horton parameters are related to the velocity diagram parameters as follows

$$C = \frac{Q_{in}}{L_m} \qquad 23$$

and

$$F=\frac{Q_{in}}{V_o}x\frac{\left(1-\frac{L_o}{L_m}\right)\left(1-\frac{V_o}{V_m}\right)}{1-\frac{V_oL_o}{V_mL_m}} \qquad \ldots 24$$

2.3.4.5 The one point method

The one point method proposed by Shepard *et al.*, (1993) has two key assumptions; firstly, the infiltration characteristics of the soil are described by the Philip equation

$$Z=St^{1/2}+At \qquad \ldots 25$$

Where: Z is the volume of infiltrated water per unit length of furrow, S is the sorptivity, and A is transmissivity; and secondly, the advance characteristics of the water front in furrow is described by

$$x=pt^{1/2} \qquad \ldots 26$$

Where x is the distance of the waterfront has advanced in time t and p is an empirical fitting parameter.

The input data required are the inflow, average flow area and advance time to the end of the field. The parameters of the Philip equation are then calculated from the following equations as derived by Shepard *et al.*, (1993)

$$S=\frac{Q_{in}t_2-3cx_2}{\frac{\pi}{4}t_2^{0.5}x_2} \qquad \ldots 27$$

and

$$A = \frac{3c}{t^2} \qquad \cdots 28$$

2.3.4.6 The optimization method

Various procedures are employed to produce the time space trajectory of water movement and, thereafter, system performance.

The major difficulty with the above methods is the use of particular forms of advance and infiltration equations. In many field situations, the form of a particular advance and infiltration equation may not fit the field data, and therefore renders those methods unsuitable. In order to overcome these restrictions, alternative methods for parameter estimation without the above-mentioned restrictions have been used by a group of researchers. Several optimization algorithms have been developed to solve the inverse problem.

Maheshwari *et al.,* (1988) adopted a Hooke-Jeeves pattern-search optimisation algorithm to solve a volume balance model. The objective function was the minimisation of the difference between measured and estimated infiltrated volumes. The model allowed for the adoption of any time dependent infiltration equation, and any form of advance equation. Data requirements included measurements of advance, surface storage depth, runoff, channel geometry and inflow.

Conjugate gradient and variable matric optimisation techniques were used by Katopodes (1990) to determine three parameters from the zero inertia model. Two of the parameters were a and k from the Kostiakov model while the third parameter was the Manning n. The objective function was the minimisation of the error between the measured and estimated depths of flow on the surface. The method is limited in that it requires the measurement of waterfront advance, surface storage depths, field slope, inflow, and channel width.

Walker & Busman (1990) used a simplex optimization technique that minimizes the sum of squares of differences between measured and simulated advance times by fitting the three parameters of the modified Kostiakov equations. Katapodes & Tang (1991) used a combined procedure of optimization. First, they obtained initial values from the parameters using the two-point method. Later, they used a multidimensional optimization technique, called the Poweel method. This method considers the obtained with the two-point method as initial values. That technique combined with a kinematic wave model permits the best search direction to be found. Finally, they used a one dimensional optimization technique called the Brent method to obtain the parameters; *k*, and f_o of the Kostiakov–Lewis equation. The parameter *a* is determined by the two point method.

Baustista & Wallender (1993) developed a parameter identification model, based on a hydrodynamic model, to compute furrow infiltration parameters from irrigation advance measurements. Parameters were computed by minimizing the squared difference of observed and predicted advance times to specified locations on the field or alternatively from advance rates. The Marquardt optimisation algorithm was used by Baustista & Wallender (1993) to solve a hydrodynamic model for the three parameters in the Kostiakov–Lewis infiltration equation. They either found these parameters by minimising the error between the advance times or velocity, the latter of which was more successful.

Smith (1993) developed a method utilising the volume balance from the two points of Elliot and Walker (1982). In this method, The Kostiakov-Lewis parameters were found by minimising the volume balance error using a Steepest Descent optimisation procedure. However, unlike the two-points method, the steady state infiltration rate did not need to be measured, as it was determined in the optimisation. Data required were the cross sectional area of water at the upstream end of the furrow, inflow rate and three or more points on the irrigation advance.

2.3.4.7 Principles of the McClymont method

The McClymont method is based on the volume balance equation derived by Elliot & Walker (1982) for the two-points method, and is applicable where there is no runoff at the end of the field.

Algebraically, the volume balance can be stated as follows;

$$Q_{in}t = Vi + V_S \qquad \cdots 29$$

Where: Q_{in} is the inflow (m^3min^{-1}), t is time in minutes from the commencement of the irrigation; V_i is the volume (m^3) of water infiltrated; and V_s is the volume (m^3) of water temporarily stored on the surface.

Equation 29 can also be written as:

$$Z = k(t - t_x)^a + c(t - t_x) \qquad \cdots 30$$

Where Z is the depth of infiltration (m) at a distance x (m) from the top of the field, t_x is the time (min) for the advance to reach the distance x downstream.

The equation can be expressed in terms of distance x by assuming that the advance follows a power curve just like equation 9.

V_i is derived from

$$V_i = \int_0^x Z\,dx \qquad \cdots 31$$

Where r and p are empirical parameters. Substituting into equation 30 and integrating over the wetted length of the field determines the total volume V_i of the water infiltrated in time t;

The parameter p disappears in the integration. The volume of water V_s stored on the surface can be calculated from

$$V_s = \sigma_y A_o x \qquad \cdots 32$$

Where: σ_y is the dimensionless storage shape factor; A_o is the average cross sectional area (m^2) of surface water at the upstream end of the furrow.

Substitution of equation (31) and (32) into equation (29) gives the volume balance as used in the two points method of Elliot & Walker (1982):

$$x = \frac{Q_{in} t}{\sigma_y A_o + \sigma_z k t^a + \frac{f_o t}{1+r}} \qquad \cdots 33$$

To solve the above the equations for the infiltration parameters, an objective function is formulated based upon minimising the sum of squares of the error between the predicted and measured advance.

$$SSE = \sum_{i=1}^{N} \left(x_1 - \frac{Q_{in} t_i}{\sigma_y A_o + \sigma_z k t_i^a + \frac{f_o t_i}{1+r}} \right) = minimum \qquad \cdots 34$$

The advantages of a two-point method lie in the simplicity of its determination for the volume balance analysis. It is easily implemented with a hand held calculator, and it yields excellent results, unless the time interval between the two points is small. Generally however, simplicity and accuracy of the two-point method makes it an attractive model for general application. The major drawback of the two-points approximation volume balance method is that the description of the advance phase is based on two measurements of advance. Thus if one or both of these advance measurements is atypical, or an outlier in the statistical sense, then this method may perform poorly (Walker & Busman, 1990). However, if it is suspected that two-measured advance–time data may be atypical, then several advance measurements should be made, and a smooth curve fitted to the data. This curve may then be used to determine two advance time data sets representative of the entire advance phase.

Renault and Wallender (1992) reported that the use of advance rate in the ALIVE approach provides more information on the behaviour of the irrigation water than models using advance distance The ALIVE models uses a Horton equation which allows physical examination involved irrigation. The one point method, on the other hand, uses a Phillip equation (4) which is based on the assumptions that the soil is homogenous and non- cracking and the initial water content is uniform. These assumptions are not often satisfied for soil resulting in a poor fit of the equation to field data.

The major difficulty with the above methods is the use of particular forms of advance and infiltration equations. In many field situations, the form of a particular advance and infiltration equation may not fit the field data, and therefore renders those methods unsuitable. In order to overcome these restrictions, optimization without the above-mentioned restrictions have been used by a group of researchers. However, the McClymont optimisation method is based on the volume balance equation derived by Elliot & Walker (1982) for the two-points method is only applicable where there is no runoff at the end of the field.

Although these models are theoretically less accurate than the sophisticated numerical models, they are referenced to this day in classic textbooks as the basis of the design and evaluation procedures for use in surface irrigation systems (Walker & Skogerboe, 1987). These techniques are particularly simple and easy to use. This characteristic provides for a relatively easy approach to evaluating and managing a furrow irrigation system.

At 25 % of the production costs at Ubombo Sugar, irrigation is the single most costly practice in growing sugarcane. Consequently, there has been an increased and continuous effort towards improving management in all three of the irrigation systems used on the estate. The greatest challenge to the management of irrigation is encountered in furrow irrigation. The soil and not the system hardware control infiltration in surface irrigation systems to a greater extent than in other systems.

In furrow irrigation, soil infiltration properties control the major phases of irrigation: advance, recession, run-off, depth and uniformity of applied water. Soil infiltration characteristics are thus an extremely important soil parameter in the management of surface irrigation. Infact, optimal design and management of surface irrigation systems rely entirely on detailed knowledge of soil infiltration properties (Baustista & Wallender, 1993). Therefore, an insight into the infiltration process, and determining and possibly predicting infiltration in time and space remains a vital, and a first step in improving the management of furrow irrigation systems (Vogel and Hopmans, 1992; Shepard *et al.,* 1993).

Sugarcane production at Ubombo is fully irrigated as the estate is located in the Swaziland Lowveld in a semi- arid climate. Thus, irrigation is a crucial and an integral activity of sugarcane production. Under such conditions, economic sugarcane production requires large amount of water (2300mm Class A pan). However, water is a limiting factor in the production of sugarcane. Consequently, efforts are made to conserve water and increase water use efficiency, either by reducing irrigation adequacy or by eliminating the least productive irrigations. Hence the objectives of the study were firstly to determine and examine the soil infiltration characteristics of the Sibaya (Si) soil series at the experimental site as affected by different deficit irrigation schedules; so as to enhance the efficiency of irrigation through establishing if one could use infiltration characteristics determined in the study to apply to managing the furrow irrigation system at Ubombo. Secondly to investigate the response of sugarcane to the different irrigation regimes.

CHAPTER 3

MATERIALS AND METHODS

3.1 Site description

A field experiment was conducted at Big-Bend (26°46′04″S, 31°56′11″E, 106m asl) lying West of the Lubombo Mountains. The climate of the area is subtropical with hot summers and cool winters. It has mean annual temperature of 22^{0}C. The mean annual rainfall is about 650 mm, with most of the rainfall occurring in summer between November and January. The mean annual potential evapotranspiration (Class A Pan) is 1475 mm of which about 15 % occurs in January alone.

Five irrigation schedule treatments were studied based on estimated crop evapotranspiration (ET): Ubombo irrigation schedule (T_1), 1.25 (T_2) x; 1.00 (T_3) x; and 0.75 (T_4) x Penman-Monteith (PM) estimated ET; and an alternate inter-row irrigation (T_5). The alternate inter-row irrigation was, in the first season, scheduled as the Ubombo system (T_5, 2000) whereas in the second season it was scheduled according to 1.00 x PM. (T_5, 2001). The treatments were arranged in a randomised complete block design and replicated four times (Figure 4). In brief, the Ubombo (T_1) schedule involves filling up the profile with water after harvest. Crop water use is estimated using canopy factors ranging from 0.1 to 1.0 depending on season and age of crop. The soil moisture is depleted to between 20% and 50% of total available water (TAW) before irrigation depending on season (appendix 1).

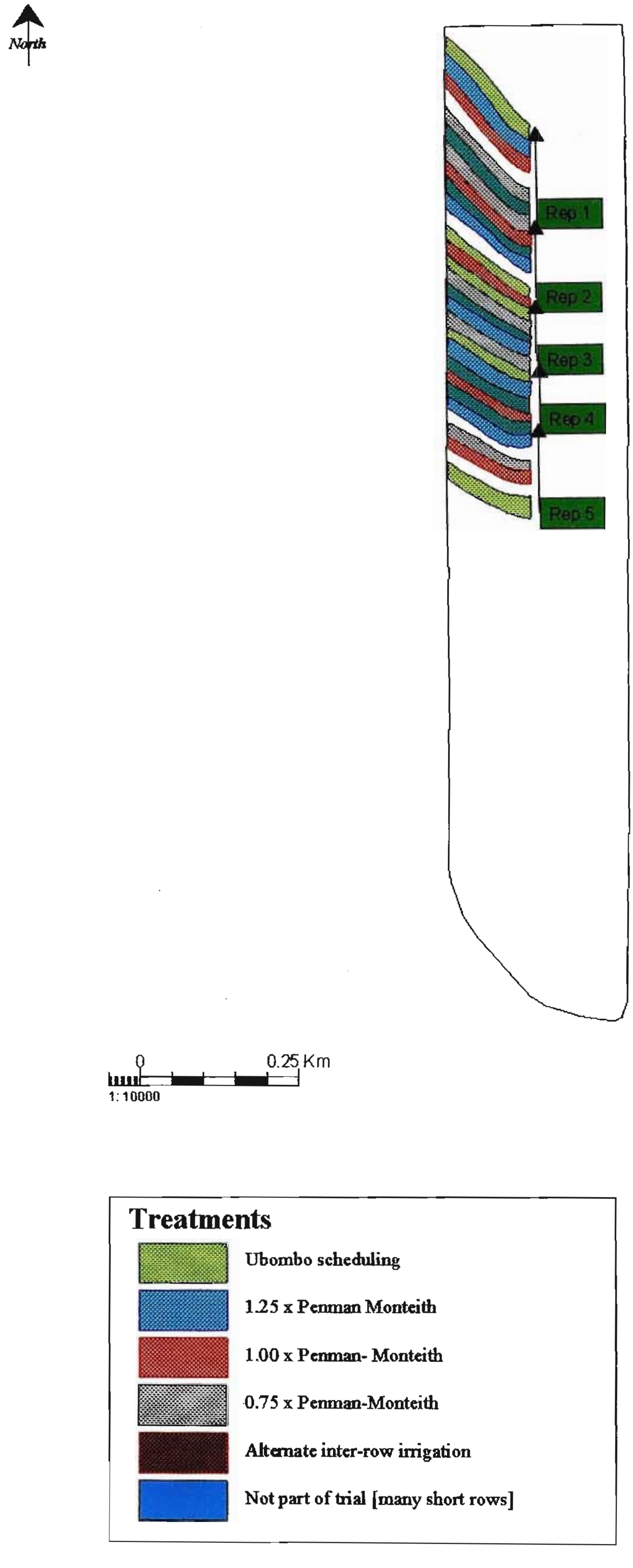
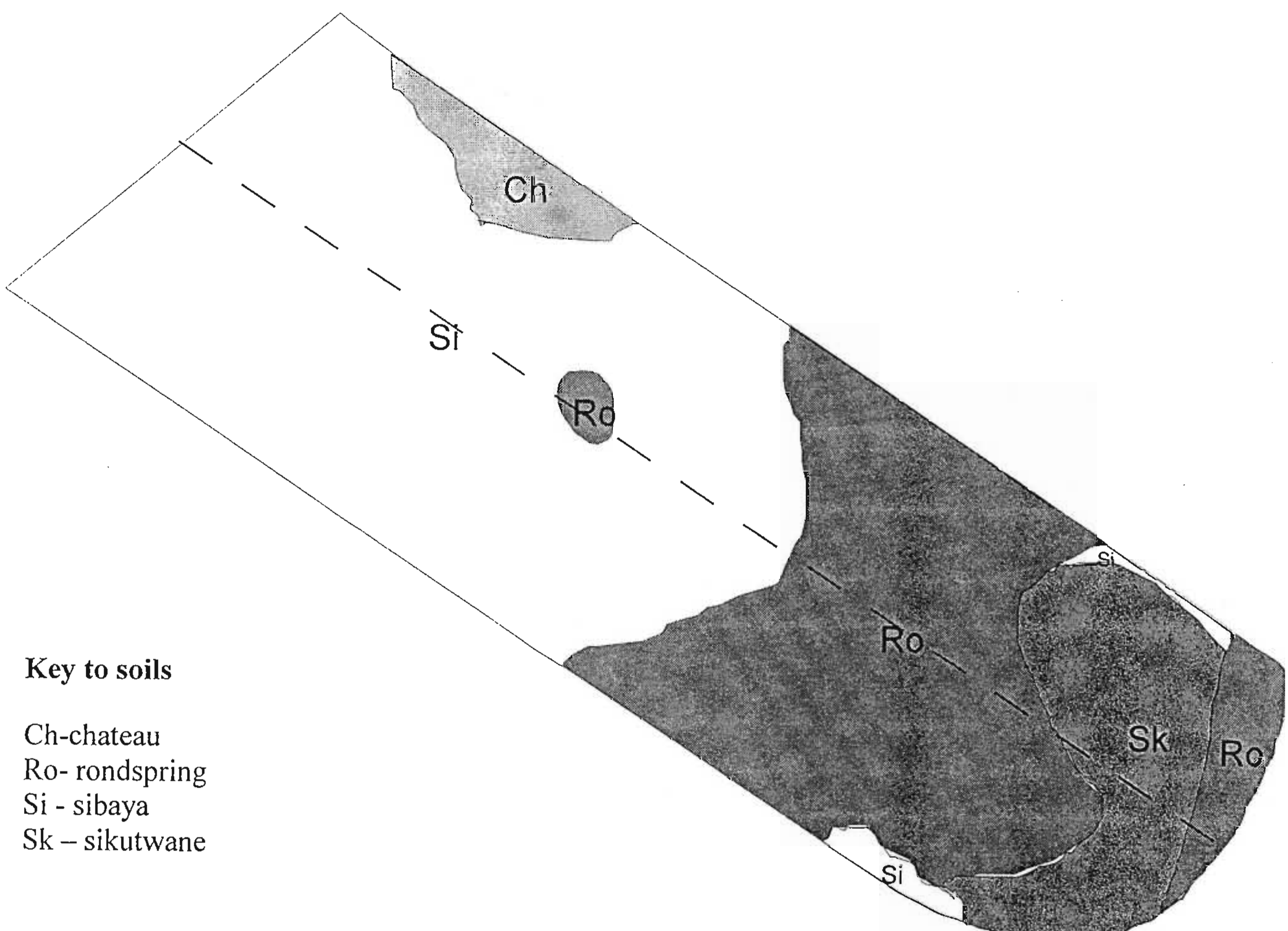


Figure 4 Location of the field trial and treatment layout of the field.

