IMPLICATIONS OF SHALLOW GROUNDWATER DYNAMICS ON WATER AND SALINITY MANAGEMENT AT KASINTHULA SUGARCANE IRRIGATION SCHEME, MALAWI

by

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Declaration

I hereby certify that this research dissertation is my own work, except where duly acknowledged. I also certify that no plagiarism was committed in writing this report.

Signed: Date: 6th February 2019

Trencio Enock Hanwell Kandinga

Dedication

To my departed parents. May your precious souls rest in eternal peace.

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Abstract

A study to understand the implications of shallow groundwater dynamics was carried out at Kasinthula Irrigation Scheme in Chikwawa District, Malawi. Water table fluctuations, groundwater salinities and soil solute levels were monitored every week from August to December 2017. Soils in the area are clay to clay loam and there is a uniform aquifer with a low hydraulic conductivity of 0.06 m/day and very high soil salinity reaching up to 8.5 dS/m. Effect of water table fluctuations on historical sugarcane yields were assessed and was observed to have very little effect on yields, however, a comparison of actual yields against expected yields from the Maas Hoffmann salinity function revealed low correlation since some areas with highest soil salinity had higher yields as compared to the areas with low soil salinity that were expected to produce higher yields. The area with highest soil salinity happened to have average water table closer to 1 m which is known to help supplement irrigation water requirements. However, sugarcane yields were noted to be declining over time as some fields registered as low as 26 ton/ha from their previous highest yields of 120 ton/ha. These low yields can be attributed to poor water management and agronomic practices carried out at the scheme that lead to waterlogging and nutrient leaching. It is from this background that a shallow groundwater monitoring tool known as a floating flag is proposed so that farmers can easily observe water table fluctuations in their fields which can help them better manage water application through adjusted irrigation schedules through observing colour changes in the floating flags. This will help reduce waterlogging and salinization problems because the groundwater will be utilised to supplement irrigation and thus reduce operational costs to the farmers.

Introduction

Background

Irrigation has made food production fairly stable, but agricultural water resources have been overused and misused, resulting in large-scale waterlogging and salinity in many irrigation schemes (Northey et al. 2006). Irrigation productivity is now at risk because of poor solute management which has caused losses of productive lands the world over (Dandekar and Chougule 2010; Stirzaker 2011). Over application of water tends to raise water tables on farms and in surrounding fields, resulting in waterlogging (Northey et al. 2006). This results in salts rising to the surface and tends to cause salinity problems which affect soil physical and chemical properties, as well as crop yields (Malota and Senzanje 2016).

This is very common in irrigation farms in Malawi and in Chikwawa District in particular. Malawi, just like many sub Saharan countries, is a semi-arid tropical country with long dry periods and short rainy seasons. The dry periods necessitate use of irrigation for production, especially for perennial crops. This heavy reliance on irrigation has resulted in saline soils that have prevented many schemes from meeting their potential (Umali 1993). Chikwawa is a district that has high potential for irrigation development due to availability of many perennial rivers and good soils with gentle slopes. However, it is also one of the districts with high salinity due to its geological history (Sehatzadeh 2011). The country depends on sugar as one of its largest export earners (Ministry of Agriculture (MoA) 2010), but of late, sugarcane *(Saccharum officinarum)* yields have decreased at an alarming rate. This necessitated this study, to ascertain possible causes of waterlogging and salinity and whether this is the cause of the low yields, and if so, to recommend possible management solutions.

Waterlogged soils are those soils that are saturated with water for large parts of the year. Waterlogged soils tend to have slow organic matter oxidation from NH_4 to NO_2 (Tusneem and Patrick Jr 1971) and transformation of NO_2 to NO_3 is inhibited due to lack of oxygen in the soil. In submerged soils, all pore spaces are filled with water, thereby reducing aeration of the rootzone which reduces root respiration and leads to crop senescence, which subsequently affects yields.