3.2 Soils

The soils on the trial site were predominantly Sibaya (Si) sets and some Rondspring (Ro) sets (Figure 5) (Murdoch, 1972).The Ro and Si soil sets are characterised by their essentially red colour hues of 2.5 or redder, and clay loam to clay texture. Organic matter content is moderate. The Si sets are shallow (< 0.35 m to weathering rock), and dark red. The Ro sets are between 0.4 m to 0.9m in depth. In the South African Soil Classification system, the Si and Ro sets correspond to the Glenrosa and Hutton series, respectively (Nixon, 1986). Parent material is basalt and post karroo dolerite.



Key to soils

Ch-chateau
Ro- rondspring
Si - sibaya
Sk – sikutwane

Figure 5 Soil types of the field where the trial field was conducted.

3.3 Experimental layout

The trial was located in one furrow irrigated fields of the estates called Hollander South 1, a field of 52.0 hectares. The trial site was approximately 6.84 hectares and located in the western end of the field (Figure 4). On average, the gross plot size of each plot was 0.30 hectares and made up of fifteen gross rows of sugarcane, and row spacing of 1.52 m. The net plot consisted of five inner rows boarded by five rows on each side. The trial was laid out in a randomised complete block design with four replications (Figure 4).

3.4 Planting and furrow forming

Cultural management and conditions at the field were typically those commonly applied on the estate where furrow irrigation is practised. Planting was conducted on 17th November 1999 following the standard practices of the company (Table 3). This encompasses using an inter-row spacing of 1.52 m, a longitudinal slope of about 0.004m m^{-1}, and parabolically shaped furrows. In this particular field, the cane rows were running north-south, and furrow length varied between 130 to 160 m.

The width and shape of a furrow have a marked effect on contact time and hence on the amount of water applied The shape of a furrow is important to the adequate replenishment of depleted soil water and performance of the furrow irrigation system. Furrow forming involved, firstly, shallow ripping (chisselling) of the soil and later spreading out of the soil (middlebursting) onto the sides resulting in a parabolic shape (Plate 1). As such, the shape of the furrows could be described as parabolic (u-shaped), with a constant gradient of 1: 250. The top of the furrow was 0.6 to 0.8 m, and water flow depth varied between 0.06 to 0.1 m (Plate 2). This is a standard procedure for the company.

Plate 1 Tractor mounted equipment used to form a parabolic furrow shape .

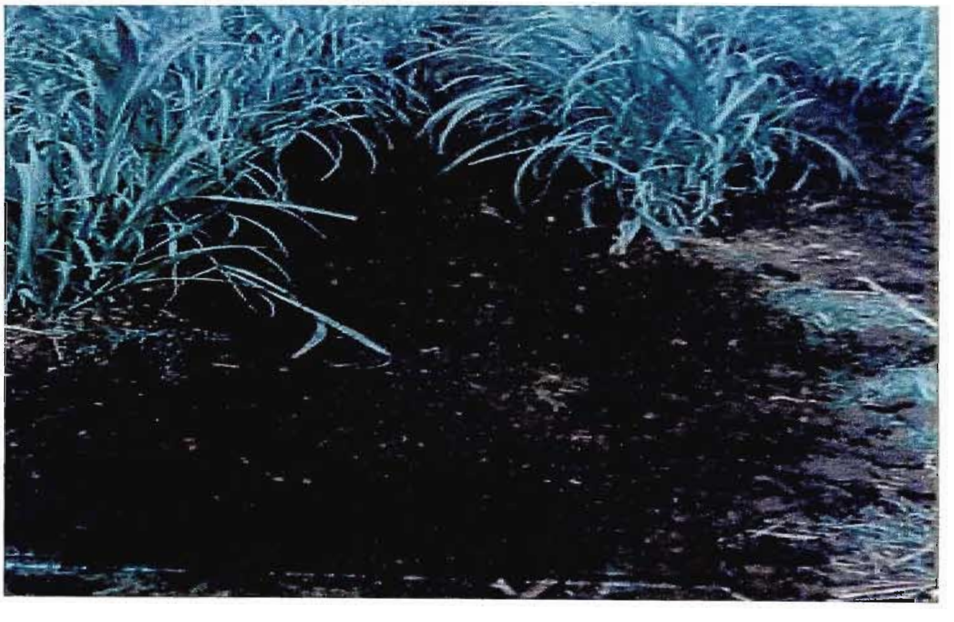


Plate 2 Parabolic furrow shape before closing the end of the furrow (rows planted at 1.52m apart).

3.5 Fertilization

Standard practices of the estate fertilization were given to the trial site, the soil was analysed for four macro-elements and pH (water) and then fertilizer requirements were based on soil analysis findings. For the plant cane, 202kgN ha^{-1} was applied as urea (46 %), 200kg K ha^{-1} as KCl (50 %), and 150 kg P ha^{-1} in the form of diammonium phosphate (DAP, 20 % P). The N and K were applied ten weeks after planting whereas P was applied on the day of planting. Meanwhile, for the first ratoon crop, 160kgN ha^{-1} was applied as urea (46 % N) and180 kg K ha^{-1} was applied as 0.5 KCl (50 % K) two weeks after harvesting. According to the soil analysis results there was no phosphorus required for the first ratoon hence it was not applied. The dates of applying fertilizer and a summary of dates on which some of the cultural practices were conducted is given in Table 3.

3.6 Leaf sampling

The mineral content of N, P, K, Ca, and Mg as a percent of dry matter of leaves was determined at 5 months of sugarcane age in both the plant and first ratoon crops. In each treatment, in all the replications, a total of ten leaves was taken at an interval of 15m from the upstream to the downstream ends of the field. In each selected stalk, the third leaf from the top (first leaf from the top being a leaf that is at least half unfurled) was sampled. Holding the leaves in a bundle, per treatment, the top and bottom parts of the leaves were cut off leaving a central portion of about 0.30m long. Immediately thereafter, the midrib was stripped off and the leaves were air - dried in the laboratory, and, when dry enough, analysed for mineral content. The mean value was derived according to treatment in all the replications. This was undertaken to establish whether the crop met the established threshold norms of the estate at five months of age. In both seasons, crop nutritional status was above the estate's nutrient thresholds (Table 2).

Table 2 Leaf mineral analysis (%) of plant and first ratoon sugarcane crops grown under varying irrigation regimes.

Irrigation treatment	2000 (Plant cane)					2001 (1st ratoon)				
	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	N (%)	P (%)	K (%)	Mg (%)	Ca (%)
1. Ubo	2.11	0.23	1.49	0.17	0.19	1.96	0.25	1.36	0.17	0.19
2. 1.25 x Penman-Monteith	2.10	0.22	1.50	0.16	0.20	1.96	0.25	1.30	0.19	0.21
3. 1.0 x Penman-Monteith	2.09	0.23	1.42	0.16	0.19	1.98	0.24	1.30	0.19	0.20
4. 0.75 x Penman-Monteith	2.11	0.22	1.39	0.15	0.19	1.99	0.25	1.40	0.20	0.19
5. Alternate inter-row[1]	2.11	0.23	1.51	0.15	0.17	1.99	0.25	1.29	0.19	0.21

[1] Alternate inter-row irrigation using Ubombo scheduling for 2000, and using derived 1.00 x Penman-Monteith factor for 2001 .

Nitrogen, for the plant cane, was found to be above the threshold of 2.0 % N in the dry matter of the third leaf. However, in the first ratoon nitrogen was marginally lower than the threshold.

At five months, levels of P were found to be above the threshold of 0.21% in the dry matter of the third leaf for both the plant and first ratoon crops (Table 2). Likewise, K levels were found to be above the threshold level of 1.05% for both the plant and ratoon crops at five months.

3.7 Weed and smut control

The weeds emerging after planting or ratooning were mainly grasses, broadleaf leaf weeds and sparse population of watergrass (*Cyperus esculentus L.*). After the fertilizer application and the first irrigation, the soil was allowed to dry slightly but wet enough to apply herbicides, and immediately irrigate again. A herbicide combination [Falcon gold (960g L^{-1} metalachlor, emulsifiable concentrate), Gesaprim (900g kg^{-1} atrazine, wettable granules) and Gesapax (500g L^{-1}ametryn, soluble concetrate)] was applied at the separate rate of 2.5l ha-^{1}, 3.0 l ha-^{1} and 3.0 L ha^{-1}, respectively using tractor–mounted boom sprayer with flat-fan nozzles. For the watergrass, spot spraying with servian (750 g kg^{-1} halosulfuron, wettable granules) at 50 gha^{-l} was undertaken when about 10 % of the watergrass had flowered. The cultivar N23 is more tolerant to smut than NCO 376, but still requires routine roguing of the field for infected cane, which was carried out every six weeks until the smut levels had stabilised to less than one percent (1%).

3.8 Irrigation

3.8.1 Water application and flow measurement

When a treatment was due for irrigation, water was fed into individual furrows using spiles. Inflow rate, depth of flow with time, advance and recession times were some of the measurements made during an irrigation event. The inflow rate was measured with a low-pressure propeller meter (Plate 3) and readings were manually taken at two-minute intervals. The times for water to advance every 10 m stretch was monitored (Figure 6) and recorded until the waterfront reached the downstream end of the field. After the closure of the spiles, which was done when the waterfront advance reached 10 m from the end of the furrow, the times at which water receded along the 10m intervals were recorded. The cross sectional area was determined using a profilometer (Walker and Skogerboe,1987) at five places along the furrow length and the mean value was used.

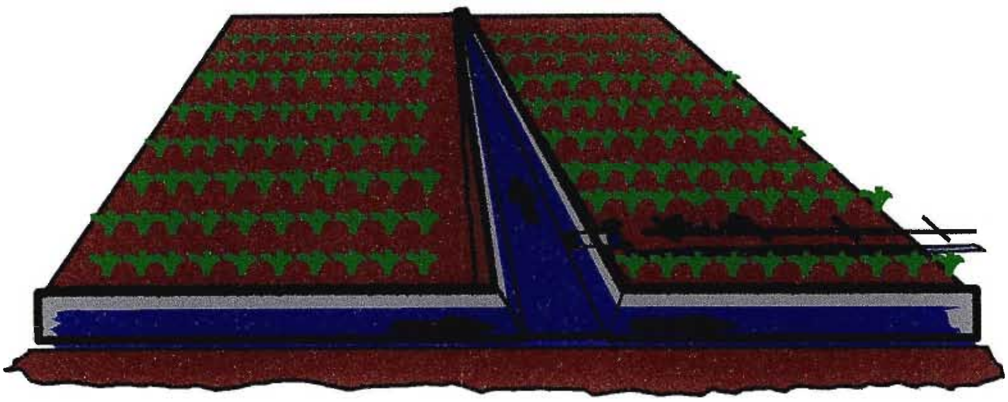


Figure 6 Determination of soil infiltration properties from large area methods (large arrows indicate the direction of canal water flow; crossbars indicate the positioning of 30 m intervals).

Plate 3 A low-pressure propeller metre that was used to measure water inflow.

3.8.2 Soil water content and soil water potential measurements

Soil water content was monitored by using neutron probe (503 DR model). Access tubes were installed along the furrow length of all treatments in two of the five replicates (Figures 7 and 8). A neutron probe provides a convenient and effective technique for measuring soil water content at various depths in a soil profile, and allows periodically repeatable measurements at the same location (Cuenca,1989). Access tubes, made of aluminum, 50 mm in diameter were inserted in the centre of the ridge at five sites along the sugarcane row (Figures 7 and 8). The tubes were covered with open-ended empty soft drinks cans to prevent water entering them, either during irrigation or by rainfall. During soil water content determinations, within each access tube, the water content was measured at a depth of 0.1 m to 0.7 m (if the soil was deep enough) at a fixed interval of 0.1m. Measurements were conducted in the mornings. This was undertaken before and after irrigation, and sometimes, where possible, two times before the following irrigation event.

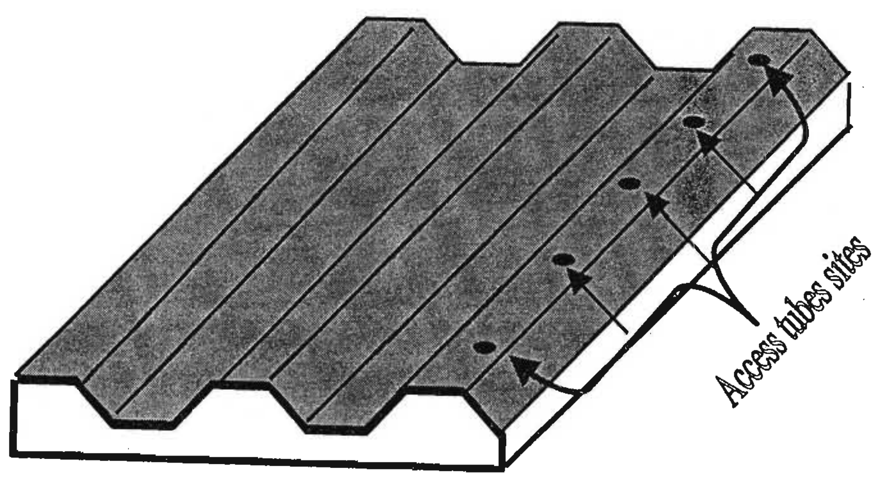


Figure 7 Insertion position of aluminium pipes to accommodate neutron probe access tubes at the centre of the ridge.

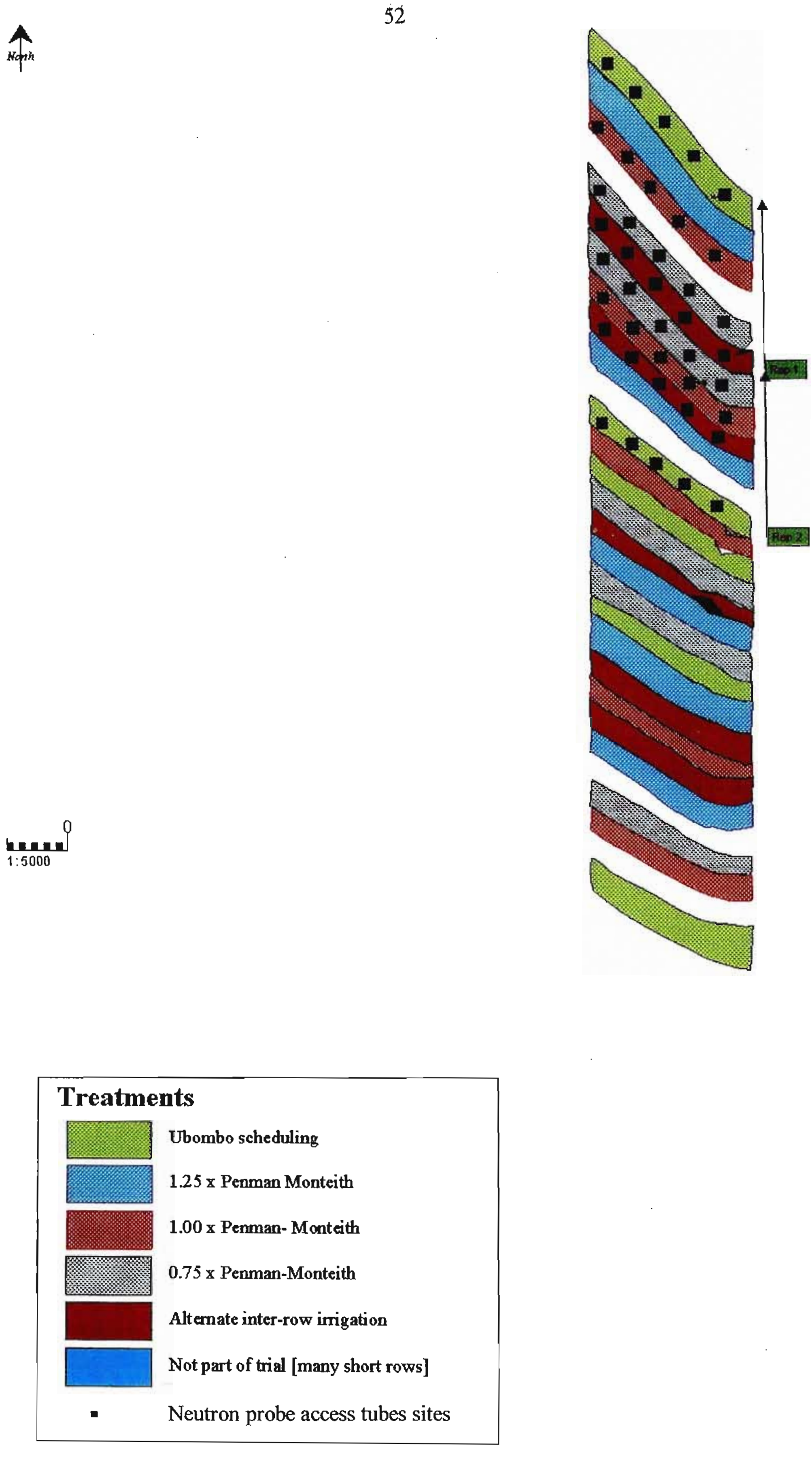


Figure 8 Positioning of neutron probe access tube along the furrows.

Soil water potential was monitored with the use of tensiometers (Irrometer Company, California, USA). Along with the neutron probe access tubes, and adjacent to each one of them, tensiometers were placed at the centre of the ridge but at three soil depths (0.15m, 0.30m, and 0.45m) measured from the top of the ridge. At installation, a hole was bored by pushing a standard metal probe into the soil, and then the tensiometer was inserted into the bored hole. The tensiometers were then filled with a solution of irrometer fluid diluted with cold, boiled water, up to the circle of the reservoir. To extract air from the tensiometers, a vacuum pump supplied by the same company was used to pull a vacuum of 85 kPa as registered on the gauge. From there, the tensiometer cap was replaced until the stopper came into contact with the bottom of the reservoir. The same procedure was repeated when servicing the tensiometers. Readings were taken in the morning on alternate days from cane canopying stage until dry- off period.

Plate 4 A neutron probe with tensiometers at 0.15m, 0.30m,and 0.45 m depth in the centre of the cane row.

Table 3 A summary of the dates on which some of the cultural practices were conducted.

Activity		Plant crop			1 st ratoon		
Harvesting of previous crop	17/07/99						
Planting (N23)		12/11/99			n/a		
Fertilizer & furrow forming		26/01/00			14/01/01		
Nutritient Application		kg N ha^{-1} 120	kg P ha^{-1} 30	kg K ha^{-1} 100	kg N ha^{-1} 160	kg P ha^{-1} 0	kg K ha^{-1} 180
Fertilizer source		urea	DAP	KCl	urea		KCl
Fertilizer application		202	150	200	348	0	360
Trial layout		19/01/01			n/a		
Leaf sampling		22/04/00			18/05/01		
Ethapon ripening		Not applied					
Fusilade ripening		15/11/00 @ 0.35L ha^{-1}			17/10/01 @0.50 Lha^{-1}		
Harvesting		31/12/00			12/11/01		

3.9 Growth measurements

In both the plant and first ratoon crops, seasonal measurements were taken from five sampling units. The first sampling unit was inserted 20 m from the upstream end of the field in each plot with subsequent units inserted at intervals of 30m down the plots. At each sampling unit, comprising 2.0 m length of the central row of each plot, the required sugarcane growth measurements were taken.

Stalk population

Stalk population was monitored from three months after planting or cutting at monthly intervals until the sugarcane was ten months old. At each sampling unit, all cane stalks were counted within the 2 m length of the sampling site.

Stalk height

Stalk height measurements were undertaken monthly once stalk elongation had commenced. In the plant cane, plant height measurements commenced at four months after planting until the ninth month, whilst in the first ratoon plant height measurements commenced at two months after harvest until the tenth month.

The height was measured from ground level (ridge top) to the topmost visible dewlap of each stem. A calibrated metal bar of 3.0 m was used in the determination of plant height. At the beginning, the sugarcane stalks to be used for measurements were tagged for identification purposes. Five plants each in the 2 m sampling units were used for the determination of plant height, and the mean was calculated per plot. Dead plants, mainly due to stalk population reduction, during the growth cycle of the cane were not replaced in the determination of the mean.

Internode number

The number of internodes was counted monthly on each stalk that was measured for its height.

Stem diameter

Sugarcane stem diameter at 0.30 m above the ground was determined, using a vernier-calliper, monthly on the same stalks that were measured for plant height.

Sugarcane mass

The yield of sugarcane for each plot was determined from twelve sub-plots (Figure 9), and the sub-plots were located at 30 m intervals from the upstream to the downstream ends of the field. Each sub-plot comprised five sugarcane rows and 2 m length. The mass of sugarcane yield was measured using a tractor- mounted scale (Plate 5).

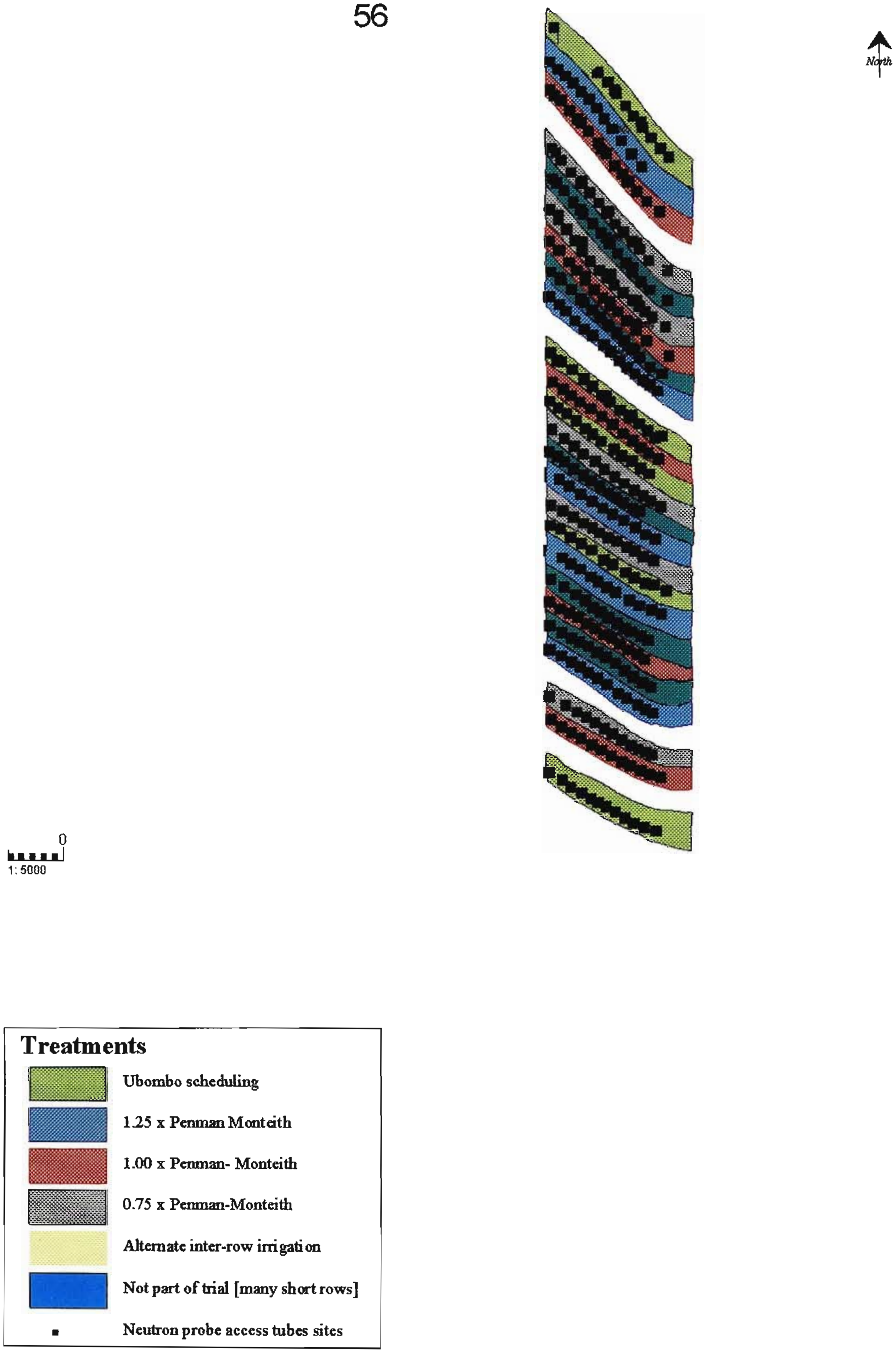


Figure 9 Sites in the field at which sugarcane yield was measured

Plate 5 Yield mass (tch^{-1}) measurement at harvest using a tractor mounted boom scale.

Sucrose analysis

For quality evaluation a total of twelve stalks were randomly taken from each yield sub-plot at harvest, one from each sub-plot. The samples were sent to the laboratory for standard quality analysis (Sugar Milling Research Institute, 1977). On receipt at the laboratory, the sugarcane samples were shredded, then moisture content was determined using the oven dry weight method. After that % sucrose was determined using the polarimetry. Sucrose yield was computed from the sucrose percentage and the sugarcane yields obtained from each plot.

3.10 Data analysis

Classical statistical analyses, using Minitab statistical software release 13, were applied in the characterisation of crop yield parameters. In an attempt to establish significant differences between the irrigation schedules on harvest yield and quality variables, a two- way analysis of variance was employed.

In the estimation of soil cumulative infiltration, two computer software programmes were used; two points method using a SIRMOD software (Walker and Skegorboe, 1999). For the optimisation solution, the Infil v was used (MycClymont and Smith, 1999). Kostiakov exponent *a* varies from 0 to 1 depending on initial soil water content (Maheshwari *et al*, 1988). Low values of Kostiakov infiltration exponent *a* indicate low initial soil water content, and high values of the exponent will result where the initial soil water content is high. Antecendent soil water content is an important factor affecting infiltration, and the effect of initial soil water content was studied by comparing the distribution of the Kostiakov exponent, *a*, between the irrigation schedules. For purposes of analysis, five frequency classes were established with class intervals of 0.2, the classes being: 0-0.2, 0.2-0.4, 0.4-0.6, 0.60.8, and 0.8-1.0. The distributions of Kostiakov exponent, *a*, was expressed in percentages for classes within each irrigation schedule using all the irrigation events for that particular season.

The infiltration process affects total applied water irrigation performance. Because of the enormity of the irrigation events data, the data were divided into three categories: early , mid, and late season irrigation events and the means used in the interpretation. The same procedure was adopted in the performance measures described in the irrigation efficiency and uniformity section.

The reason for categorizing the data into early, medium and late is because Childs *et al.*, (1992) reported that it is a common observation for infiltration to decrease dramatically after the first irrigation, as the silt particles may clog the soil pores and homogenise the soil surface. Soil capillarity decreases right from the first irrigation event to the next during the entire season. This could in part explain the temporal variation of infiltration exponents. Generally, there is a reduction in the infiltration function from one irrigation to another during any of the irrigation seasons; also, there is a reduction in the infiltration function from one season to the next. Such findings were consistent with those of Maihol *et al.,* (1999) who reported that infiltration properties might vary from one irrigation event to the next even in similar soil water conditions. Collis-George (1977) attributed variation of infiltration from one event to another even on soils with similar soil water contents to soil structural changes induced by wetting and flooding.

The declining infiltration functions may be attributed to many factors including soil compaction caused by farm machinery, soil sealing due to heavy sediment loads in the irrigation water, and climatic factors. Soil cracking, on the other hand, enhances soil infiltration, and as a result, some workers have found no evident trend in seasonal variation of infiltration properties (Clemmens, 1983). The different reports by different workers could mainly be because of soil types on which the experiments were conducted. Vertisols, for example, crack immensely because of their montmorillonite when dry, resulting in an initially high infiltration rate, but upon swelling the infiltration rate is dramatically reduced. When the furrow is rough, the velocity of the flow is retarded and generally, the depth of water in the furrow will increase. Management of furrow irrigation system has a pronounced effect on infiltration rates, and to improve the hydraulic performance of irrigation furrow systems, infiltration rates need to be known and possibly predicted. Hence in this study, the infiltration process was studied by both the distribution of Kostiakov exponent a and temporal variation of the exponent throughout the seasons, as well as the applied volume per irrigation event. The distribution of Kostiakov exponent a into different classes reflects on the antecedent soil water content status.The temporal variation is mainly an effect of irrigation schedule regime.

Differences in cumulative infiltration for the different treatments give information on infiltration process as affected by different irrigation schedules. Cumulative infiltration along the furrow length was obtained using Kostiakov model (Equation 1) and opportunity time at each point along the furrow length. This was obtained from the Kostiakov infiltration parameters a and k using the computer software sirmod (Walker & Skogerboe, 1999).

3.11 Performance measures of irrigation efficiency and uniformity

Quantifying infiltration is necessary to predict irrigation system performance (Eisenhauer, Heermann, 1992). A key factor in the evaluation of irrigation is uniformity. Another important consideration is how adequately crop water needs are met. It has been demonstrated that uniformity of water application has an effect on crop yields (Solomon, 1985). A relatively complete description of irrigation effectiveness and the water application is attained if the frequency distribution is known. To that end, the following parameters were used to analyse the performance of the irrigation events as affected by irrigation regimes:

1. Application efficiency;
2. Requirement efficiency; and
3. Distribution efficiency.

Application efficiency

Application efficiency (AE), equation 35, is related to the amount of water delivered, the intake characteristics of the soil and the rate of advance of water over the soil surface. It is estimated as:

$$AE = \left(\frac{Volume \quad stored \quad in \quad the \quad root \quad zone}{Total \quad volume \quad of \quad flow} \right) x\ 100 \qquad \cdots 35$$

Distribution uniformity

Distribution uniformity (DU), equation 36, like application efficiency, was computed for all irrigation events and for the two seasons. The definition of the distribution uniformity used in this work was the one proposed by Burt (1997). It was defined as the uniformity with which irrigation water is distributed to different areas in a field. The ratio of the two extreme average depths, one based on the extreme value (low quarter) and the other on the other based on all the values.

$$DU = \left(\frac{Average \quad depth \quad in \quad the \quad least \quad quarter}{Average \quad depth} \right) x\ 100 \qquad \cdots 36$$

Requirement efficiency

Requirement efficiency (RE), equation 37, relates to the amount of water delivered to the rooting zone of a crop to the amount required to that zone in an irrigation event.

$$RE = \left(\frac{Volume \quad stored \quad in \quad the \quad root \quad zone}{Volume \quad required} \right) x\ 100 \qquad \cdots 37$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of soil water on antecedent parameters of the infiltration equations

In the case of the Ubombo schedule (T_1) the Kostiakov exponent *a* tended towards unity for a majority of irrigation events especially in the first season (Table 4). The Kostiakov exponent was clustered between 0.2 and 0.6 for the 0.75 (T_4) and 1.00 x PM (T_3) treatments, in both seasons. The alternate inter-row irrigation using the Ubombo schedule (T_5, 2000) in plant cane also had its distribution skewed toward unity whilst the alternate inter-row irrigation using 1.00 x PM (T_5,2001) in ratoon cane had a distribution clustered around 0.4 to 0.6. These findings are in agreement with those of Maheshwari and Jawardane (1988) and Hume (1993) who reported that variation in the value of infiltration parameters depend largely on soil water content before irrigation. Infiltration variables have been shown to vary with soil water content prior to irrigation. At higher soil water contents, the capacity of the soil to absorb water is reduced (Mailhol *et al.*, 1999), and the effect of the initial soil water content is reflected in the values of the constant of the adopted infiltration model. For the Kostiakov and the extended Kostiakov equations, the values of infiltration parameters, *a* and *k*, increase and decrease, respectively, as the soil water content increases (Maheshwari *et al*, 1988). Antecendent soil water content is an important factor affecting infiltration, and the effect of initial soil water content was studied by comparing the distribution of the Kostiakov exponent, *a*, between the irrigation schedules. The value of exponent *a* depends on the initial soil water content. Low values of Kostiakov infiltration exponent *a* indicate low initial soil water content, and high values of the exponent will result where the initial soil water content is high.

The variation in the distribution of the Kostiakov exponent *a* amongst the different schedules can be attributed to irrigation scheduling. Frequent irrigation prevents the development of a suction gradient, as soil water is consistently maintained at high levels (Figure 10a). The decrease in infiltration rate on soils with an initial high water content is principally due to a decreased matric potential gradient between the wetting front and the underlying soil. This is otherwise a dominant component on an initially dry soil under furrow irrigation systems, where the infiltration is essentially two-dimensional. In the early stages of an irrigation event, suction gradient can be as significant as gravitational gradient especially on an initially dry soil under furrow irrigation systems (Fonteh and Podmore, 1993). Mailhol *et al.*, (1999) also reported that at higher soil water contents, the capillarity capacity of the soil to absorb water is reduced. Infiltration from a furrow also occurs around the wetted perimeter, which means that a significant portion of the total infiltration moves laterally through the sides of the furrow rather than vertically downward (Samani *et al.*, 1985; Strelkolf & Souza, 1984). Assuming that infiltration rate at the bottom of the furrow is not significantly affected by changing water levels, an increase in infiltration must occur by an increase in the wetted perimeter. Apparently, infiltration along the sides of the furrow and the increase in soil water pressure gradient across the seal can considerably compensate for the decreasing conductivity of the furrow bottom.