When the soil is waterlogged, soil temperature is lowered because wet soils have greater specific heat than drier soils. In addition, the longer the soil is under water, the greater the likelihood that soil structure is destroyed, resulting in compacted soils. This results in soil organic matter being leached, leaving the inorganic components without binding factors (van der Zee et al. 2010). There are more nitrogen deficiency problems in waterlogged soils and there are reports of soil pH reversal in such soils (van der Zee et al. 2010). This is where pH increases in acidic soils and decreases in alkaline soils. All these factors tend to impact heavily on field crops, except rice, as there is low aeration and unavailability of nutrients.

Salinized soils, on the other hand, refer to those soils that have salt build-up that is toxic or detrimental for plant growth. Soil salinity decreases osmotic potential of the soil so that water is less available for crop uptake. Irrigating with poor quality water (high salt load) can lead to salinity problems. Soil salinity is a major concern in poorly drained soils especially when groundwater is within 3 m of the surface, depending on the soil type (Malota and Senzanje 2016). In such cases, water rises to the surface by capillary action and crop water uptake through transpiration, rather than percolating down through the entire soil profile, and then evaporates from the soil surface. This is more pronounced in semi-arid areas where there is insufficient water to leach out salts and especially in lower lying areas of irrigation schemes.

In studies conducted in sugarcane fields in Pakistan, it was found that highest crop yields were obtained when water tables were deeper than 2 m (Kahlown et al. 1998; Kahlown et al. 2005). Therefore, there is a need to develop water management strategies that will ensure improved drainage in areas with water tables close to the surface. One way is the reduction of irrigation water that does not affect crop yields or increase salinity (Kahlown et al. 2005). Ideally, shallow groundwater can be effectively utilised as a water resource (Hurst et al. 2004) if it is of good quality and within the rootzone (Northey et al. 2006).

Malawi has a high population per unit area and is frequently hit by droughts, but mostly relies on subsistence farming practices. There is very little commercial farming due to high illiteracy levels among farmers and fragmentation of the landscape into small parcels of land. However, farmers are encouraged to form irrigation groups where they farm together as smallholders. Unfortunately, most irrigation schemes like Kasinthula Scheme, face salinity challenges, and as much as 69 000 ha are reportedly affected by salinity (Mashali 1999). Therefore, this research will not only help farmers at Kasinthula, but the whole country, to achieve Malawi's Growth and Development Strategy (MGDS) III. The MGDS recognises that meaningful agricultural productivity can only be improved if there is good water management, prevention of land degradation and pollution of the environment and natural resources (Malawi Government 2017). In Malawi, sugarcane is grown along the western shores of Lake Malawi and the Shire Valley, using furrow and pressurised irrigation systems. The sugar is exported to most European countries and helps the country source forex revenue (Ministry of Agriculture 2010).

Objectives

This research was conducted to address the following concerns related to salinity and shallow water table fluctuations related mainly to water management in the scheme.

1. To investigate the effect of amount of applied irrigation water on water table fluctuation in order to develop irrigation water management guidelines for Kasinthula Scheme.
2. To estimate the effect of soil salinity on sugarcane yield at Kasinthula Scheme so as to estimate potential yield improvement with better water management.
3. To estimate the effect of amount of applied irrigation water on the yield produced at Kasinthula Scheme.
4. To estimate the effect of amount of applied water on soil salinity levels at Kasinthula Scheme.
5. To estimate the soil salinity threshold for action or water table level at which growers need to actively reduce applied water.

Hypotheses

The hypotheses to be tested by this research (**H_o** null hypothesis, and **H_a** the alternative hypothesis) were that:

I. **H_o:** The groundwater table will rise to within 2 m of the soil surface in the low elevation land due to irrigation activities as compared to the high elevation land within the irrigation scheme

   H_a: Irrigation water application will not influence groundwater table fluctuation within the scheme based on elevation

II. **H_o:** Sugarcane yields will be depressed in areas with higher soil salinity in the rootzone (whose saturated paste extract EC is above the sugarcane threshold of 1.7 dSm^{-1}), while higher yields are expected in areas of low salinity

   H_a: Soil salinity levels in the scheme have no effect on sugarcane yields

III. **H_o:** Sugarcane yields in the scheme will be depressed when water table rises above 2 m from the surface

   H_a: Ground water table depths will not affect yield of sugarcane in the scheme

IV. **H_o:** Groundwater and soil salinities will increase from higher lying areas to lower areas in the scheme due to salt transport by irrigation water