On the other hand, with treatments like 0.75 x PM (T_4) (Figure 10 d), which are usually drier at the soil surface before irrigation, as irrigation is withheld for an extended period, the hydraulic gradient increases as the soil water is depleted and the effect of the initial soil water content is thus reflected in the values of the parameters *a* and *k* of the Kostiakov infiltration model upon irrigation. Under such circumstances, the Kostiakov infiltration exponent *a* tended to cluster between 0.4 to 0.6 (Table 4).

The distribution of Kostiakov component *a* of the drier treatments, 0.75 x PM (T_4) and alternate inter-row irrigation using 1.00 x PM (T_5), was surprisingly not clustered around zero. This could be attributed to irrigation being due normally when the crop had just, or was about to, exhaust the freely available water in the profile (Figures 10 d and 10i). The irrigation schedules, by their nature, did not permit the crop to deplete soil water beyond the readily available range (less than -100kPa) and under such circumstances the infiltration exponent tended to be between 0.4 to 0.6. With the Kostiakov exponent *a* varying between 0.4 to 0.6, and not significantly different from 0.5, this exponent can be fixed at 0.5 with minimal error introduced, and subsequently the infiltration model be interpreted physically using Philip's infiltration model (Hartley, 1992).

Table 4 Class distribution frequency (%) of the Kostiakov exponent *a* among different deficit schedules based on the Ubombo system or Penman-Monteith evapotranspiration factors.

Irrigation schedule	Season									
	1999/2000					2000/2001				
	Class limits of exponent "*a*"(%)					Class limits of exponent "*a*"(%)				
	< 0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	< 0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
Ubombo schedule	4.6	4.5	18.2	29.6	43.2	17.9	32.5	11.4	6.5	31.8
1.25 x Penman-Monteith	7.5	2.00	21.0	31.3	38.3	15.0	24.3	18.8	11.2	30.7
1.00 x Penman- Monteith	9.09	11.4	43.2	18.2	18.2	3.9	42.3	25	7.7	21.2
0.75 x Penman – Monteith	15.2	30.3	27.3	15.2	12.1	11.4	37.2	45.7	8.6	8.6
Alternate inter- row irrigation[1]	9.8	9.8	31.7	24.4	24.4	14.6	45.8	20.8	10.4	8.3

[1] scheduled according to Ubombo system in the 1st season and 1.00 x PM in the 2nd

Generally, the distribution of the infiltration exponent *a* particularly for the Ubombo schedule (T_1) was more skewed towards 1.0 in the first season than in the second (Table 4). This means that the soil conditions were slightly drier in the second season than in the first, and that agrees well with the tensiometer data (Figures 10a and 10b). The explanation is that it could have been a result of a better-developed canopy and root system in the ratoon than in the plant cane, hence leading to higher water uptake. Nixon (1992) reported that first ratoon crops have a more extensive root system than that of plant cane. This, in turn, might have lead to overestimation of Et for the plant crop hence the reason for overirrigation. For the other treatments, the light rainfall events that were regularly received in the first season could have kept the soil surface slightly wet, thus altering the infiltration processes. With this treatment, the tensiometer readings, for Ubombo schedule (T_1) just prior to irrigation in the first season, would range from –55 to –75 kPa; -50 to -65 kPa; and –8 to –12 kPa at 0.15 m; 0.30 m, and 0.45 m soil depth respectively. Likewise, 0.75 x PM was irrigated when the soil water content was greater than 50% DPAW. In this treatment, tensiometer readings nearly always showed a higher matric potential than –80 kPa at both 0.15 m and 0.30 m soil depths, and –75 kPa at 0.45 m depth. Further examination of the tensiometer data suggested that irrigation scheduling determined the preferential depth of water uptake by the crop.

When the antecedent soil water content is higher than that assumed for design, the rate of advance will be faster and the average infiltrated depth will be less than the design would specify. High soil matric water potential, as previously alluded to, as it was the case with the Ubombo schedule, leads to rapid advance towards the downstream end of the field with the water having little time to infiltrate (Figures 10a and 11). Again, the amount of water applied per unit length is small compared to the other treatments, which were drier than Ubombo.

Assessment of the impact of the different irrigation scheduling regimes was conducted by looking at the performance of the irrigation systems (Figures 11 to 13). A typical scenario is exhibited when irrigating on wet soils (Figure 11). This was typical with soils irrigated according to the schedules of Ubombo system, 1.25 x Penman Monteith, and alternate interrow irrigation using the Ubombo system. Water advances fast from the upstream to the downstream end of the furrows, and because in this case, closed end furrows is practiced, substantial amount of water ponds on the check dam at the downstream end of the furrow, resulting in over application at the furrow end. On the other hand, when irrigating on dry soils, the dryness of the soil retards water velocity and allows more rapid infiltration of water particularly at the upstream than downstream end of the field (Figure 13). This was the case with soils scheduled according to 0.75 x Penman-Monteith and alternate interrow irrigation using 1.00 x Penman-Monteith. Meanwhile, if the irrigation is conducted at optimal soil water conditions, a fairly uniformly water distribution can be achieved even though there could be slight under-application at the downstream end of the field (Figure 12). This was observed to be the case with soils irrigated according to the 1.00 x Penman-Monteith Et.

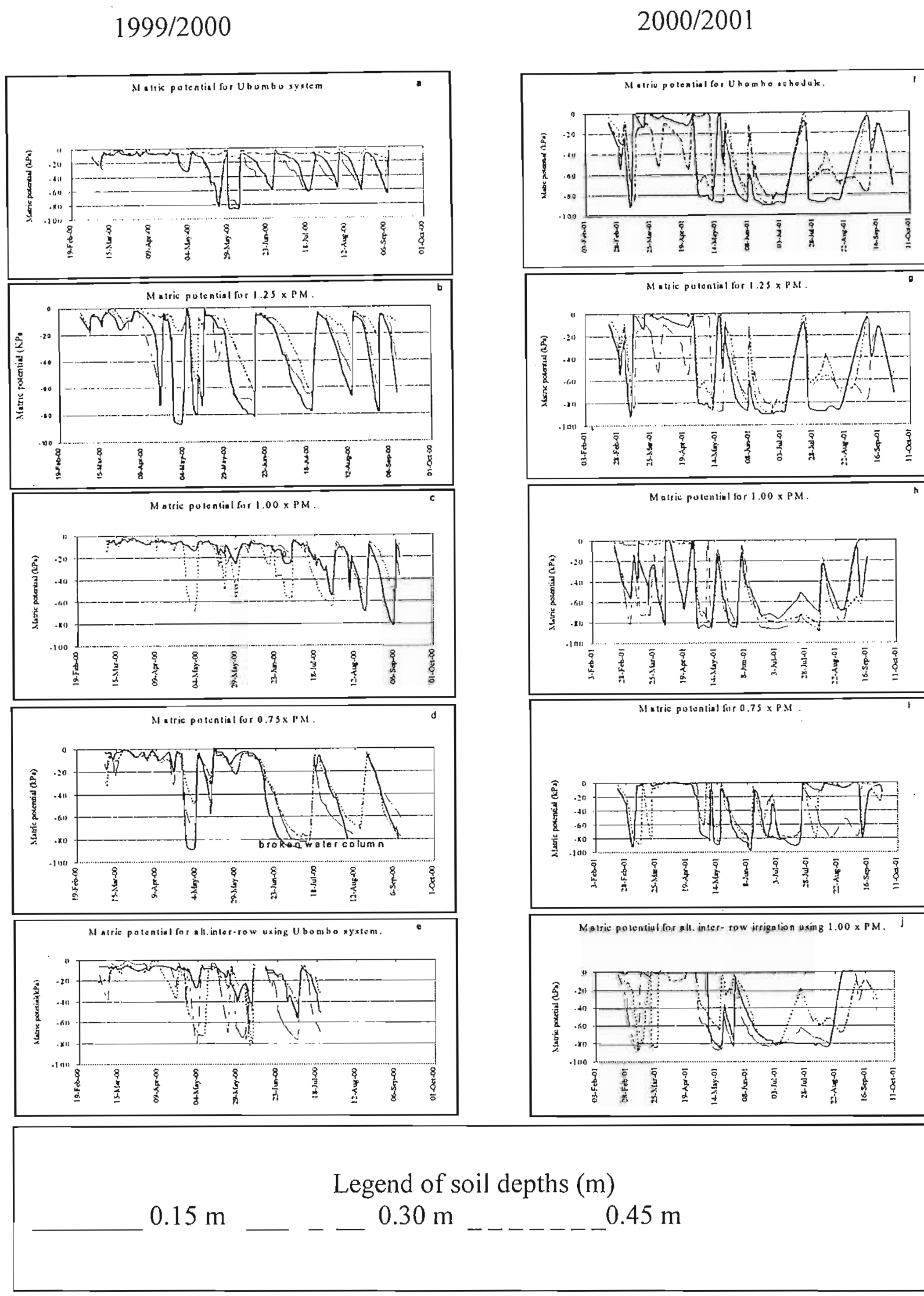


Figure 10 Effect of different deficit irrigation schedules in plant (1999/2000) and ratooon cane (2000/2001) on soil matric water potential measured at different soil depths using tensiometers.

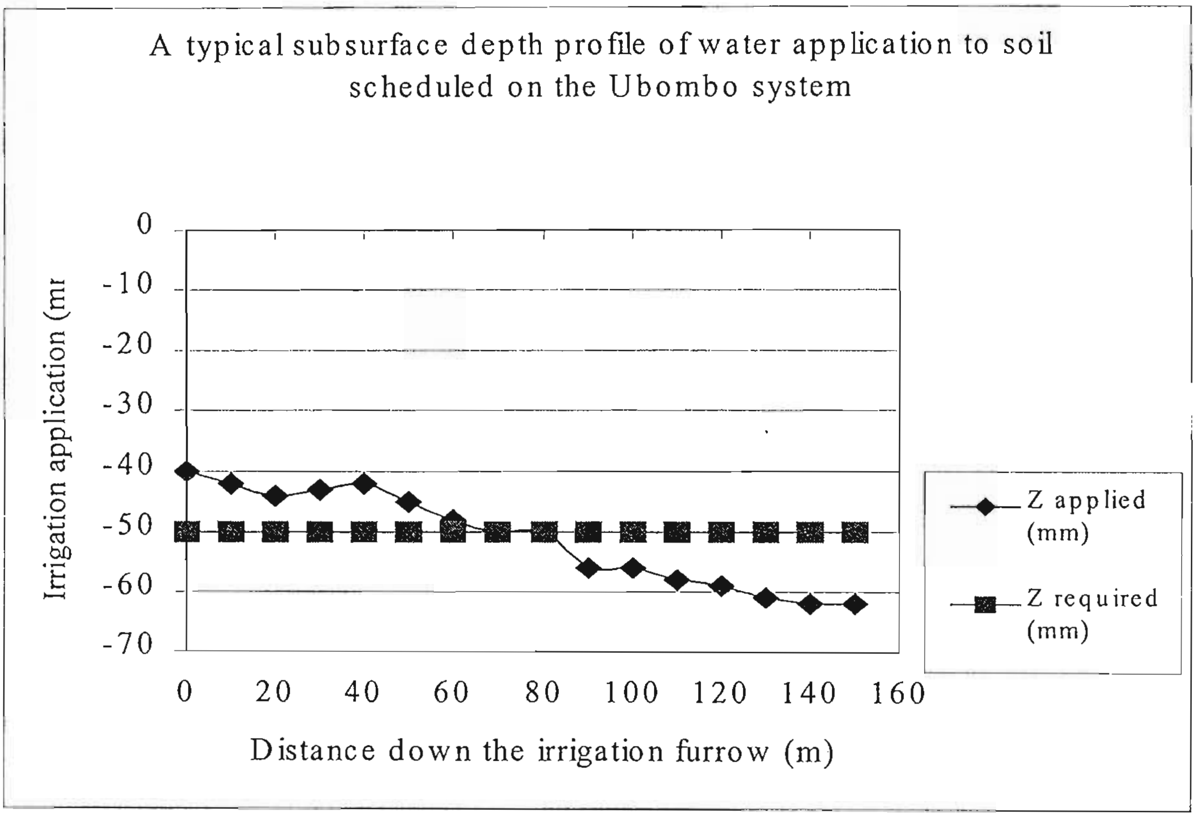


Figure 11 A typical subsurface depth profile of water application to soil scheduled for irrigation on the Ubombo system.

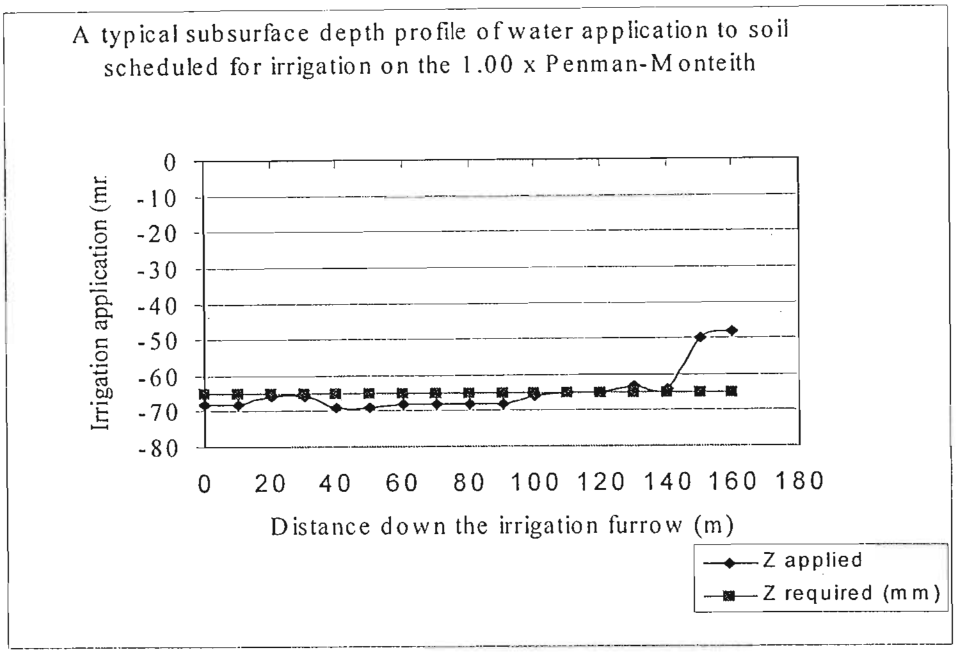


Figure 12 A typical subsurface depth profile of water application to soil scheduled for irrigation on the 1.00 x Penman- Monteith.

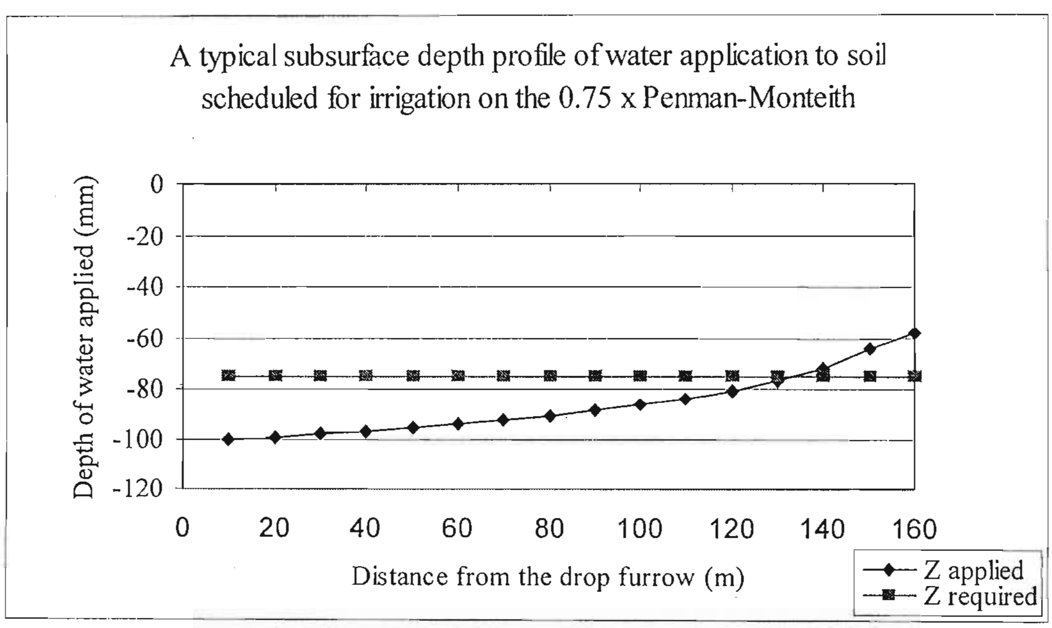


Figure 13 A typical subsurface depth profile of application to soil scheduled for irrigation on the for 0.75x Penman-Monteith

4.2 Cumulative infiltration

In furrow irrigation systems, the soil serves two purposes: a) infiltration and b) water conveyance from the upstream to the downstream end of a field. High frequency irrigation keeps the soil water levels high, and during irrigation, the conveyance component dominates the infiltration process. Consequently, the water front advances relatively fast leading to less water applied per irrigation event. However, in cases where irrigation is delayed for an extended time, the infiltration component tends to dominate over the conveyance. In turn, the water-front usually advances rather slowly leading to higher amounts of water being applied per unit length per irrigation event. The Ubombo system (T_1), which produced a frequent irrigation schedule (Figures 10a and f), typified the former, resulting in reduced water amount applied per unit row length per irrigation event as opposed to the 0.75 x PM (T_4) and alternate row irrigation using 1x 00 PM ($T_{5,}$2001), (Table 5), (Figures 10d, i and j) which resulted in comparatively higher amounts of water applied per unit row length per irrigation event (Table 5). A typical Ubombo (T_1) schedule was found to apply between 35 and 45 mm, yet about 48 to 52 mm would be applied in the 1.25 x PM (T_2) (Table 5). In the 1.00 x PM (T_3), about 58 - 65 mm would be applied and 85 - 92 mm was applied on the 0.75 x PM (T_4). The alternate row irrigation using 1.00 x PM ($T_{5,\,2001}$) would apply around 100 mm.

The differences in cumulative infiltration between alternate inter-row irrigation using 1.00 x PM (T_5, 2001) and every inter- row 1.00 x PM (T_2) schedules demonstrate the influence of a dry adjacent furrow as compared to adjacent water filled furrows (Figures 10c, h and j; Table 5). The differences in cumulative infiltration gave information on the significance of lateral water movement near the soil surface. Thus, the data suggest that with an alternate inter-row irrigation using 1.00 x PM (T_5), lateral flow remains significant for an extended time, and subsequently the rate of advance is slow, taking a long time before the wetting front in a horizontal direction is midway between the two wet furrows (Table 5). This is in contrast to the observation of alternate inter-row irrigation using Ubombo schedule (T_5), where water filled furrows bordered by a dry or wet furrow had little effect on infiltration indicating that

Table 5 A typical average infiltrated depth amongst different deficit schedules based on the Ubombo system or Penman- Monteith evapotranspiration factors for plant (1999/2000) and ratoon (2000/2001) sugarcane.

Irrigation schedule	Targeted and applied irrigation	1999/2000			2000/2001		
		Early season (mm)	Mid season (mm)	Late season (mm)	Early season (mm)	Mid season (mm)	Late season (mm)
Ubombo schedule	applied	45	35	36	46	37	33
	required	50	50	50	50	50	50
1.25 x Penman-Monteith	applied	52	54	48	56	47	51
	required	55	55	55	55	55	55
1.00 x Penman-Monteith	applied	65	63	66	61	58	62
	required	60	60	60	60	60	60
0.75 x Penman-Monteith	applied	85	90	80	90	92	87
	required	75	75	75	75	75	75
Alternate inter-row irrigation[1]	applied	50	55	53	110	103	97.2
	required	60	60	60	80	80	80

[1] scheduled according to Ubombo system in the 1st season and 1.00 x PM in the 2 nd

lateral water movement is not significant in soils with an initial high water content. The matric potential gradient in initially dry soils drives the increase in infiltration as well as lateral spread of water.

Differences in cumulative infiltration for the different treatments gave information on infiltration process as affected by different irrigation schedules. A comparison of cumulative infiltration shows, as expected, that less water is applied per unit length in wet soils and, in contrast, with dry soil, water applied per unit length increases as the soil moisture decreases.

The data also suggested temporal changes in the mechanism of water entry. Generally, early in the season, irrigation events were characterised by low a exponents and consequently deeper application levels of water, later in the season, higher exponents and lower amount of water infiltration was observed (Figure 14). The low a exponents early in the season could be attributed to many factors, but the most conspicuous one is land preparation. Immediately after cultivation (Maihol *et al.*, 1999) as was the case in the plant cane, or ripping (Childs *et al.*, 1992), as was the case for the first ratoon, the open structure of the soil retards water velocity and allows rapid infiltration of water. Later when the aggregates on the perimeter of the furrow have disintegrated, the infiltration rate could only be a fraction of what it was during the initial stages of the first irrigation (Zehurin *et al.*, 1997). Childs *et al.*, (1992) reported that it is a common observation for infiltration to decrease dramatically after the first irrigation, the silt particles may clog the soil pores and homogenise the soil surface, which supports such an observation. Soil capillarity decreases right from the first irrigation event to the next during the same season. This could in part explain the temporal variation of infiltration exponents. Generally, there was a reduction in the infiltration function from one irrigation to another during any of the irrigation seasons; also, there was a reduction in the infiltration function from one season to the next. Such findings were consistent with those of Maihol *et al.*, (1999) who reported that infiltration properties might vary from one irrigation event to the next even in similar soil water conditions. Collis-George (1977), Zerihun *et al.*, (1984) and Elliot & Walker (1982) attributed variation of infiltration from one event to another even on soils with similar soil water contents to soil structural changes induced by wetting and drying cycles.

The declining infiltration functions may be attributed to many factors including soil compaction caused by farm machinery, soil sealing due to heavy sediment loads in the irrigation water, and climatic factors. Soil cracking, on the other hand, enhances soil infiltration, and as a result, some workers have found no evident trend in seasonal variation of infiltration properties (Clemmens, 1983). The different reports by different workers could mainly be because of soil types on which the experiments were conducted. Vertisols, for example, crack immensely when dry because of their montmorillonite, resulting in an initially high infiltration rate, but upon swelling the infiltration rate is dramatically reduced. When the furrow is rough, the velocity of the flow is retarded and generally, the depth of water in the furrow will increase. The increased stem diameter and higher plant population did not seem to have an effect on the water applied per unit length in this study.

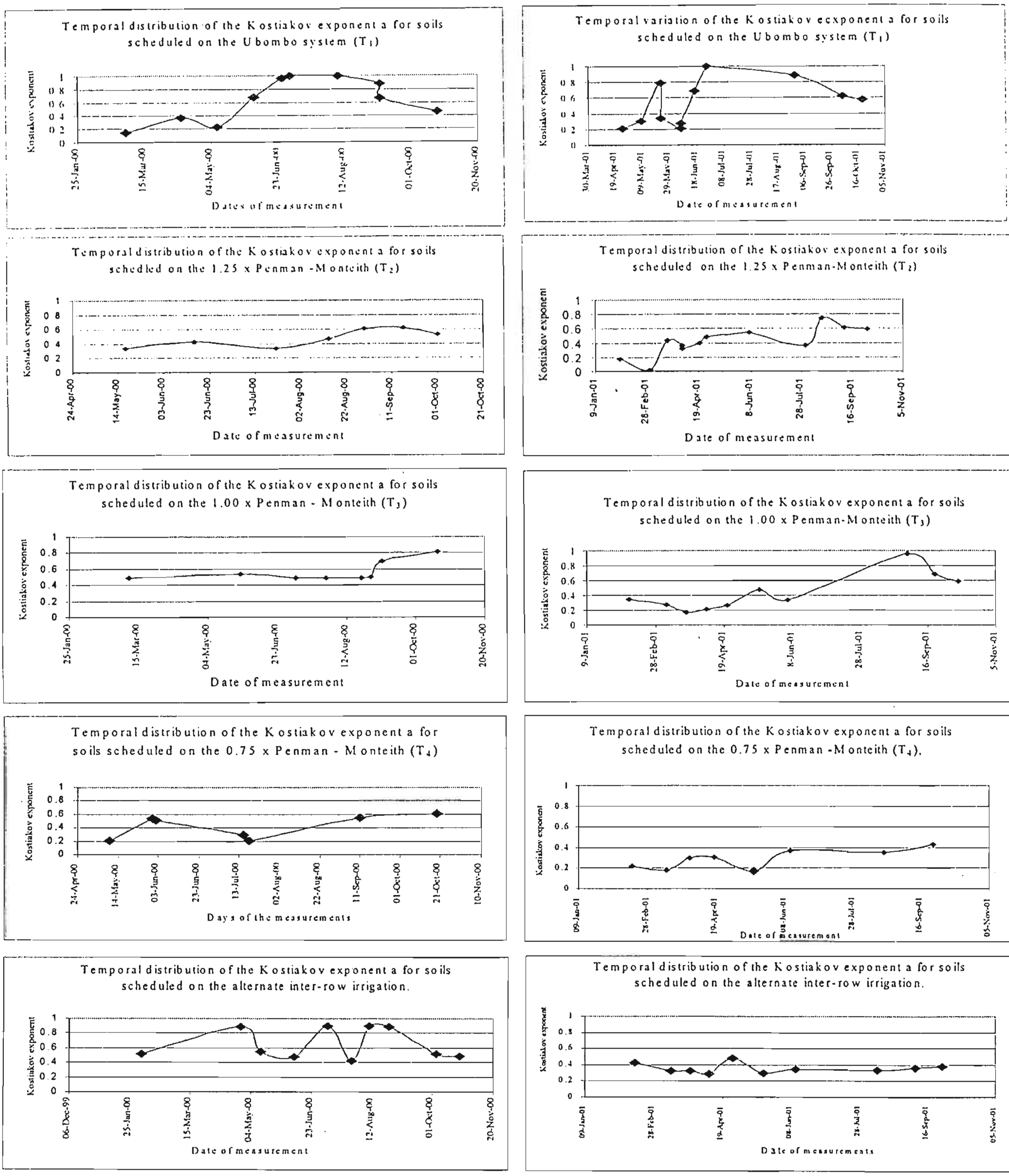


Figure 14 Effect of irrigation scheduling based on Ubombo or Penman-Monteith evapotranspiration factors on temporal variation of Kostiakov exponents.

4.3 Irrigation performance

The Ubombo system (T_1) and the 1.25x PM (T_2) generally had higher application efficiency, distribution uniformity as well as the requirement efficiency than the 1.00 x PM (T_3), 0.75 x PM (T_4) and alternate inter-row irrigation using the 1.00x PM (T_5). The irrigation indices indicated that the performance of the Ubombo system (T_1) and the 1.25x PM (T_2) irrigation schedules were satisfactory, yielding well above 80% efficiency (Tables 6 and 7). The 0.75 x PM (T_4) and the alternate inter-row irrigation using 1.00 x PM (T_5), on the other hand, recorded satisfactory levels of application efficiency and often low levels of distribution and requirement efficiencies (Tables 8 and 9). The observed differences can be explained in terms of the proportion of soil infiltration to water conveyance during irrigation events. With the former (T_1 and T_2), the conveyance component dominated, resulting in water moving fast from the upstream to the downstream end of the field. This resulted in almost equal intake opportunity time along the furrow length, and subsequently a uniform subsurface distribution of water. Whereas with the latter (T_3, T_4 and $T_{5,\ 2001}$), the soil infiltration process predominated, and higher amounts of water were applied on the upstream than the downstream end of the field. This led to disproportionate distribution of water at the upper end of the furrow (Figure 13) and lower requirement efficiencies (Tables 8, 9, 10).

Table 6 Irrigation performance efficiency and uniformity indices for the Ubombo (T_1) schedule.

Seasonal Irrigation events	1999/2000			2000/2001		
	Application Efficiency (%)	Requirement Efficiency (%)	Distribution uniformity (%)	Application Efficiency (%)	Requirement Efficiency (%)	Distribution Uniformity (%)
Early-season	92	89	84	90	95	84
Mid-season	83	95	83	88	94	83
Late season	80	95	77	87	93	77
Seasonal mean	85	93	81	88	94	81

Table 7 Irrigation performance efficiency and uniformity indices for a 1.25 x Penman-Monteith (T_2) schedule.

Seasonal irrigation events	1999/2000			2000/2001		
	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)
Early season	90	90	87	89	85	89
Mid-season	85	94	89	86	91	87
Late-season	88	96	82	83	93	83
Seasonal mean	87	93	86	86	89	86

Table 8 Irrigation performance efficiency and uniformity indices for a 1.00 x Penman-Monteith (T_3) schedule.

Seasonal irrigation events	1999/2000			2000/2001		
	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)
Early season	81	98	94	88	91	87
Mid-season	75	97	92	75	85	95
Late-season	80	79	98	87	84	97
Seasonal mean	78	91	94	83	86	93

Table 9 Irrigation performance efficiency and uniformity indices for a 0.75 x Penman-Monteith (T_4) schedule.

Seasonal irrigation events	1999/2000			2000/2001		
	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)
Early- season	97	95	82	98	70	70
Mid -season	95	95	92	98	86	88
Late season	90	95	75	95	85	82
Seasonal means	94	95	83	97	80	80

Table 10 Irrigation performance efficiency and uniformity indices for an alternate row irrigation scheduled according to Ubombo system ($T_{5,\ 2000}$).

Seasonal irrigation events	1999/2000		
	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)
Early season	98	95	82
Mid-season	95	96	63
Late season	81	95	69
Seasonal means	91	95	72

Table 11 Irrigation performance efficiency and uniformity indices for an alternate row irrigation scheduled according to 1.00 x Penman Monteith ($T_{5\ 2001}$).

Seasonal irrigation events	2000/2001		
	Application efficiency (%)	Requirement efficiency (%)	Distribution Uniformity (%)
Early season	98	70	75
Mid-season	97	86	75
Late season	91	95	69
Seasonal means	95	84	73

The Ubombo schedule had consistently higher application efficiencies and variable distribution uniformity. The requirement efficiency was reasonably high (Table 6). In some cases, the distribution uniformity was unexpectedly low. This was a result of the closed end furrow system, and water ponds at the downstream end of the furrow (Figure 11). It was mainly a result of late closing of water being led into the furrow and not the schedule as such.

When the antecedent soil water content is higher than that assumed for design, the rate of advance will be faster and the average infiltrated depth will be less than the design specification. This in a way inflates the application efficiency, as was the case with the Ubombo schedule (Table 6). Conversely, when the antecedent soil water content is lower than that assumed for design or management, the rate of water advance along the furrow length will be slow. This will result in a disproportionately higher infiltration volume applied at the upstream than at the downstream end of the furrow. Subsequently, there would be a lower distribution uniformity even if the application efficiency were to be high, as was the case with the Penman-Monteith evapotranspiration factors of 0.75 and 1.0 (Tables 8 and 9). Though the requirement efficiency or adequacy might be high, the crop at the downstream end of the field might suffer from water stress as a result of the disproportionate distribution of water. At the upstream, because of the extended period of opportunity time, there is deep percolation that reduces the application efficiency (Figure 13).

The 1.00 x Penman-Monteith treatment had lower application efficiency as compared to the Ubombo schedule yet a higher requirement efficiency and higher distribution uniformity (Table 8). Irrigation requirement, also known as adequacy, is defined as the percentage of the root zone throughout the field which is restored to field capacity during an irrigation event. Higher requirement efficiency, 100%, is generally not possible without incurring substantial losses (English *et al.*, 1990). In order to meet crop water needs, most fields are irrigated to an adequacy level of 75 - 87.5 % (English *et al.*, 1990).

To achieve the same level of irrigation adequacy in drier treatments such as the 1.00 x Penman- Monteith and 0.75 x Penman-Monteith, more water is needed, which also results in higher application at the upstream end of the field, and that is reflected by the low application efficiency. This can be resolved by having a higher inflow rate that will subsequently lead to higher advance rate.

The 0.75 x Penman–Monteith treatment had a comparatively low distribution uniformity and a low requirement efficiency. The application efficiency was typically high (Table 9). This is because of many reasons; the low antecedent soil moisture resulted in slow water advance down the furrow length, as did the comparatively higher roughness of the channel bed,due mainly to few irrigation events. These factors lead to higher water application per unit length upstream and less water application down the furrow length because of little intake opportunity time at the downstream end of the field. The requirement efficiency or adequacy was satisfied in most irrigation events (Table 9).

Upon successful evaluation of a surface irrigation system, it is possible to identify modifications that will enhance hydraulic performance. These include determining whether there is over-irrigation or under-irrigation, the distribution of infiltrated water over the length of the furrow, and the level of irrigation adequacy.

For the Ubombo schedule (T_1) where the velocity of flow was found to be high, it is suggested that the discharge be reduced such that the water advances more slowly. In the drier treatments, on the other hand, to reduce higher application of water at the upstream end of the field, discharge can be increased so that the flow of water velocity is also increased. The high velocity of flow, however, should not be such to lead to soil erosion. High flow rates minimises deep percolation upstream and also minimises the time of advance and thereby the variation in opportunity time along the field length, so a more uniform depth of water is applied if the soil is uniform along the field length.

4.4 Sugarcane growth measurements

Different irrigation deficit schedules did not have an effect on the growth parameters: stalk height, stalk population and number of internodes (Figure 15). Stalk population development followed the typical pattern for sugarcane, reaching a peak between three to four months, and thereafter declining due to stalk mortality caused by the shading out of weaker tillers, as the stalks compete for resources such as space and light. The over-tillering of sugarcane in the first four months is characteristic of sugarcane (Boyce, 1970; Durandt, 1978). The spatial variability of crop growth, yield and water stress has been addressed in several works dealing with surface irrigation. Warrick (1983), working on crop yield as affected by spatial variations of soil and irrigation, concluded that irrigation uniformity is the most important factor, especially for surface systems. Other workers including Letey *et al.*, (1985) and Solomon, (1985) have demonstrated that uniformity of application of irrigation water has a profound influence on crop yields. Variation in opportunity times caused by differences in advance and recession curves, and variation in soil infiltration properties significantly affect irrigation uniformity (Clemmens, 1988). The latter aspect in this experiment is not likely to feature, as the field had homogenous soil down the furrow length as indicated by the soil map (Figure 5). Spatial variability of sugarcane growth manifested itself by showing two slopes: furrow, down the cane rows; and cross-furrow, down the field length in the direction of the header canal. From the upstream to downstream ends of the field in the direction of the header canal, all the growth variables decreased with increase in distance downslope. In the inter- furrow direction moving down-slope, on the other hand, growth variables increased with an increase in distance. At the upstream end, there is the step down canal and the proximity of the cane to the step down canal could be one reason for the observed variation (Appendix 3). In the field length (header canal) direction the soil type in the field changes from a shallow to a deeper soil. Deeper soils can support and sustain crops better than shallow soils mainly because of water and nutrient retention factors and therefore buffer some variances caused by lack of uniformity in irrigation.

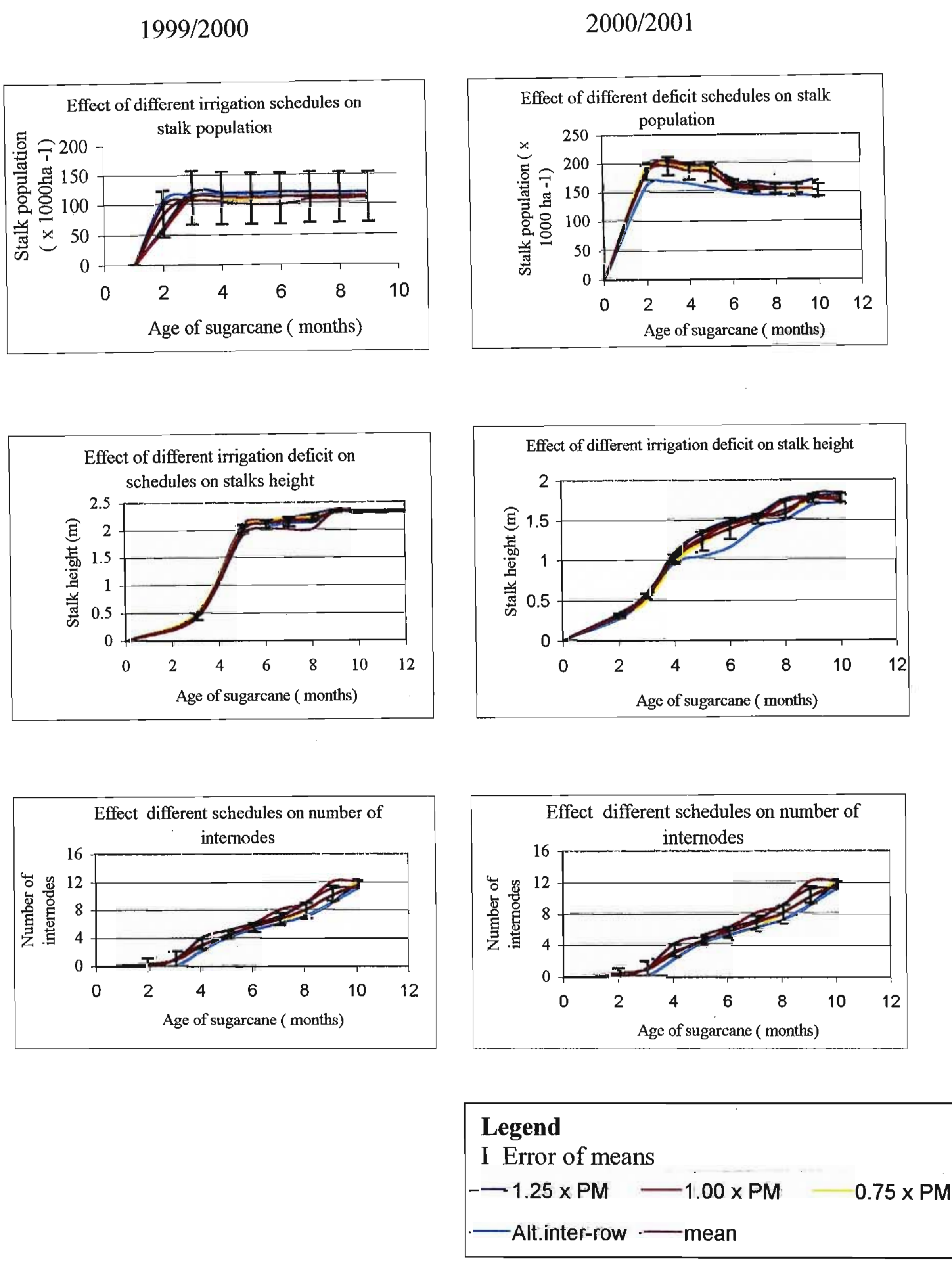


Figure 15 Effect of irrigation scheduling based on the Ubombo or Penman-Monteith evapotranspiration factors on the number of internodes, stalk height and stalk population cane (1999/2000) and first ratoon cane (2000/2001).

4.5 Sugarcane yield and quality

There were no significant differences in yield between any of the treatments either in the plant or the ratoon crops (Table 12, Appendix 2.1 to 2.12). The plant crop consistently recorded higher sugarcane yields than that of the first ratoon in all the treatments, however the plant crop consistently yielded lower sucrose than the first ratoon. Ubombo scheduling (T_1) recorded the highest sugarcane yield in both seasons at 84 t cane ha^{-1} for the plant and 82 t cane ha^{-1} for the first ratoon crop. The 0.75 x PM (T_4), on the other hand, recorded the lowest yield in both seasons at 77 t cane ha^{-1} and 74 t cane ha^{-1} for the plant and first ratoon respectively. The plant cane was not ripened whilst the first ratoon crop was ripened with fusilade (0.35litres/hectare) five weeks before harvesting, which explains the higher sucrose percent cane in the 2000/2001 ratoon crop (Table 13, Appendix 2.1 to 2.12). In the first season, cane grown on the relatively drier irrigation schedules, 0.75 x PM (T_4) and 1.00 x PM (T_3) recorded the highest sucrose percentages. The 0.75 x PM (T_4) had 14.4 % sucrose in the plant cane followed by the 1.00 x PM (T_3) with 14.1 % sucrose. In the second season, the relatively wet irrigation schedules, 1.25 x PM (T_2) and Ubombo scheduling (T_1), had the highest sucrose %. The 1.25 x PM (T_2) recorded 15.6 % sucrose followed by Ubombo schedule (T_1) with 15.4 % sucrose. The data suggest that water stress led to higher sucrose accumulation if the sugarcane was not ripened. However the frequently irrigated sugarcane crop (1.25 x PM, T_2 and Ubombo schedule, T_1), benefited tremendously from ripening. The analyses again reflect a replication effect on % sucrose in 2000/2001. This phenomenon corresponds well with the soil type. It can be said that moving from replication one to four, the soil depth relatively changes from shallow to deep and this further affirms the observation that increasing stress increases sucrose % cane (Table 14). The high moisture content of the 1.00 x Penman-Monteith (T_3) in treatment 2000/2001 season was unexpected as was the subsequently lower % purity. This could be attributed to that it being the last treatment to go for dry-off, and as a result it might have had insufficient drying-off period as compared to the other treatments.

The lack of significant differences in yield between the treatments can be attributed to the crop not being subjected to water stress beyond the readily available water range (<-100 kPa) in any of the treatments. Although, there were no significant differences between the yields amongst the treatments, increasing the irrigation interval led to a reduction in yield corresponding to a decrease in ET. In the affected treatments, actual ET declined below the potential and became soil moisture dependent thus causing a decrease in yield with the increase in irrigation interval. This was observed in the driest treatment, 0.75 x Penman-Monteith, where water column in tensiometers would break for days before the following irrigation was due (Figures 10d and i).

Table 12 Effect of irrigation scheduling based on the Ubombo or Penman-Monteith evapotranspiration factors on sugarcane yield, sucrose percent and sucrose yield produced in the plant (1999/2000) and ratoon (2000/2001) sugarcane crops.

Irrigation schedule	**Season**						**mean**	
	1999/2000			**2000/2001**				
	Cane yield (t ha^{-1})	sucrose (%)	Sucrose yield (t ha^{-1})	cane yield (t ha^{-1})	Sucrose (%)	sucrose yield (t ha^{-1})	cane yield (t ha^{-1})	sucrose yield (t ha^{-1})
Ubombo schedule	84.6	13.66	11.6	81.3	15.40	12.5	82.95	12.0
1.25 x Penman-Monteith	82	13.35	10.9	81.3	15.63	12.7	81.65	11.8
1.00 x Penman-Monteith	80.1	14.09	11.3	78.3	15.33	12.0	77.3	11.4
0.75 x Penman-Monteith	77.3	14.39	11.1	74.3	15.31	11.4	81.45	11.4
Alternate inter-row irrigation[1]	83.8	13.58	11.4	77.0	15.16	11.7		
$LSD_{p=0.05}$	NS	NS	NS	NS	NS	NS		

[1] scheduled according to Ubombo system in the 1st season and 1.00 x PM in 2nd

The analyses reflected a replication effect on % sucrose in both seasons and yield In 2000/2001. This seemed to correspond with the soil sets (Figure 5) and the growth measurements (Appendix 3). Increasing stress increases % sucrose, that is , down the length of the field, the soil type in the field changed from a shallow to a deeper soil. Deeper soils can support and sustain crops better than shallow soils mainly because of water and nutrient retention factors.

Table 13 Effect of irrigation scheduling based on the Ubombo or Penman–Monteith evapotranspiration factors on sugar quality produced in the plant (1999/2000) and ratoon (2000/2001) on sugarcane crops.

	1999/2000			2000/2001			Mean		
Treatments	Purity (%)	Moisture (%)	Sucrose (%)	Purity (%)	Moisture (%)	Sucrose (%)	Purity (%)	Moisture (%)	Sucrose (%)
Ubombo schedule	88.5	69.6	13.7	86.4	68.6	15.4	87.5	69.1	14.6
1.25 x Penman-Monteith	88.0	70.1	13.4	88.5	68.7	15.6	88.3	69.4	14.5
1.00 x Penman-Monteith	91.0	69.8	14.1	85.4	70.5	15.3	88.2	70.2	14.7
0.75 x Penman –Monteith	88.0	69.5	14.4	88.3	68.6	15.3	88.2	69.1	14.9
Alternate inter-row irrigation[1]	86.1	69.5	13.6	88.7	68.9	15.2			
$LSD_{p\ 0.05}$	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1] scheduled according to Ubombo system in the 1st season and 1.00 x PM in the 2 nd

NS represents no significant differences between the treatments.

Table 14 Replicate effect of irrigation scheduling based on the Ubombo or Penman–Monteith on sugar quality produced in the plant (1999/2000) and ratoon (2000/2001) on sugarcane crops.

Treatments	1999/2000			2000/2001		
	Purity (%)	Moisture (%)	Sucrose (%)	Purity (%)	Moisture (%)	Sucrose (%)
Replicate 1	88.8	69.5	14.7	87.6	69.3	15.8
Replicate 2	87.6	69.9	13.5	88.3	69.2	15.4
Replicate 3	87.1	69.7	13.3	88.3	69.0	15.4
Replicate 4	89.9	69.8	13.8	86.2	68.9	15.0
$LSD_{p\,0.05}$	NS	NS	*	NS	NS	*

NS not significant; * significant $P < 0.05$

CHAPTER 5

CONCLUSION

In this study, it was established that effective management of furrow irrigation systems relies on detailed knowledge of infiltration characteristics. Without this information, it is very difficult to accurately judge a system's performance, application efficiency or distribution uniformity. Higher requirement efficiency, 100%, is generally not possible without incurring substantial losses in distribution uniformity (English *et al.*,1990). In order to meet crop water needs, most fields are irrigated to an adequacy level of 75-87.5 % (English *et al.*, 1990). To achieve the same level of irrigation adequacy in drier treatments such the 1.00 x Penman-Monteith and 0.75 x Penman- Monteith; more water is needed, which, at a constant water delivery rate also results in higher application at the upstream end of the field, and that is reflected by the low application efficiency. This can be resolved by having a higher inflow rate that will subsequently lead to higher advance rate thereby increasing distribution uniformity. The findings are consistent with those of English *et al.*, (1990) who reported that under soils with initial low soil water content, water infiltrating the soil will move more in a lateral than vertical direction, hence infiltration amounts will be greater and rates slower, reducing uniformity down the field.

Upon successful evaluation of furrow irrigation system in this study, it was possible to identify modifications that will enhance hydraulic performance. These include determining whether there is over or under - irrigation, the distribution of infiltrated water over the length of the furrow, and the level of irrigation adequacy. Where the velocity of flow was found to be high, for instance in the Ubombo schedule (T_1), it is suggested that the discharge into furrows be reduced such that the water advances more slowly. In the drier treatments, on the other hand, to reduce higher application of water at the upstream end of the field, discharge into furrows can be increased so that the flow of water velocity is also increased. The high velocity of flow, however, should not be high enough to lead to soil erosion. High flow rate minimises deep percolation upstream and also minimises the time of advance and thereby the variation in opportunity time along the field length, so a more uniform depth of water was applied, as the soil was uniform along the field length.

At 25 % of the production costs at Ubombo Sugar, irrigation is the single most costly practice in growing sugarcane. Consequently, there has been an increased and continuous effort towards improving management in all three of the irrigation systems. The greatest challenge to the management of irrigation is encountered in furrow irrigation. The soil and not the system hardware control infiltration in surface irrigation systems to a greater extent than in other systems. Soil infiltration characteristics are thus an extremely important soil parameter in the management of surface irrigation. Infact, optimal design and management of surface irrigation systems rely entirely on detailed knowledge of soil infiltration properties (Baustista & Wallender, 1993). Therefore, an insight into the infiltration process, and determining and possibly predicting infiltration in time and space remains a vital, and a first step in improving the management of furrow irrigation systems (Vogel and Hopmans, 1992; Shepard *et al.*, 1993). To this effect, a comprehensive description of infiltration into Sibaya soils under various levels of wetness seasonally has been achieved by this study.

Sugarcane production at Ubombo is fully irrigated, as the estate is located in the Swaziland Lowveld in a semi- arid climate. Thus, irrigation is a crucial and integral activity of sugarcane production. Under such conditions, economic sugarcane production requires large amount of water (2300mm Class A pan). However, water is a limiting factor in the production of sugarcane. As a result, efforts are made to conserve water and increase water use efficiency, either by reducing irrigation adequacy or by eliminating the least productive irrigations. Characterisation of the infiltration properties of the major flood irrigated soil type at Ubombo Sugar Company under different irrigation regimes should enhance the efficiency and profitability of sugarcane production on the estate.

The use of volume balance approach provided a simple, convenient and reliable technique of assessing and optimising the performance of irrigation systems, and in assessing the merits of different irrigation schedules. The validity of volume balance though needs to be ascertained in cracking and swelling soils and under fields with heterogeneous soil type, under sugarcane production.

The Kostiakov model was able to provide an insight to the infiltration process for the different schedules. The infiltration characteristics of the Sibaya soil series at the site was found to vary mainly with the initial soil water content. The values of infiltration parameters, *a* and *k*, increased and decreased respectively as the soil water content increased, which is in accordance to literature (Maheshwari & Jawardane, 1988; Hume, 1993; Mailhol *et al.*, 1999). One of the many great strengths of surface irrigation as shown in this study is that it is self-compensatory. Where irrigation was frequent, less amounts of water were applied per event as it was the case with the Ubombo schedule (T_1) than the 0.75 x PM (T_4), where large amounts of water were applied per irrigation event at a lower frequency. The result is that even when there is this great variation in soil conditions, that under a constant delivery rate into furrow, that irrigation efficiency and uniformity are greatly compromised. However, with slight modifications in adjusting delivery rates into the furrow, an extremely high level of irrigation efficiency and uniformity is attainable.

Due to the fact that some of the estate's furrow fields have vertisol, cracking and swelling soils, and yet the company's management is similar across different types, it is suggested that the kind of research conducted in this study be extended onto vertisol soils to determine the combined effect of cracking and initial soil water content on irrigation performance.

The different irrigation schedules did not subject any of the sugarcane crops in the various treatments of this study to severe stress beyond that of the readily available soil water and this could explain the statistically similar yields. Thus, under the studied irrigation regimes, the sugarcane crop did not reach a water stress threshold at which sugarcane growth and yield responded adversely to water stress.

LIST OF APPENDICES

3.8 at 9 months

3.9 at 10 months

Appendix 1 Ubombo irrigation schedule for sugarcane irrigated fields harvested in different months of the year.

		Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	ELTM (mm/day)	5	4	3	4	5	6	7	7	8	8	7	7
Month Harvested													
Apr	Canopy Factor	0.1 Har	0.2	0.3	0.5	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50
May	Canopy factor	1 .0	0.1Har	0.2	0.3	0.5	0.9	1.0	1.0	1.0	1.0	1.0	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50
Jun	Canopy Factor	1.0	1.0	0.1 Har	0.2	0.3	0.5	0.9	1.0	1.0	1.0	1.0	1.0
	Refill (%TAW)	1.0	40	40	40	40	50	50	50	50	50	50	50
Jul	Canopy Factor	1.0	1.0	1.0	0.1 Har	0.3	0.5	0.9	1.0	1.0	1.0	1.0	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50
Aug	Canopy Factor	1.0	1.0	1.0	1.0	0.2 Har	0.5	0.7	1.0	1.0	1.0	1.0	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50
Sep	Canopy Factor	1.0	1.0	1.0	1.0	1.0	0.3 Har	0.5	0.8	1.0	1.0	1.0	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50
Oct	Canopy Factor	1.0	1.0	1.0	1.0	1.0	1.0	0.3 Har	0.6	0.8	1.0	1.0	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50
Nov	Canopy Factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3 Har	0.6	0.8	1.0	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50
Dec	Canopy Factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3 Har	0.6	0.8	1.0
	Refill (%TAW)	50	40	40	40	40	50	50	50	50	50	50	50

Har – harvesting time, which is usually done at or near twelve months from ratooning.

Appendix 2 Analysis of variance tables for final harvest yield and quality variables

2.1 sugarcane yield (tonnes cane hectare^{-1}1999/2000).

Source	df	ss	ms	f	p
Replicates	3	274.7	91.6	1.82	0.198
Treatments	4	141.4	35.4	0.70	0.606
Error	12	605.3	50.4		
Total	19	1021.3			

2.2 sucrose yield (tonnes sucrose hectare^{-1}1999/2000) .

Source	df	ss	ms	f	p
Replicates	3	1.31	0.44	0.35	0.793
Treatments	4	1.58	0.40	0.31	0.863
Error	12	15.15	1.26		
Total	19	18.04			

2.3 sucrose (%, 1999/2000)

Source	df	ss	ms	f	p
Replicates	3	5.600	1.867	4.33	0.028
Treatments	4	2.776	0.694	1.61	0.235
Error	12	5.175	0.431		
Total	19	13.550			

2.4 brix (%, 1999/2000).

Source	df	ss	ms	f	p
Replicates	3	12.965	4.322	5.18	0.016
Treatments	4	3.974	0.993	1.19	0.364
Error	12	10.011	0.834		
Total	19	26.95			

2.5 purity (%, 1999/2000).

Source	df	ss	ms	f	p
Replicates	3	23.70	7.90	0.85	0.492
Treatments	4	50.58	12.64	1.36	0.303
Error	12	111.16	9.26		
Total	19	185.44			

2.6 moisture (%, 1999/2000).

Source	df	ss	ms	f	p
Replicates	3	0.300	0.100	0.13	0.943
Treatments	4	1.207	0.302	0.38	0.820
Error	12	9.582	0.799		
Total	19	11.089			

2.7 yield (tonnes cane hectare $^{-1}$ 2000/2001).

Source	df	ss	ms	f	p
Replicates	3	294.0	98.0	4.13	0.032
Treatments	4	141.8	35.4	1.49	0.265
Error	12	285.0	23.8		
Total	19	720.8			

2.8 sucrose (tonnes hectare $^{-1}$ 2000/2001).

Source	df	ss	ms	f	p
Replicates	3	2.510	0.837	0.85	0.491
Treatments	4	4.495	1.124	1.15	0.382
Error	12	11.765	0.980		
Total	19	18.771			

2.9 sucrose (%, 2000/2001).

Source	df	ss	ms	f	p
Replicates	3	1.454	0.485	3.29	0.058
Treatments	4	0.467	0.117	0.79	0.553
Error	12	1.770	0.147		
Total	19	3.691			

2.10 brix (%, 2000/2001).

Source	df	ss	ms	f	p
Replicates	3	1.406	0.469	1.43	0.284
Treatments	4	1.864	0.466	1.42	0.287
Error	12	3.947	0.329		
Total	19	7.217			

2.11 purity (%, 2000/2001).

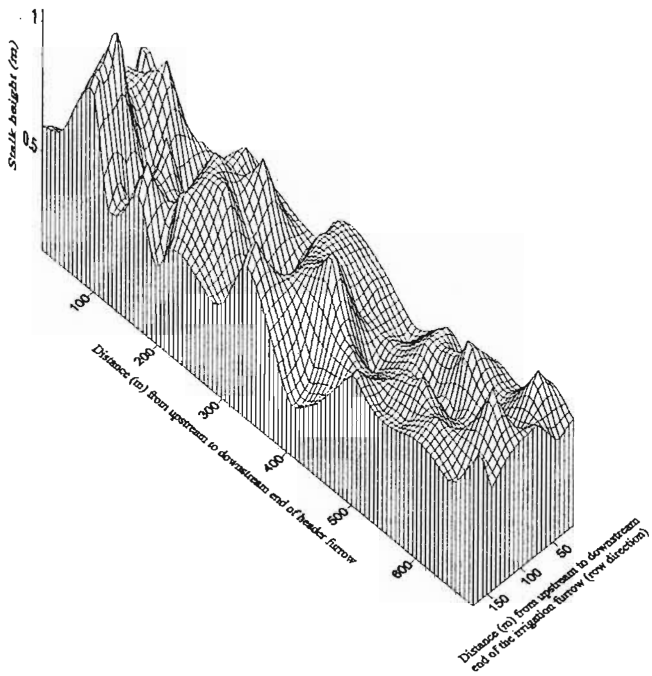
Source	df	ss	ms	f	p
Replicates	3	14.55	4.85	1.98	0.171
Treatments	4	31.56	7.89	3.22	0.052
Error	12	29.41	2.45		
Total	19	75.51			

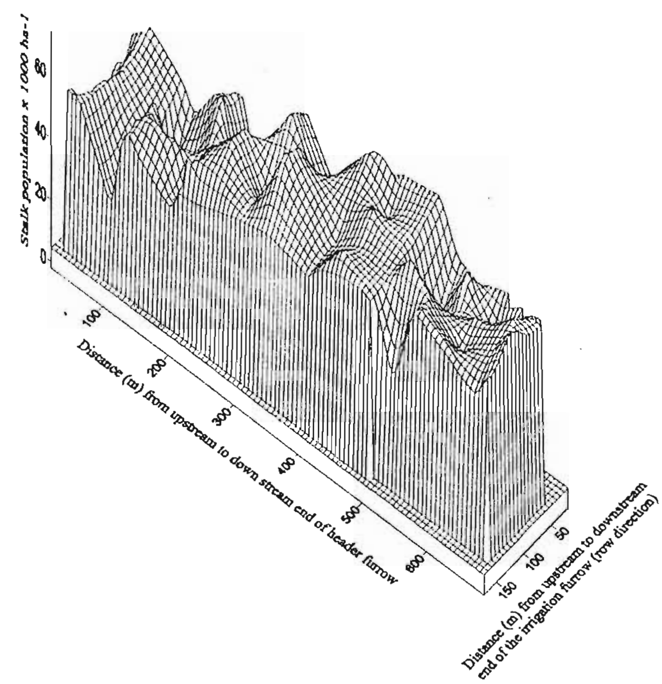
2.12 moisture (%, 2000/2001).

Source	df	ss	ms	f	p
Replicates	3	0.36	0.12	0.05	0.984
Treatments	4	10.76	2.69	1.16	0.378
Error	12	27.95	2.33		
Total	19	39.07			

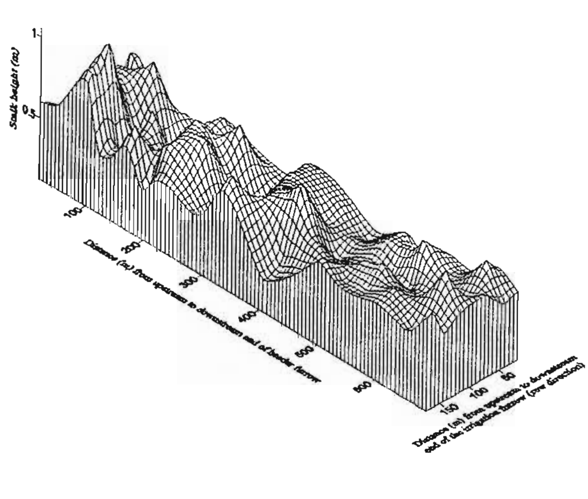
Appendix 3 Variability of sugarcane extension and population during the growing season across the trial site for the 2000/2001 ratoon cane.

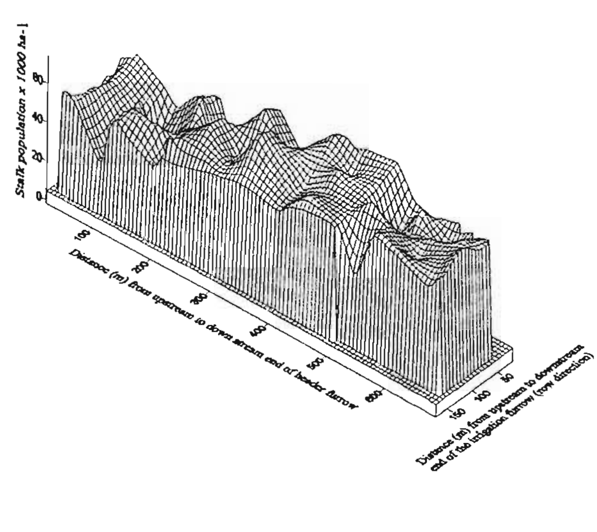
3.1 2 months



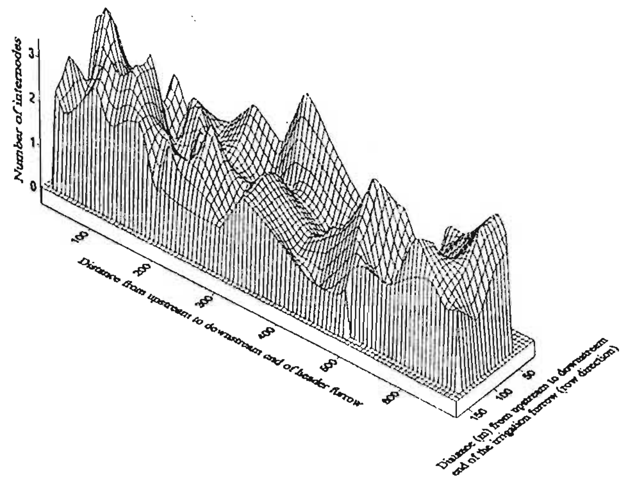


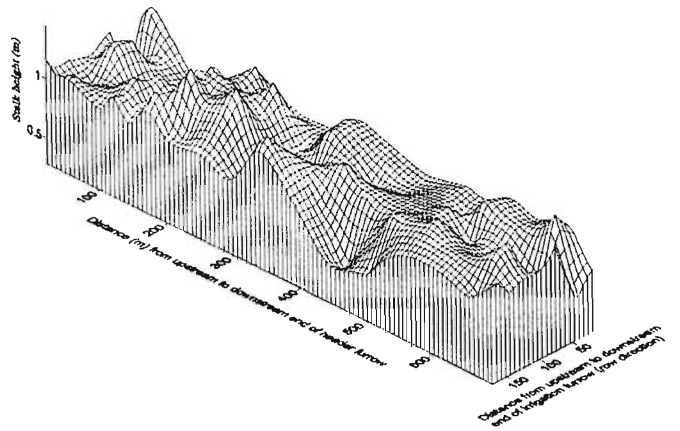
3.1 3 months

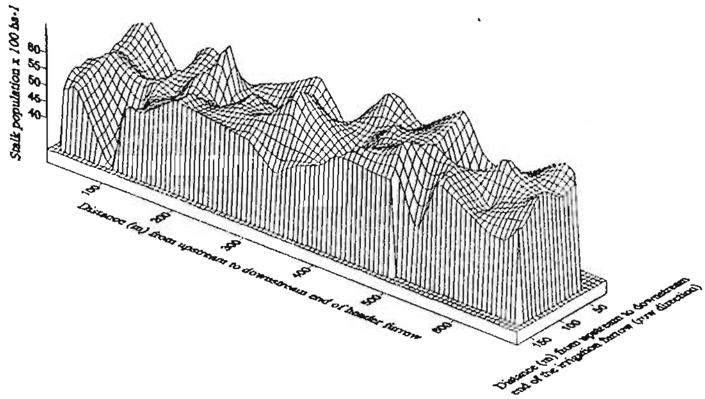




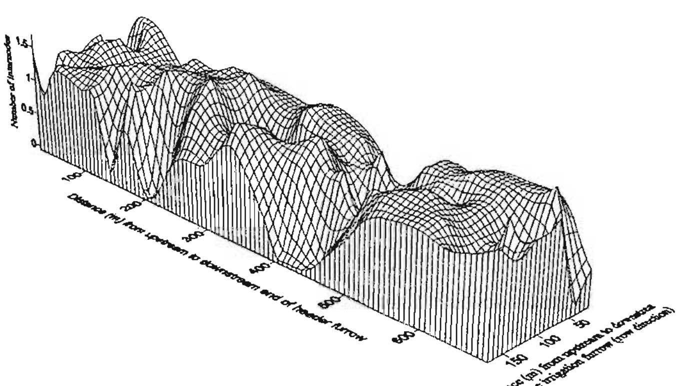
3.3 4 months

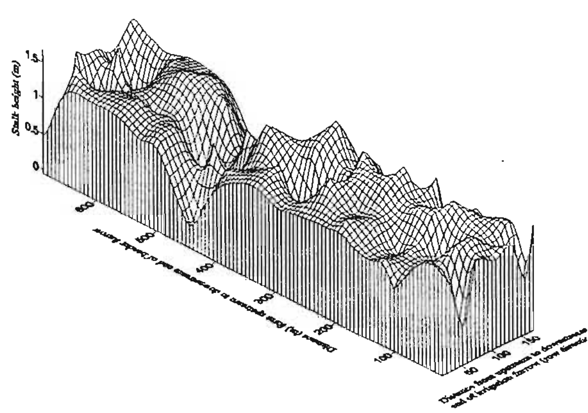


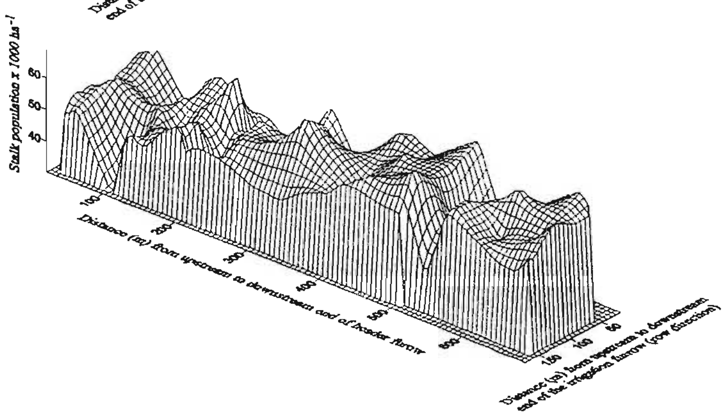




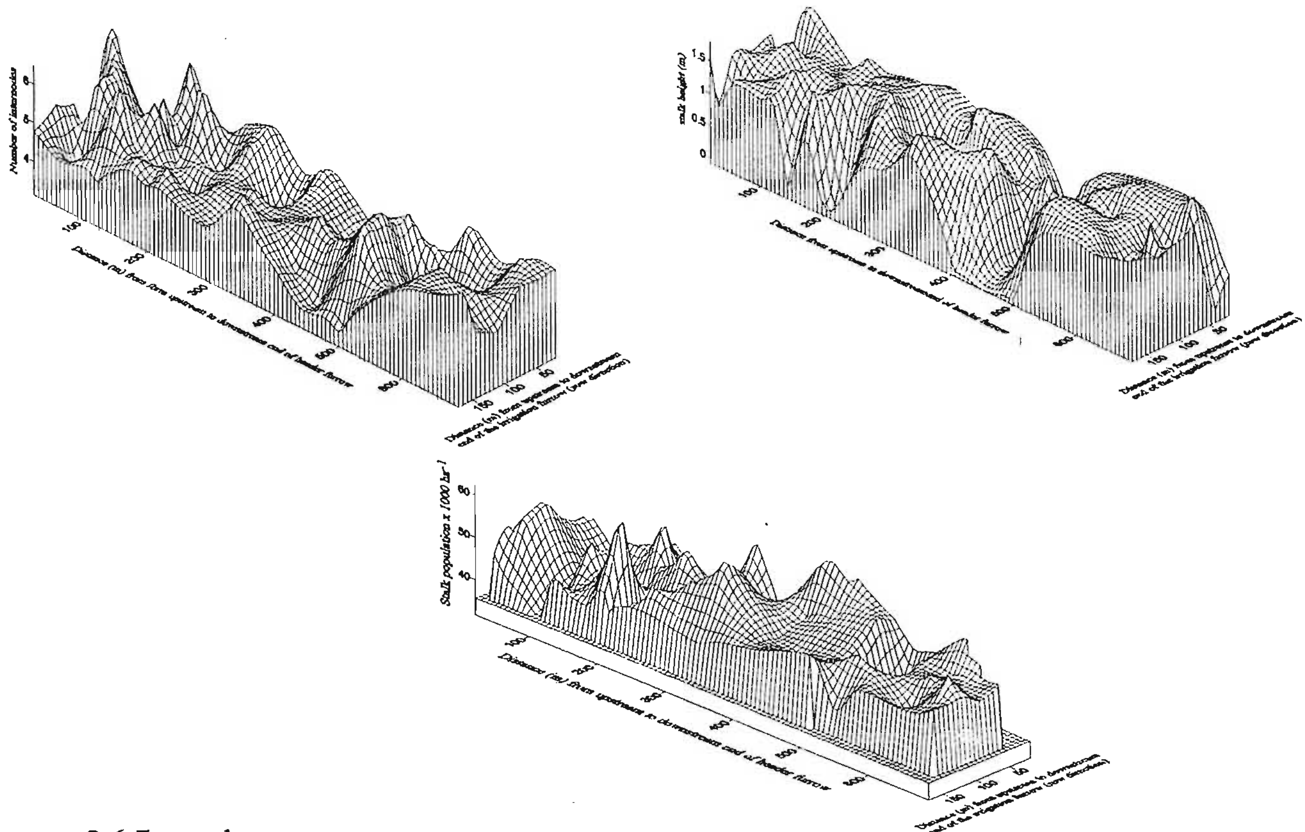
3.4 5 months



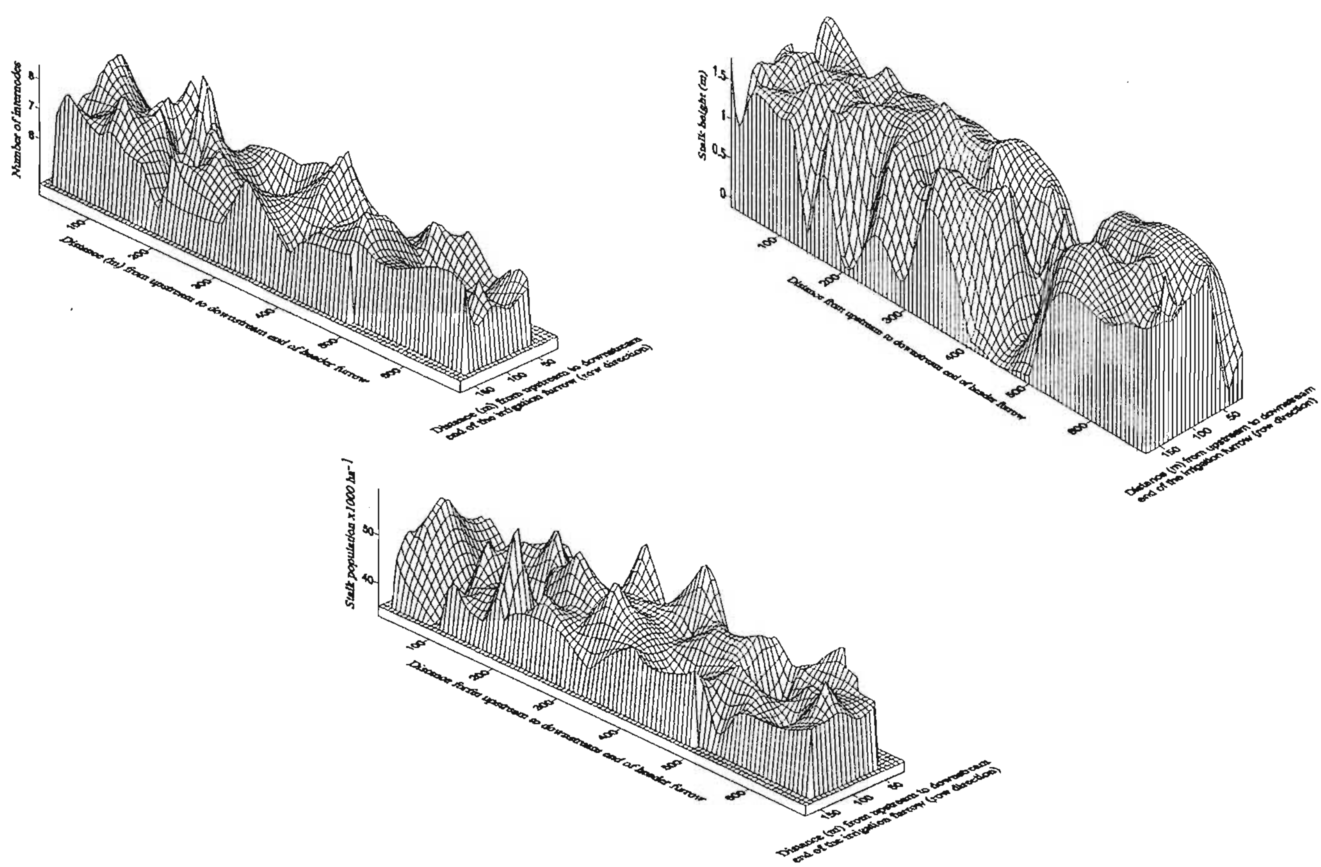




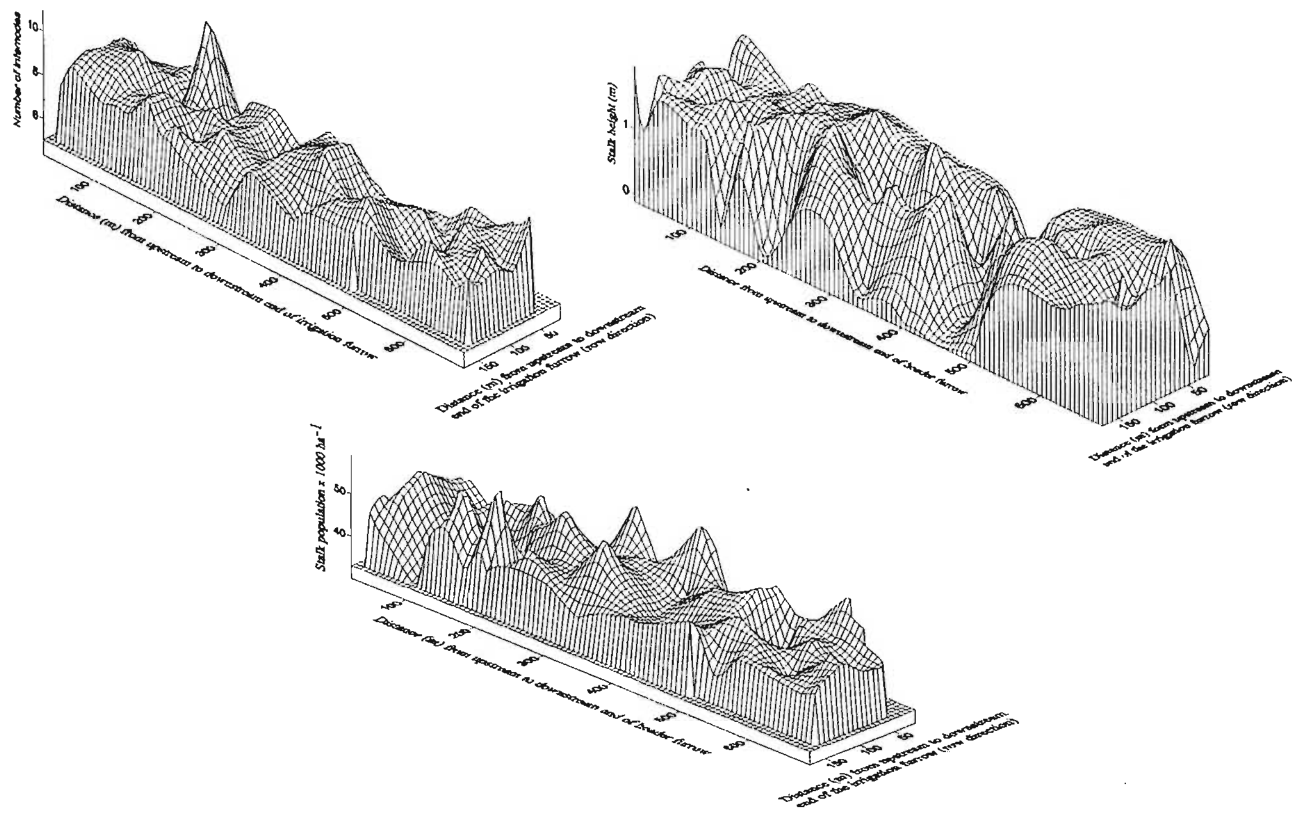
3.5 6 months



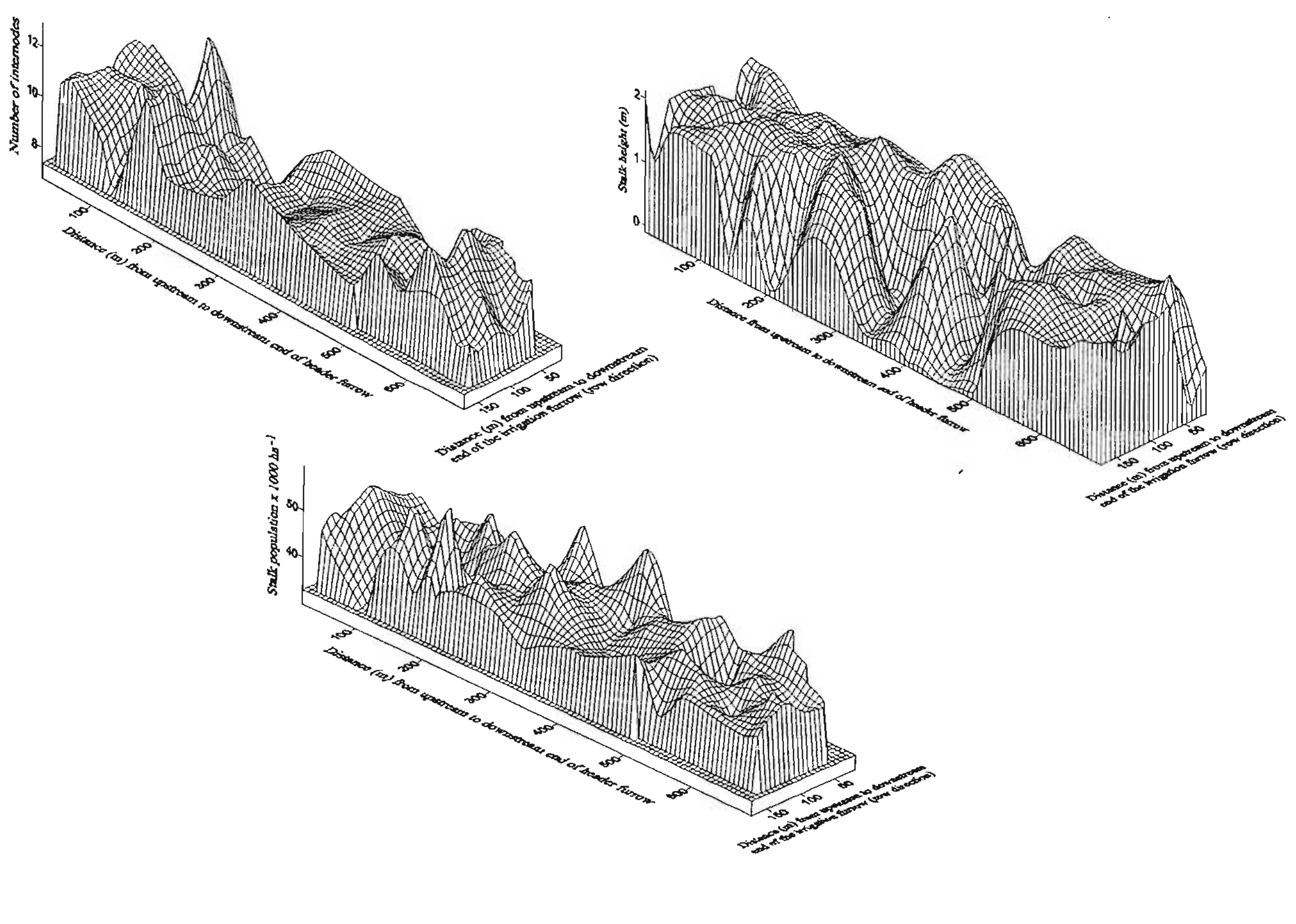
3.6 7 months



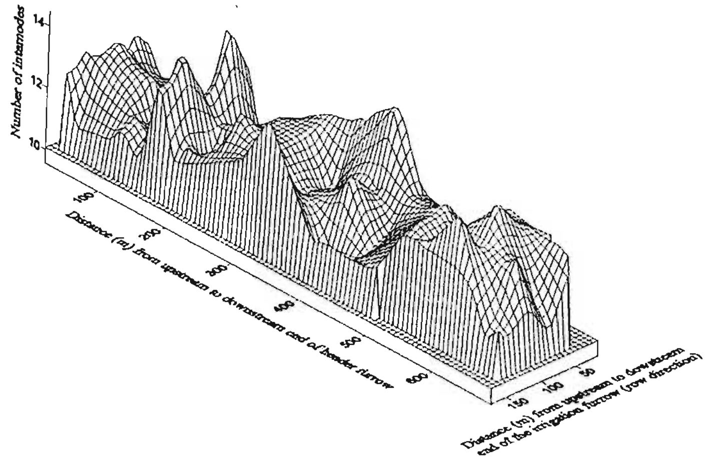
3.7 8 months

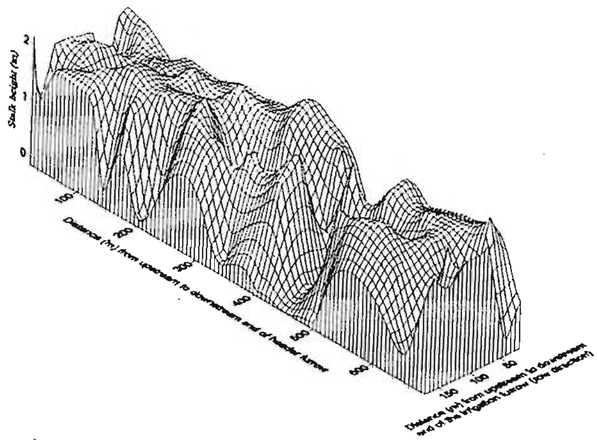


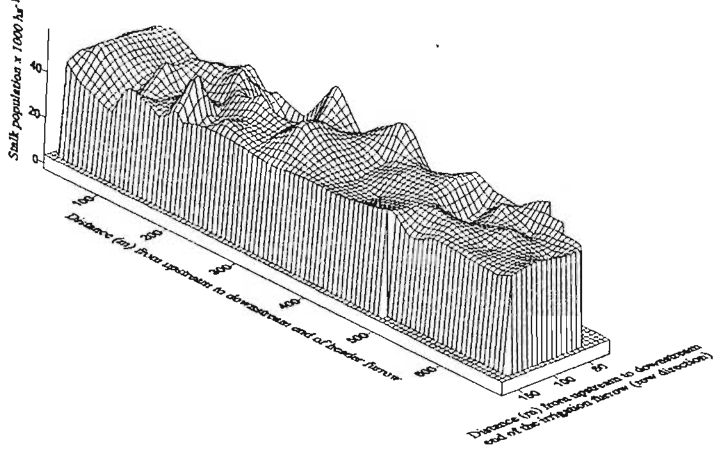
3.8 9 months



3.9 10 months


Number of internodes
14
12
10
100
200
300
400
500
600
Distance (m) from upstream to downstream end of header furrow
150
100
50
Distance (m) from upstream to downstream end of the irrigation furrow (row direction)


Stalk height (m)
2
1
0


Stalk population x 1000 ha-1
40
20
0
100
200
300
400
500
600
Distance (m) from upstream to downstream end of header furrow
150
100
50
Distance (m) from upstream to downstream end of the irrigation furrow (row direction)

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