   H_a: Irrigation water application will not influence differential distribution of soil and groundwater salinities within the scheme based on elevation

1.0 Literature review

1.1 Groundwater

1.1.1 Definition of groundwater and aquifer properties

Groundwater is defined in many ways, one of which is the "cohesive subsurface water that moves as a result of gravity" while another is "any water that has not yet exchanged with surface water" while the other definition is that "water that is retained and flows through aquifers under saturation" (Holmes 2000). Groundwater discharges its water into streams (Schmidt and Hahn 2012). Classifications of groundwater are made according to location and interaction as:

(1) Shallow aquifer, where groundwater is determined by precipitation and soil recharge;

(2) Shallow aquifer, where groundwater is determined through the interaction of surface water bodies such as rivers and lakes, and

(3) Deep aquifer, where groundwater rarely interacts with surface water.

The ability of an aquifer to store and to allow fluids to move through them is determined by the physical properties of its geologic materials (Weight 2008). When there are geologic materials which totally restrict fluids moving through them, they then form barriers which can alter the direction of groundwater movement. Some other factors also influence groundwater movement, such as thickness, clay content, water content, and intrinsic permeability of the soil materials (Dor et al. 2011). For instance, infiltrating water that encounters soils with high clay content tends to clog the pores, causing precipitation to mound up and runoff (Braunsfurth and Schneider 2008). This simply means thatsmaller pore soils led to lower infiltration rates and vice versa especially sandy soils, on the other hand, promote more infiltration of water.

In groundwater applications, atmospheric pressure of the water table surface is referenced as zero pressure (Weight 2008). This means that below the water table, water is under a pressure greater than atmospheric (Kelletat 2005), while water in the capillary fringe which is a subsurface layer in which groundwater seeps up from the water table by capillay action to fill pores and the rest of the vadose zone is under a pressure less than atmospheric (Irvine et al.2011). The vadose zone is defined as the part of the earth between the land surface and top of the groundwater. The thickness of the capillary fringe is grain-size dependent. The finer grained the material, the thicker the capillary fringe because of the smaller pore throats, increased surface area, and surface tension.

The volume of water that an aquifer can take into or release from storage for a given change in head, is often determined by its porosity (McGuire et al. 2003; Weight 2008). The porosity of earth materials is a function of size, shape, and arrangement or packing of particles. The ability of water to move through an aquifer is described by its permeability or hydraulic conductivity. The porosity is represented as the nonsolid fraction of geologic materials. This is where fluids can be held. In the vadose zone, the porosity or open spaces are filled with air and water. Porosity is often broken down into primary and secondary porosity. Primary porosity is the void space that occurred when the rock or geologic material formed. Secondary porosity refers to openings or void space created after the rock formed.

Groundwater will always move as long as there is a slope or head difference from one area to another, thus creating a hydraulic gradient (Braunsfurth and Schneider 2008); for example, from hills to wells, springs, rivers, lakes, and wetlands. This change in head causes water to flow under gravity in the soil. There may be a horizontal component to groundwater flow within aquifers and a vertical component between aquifers and in recharge or discharge areas of groundwater flow. The changes in pressure head that are experienced in the geologic formation; create a hydraulic gradient that usually controls the quantity and flow direction of leakage. Each aquifer will have its own potentiometric surface which is that imaginery level to which water in a confined aquifer would reach if opened and a hydraulic gradient propotionate to its hydraulic conductivity.

Groundwater movement is slow, usually in metres/year to centimetres/day. Hence water in recharge areas first builds up before it can be equilibrated in the system (Conant 2004; Weight 2008). The amount of water that moves down through the porous media is governed by Darcy's Law. This law states that "the volumetric rate (Q) of groundwater flow is propotional to the intrinsic permeability of the porous media (k) and the change in head over the length of a homogenous soil column" (Weight 2008). The law can be simplified as in the equation below:

$Q = K\frac{\partial h}{\partial l}A$ or usually $Q = KiA$ (from Weight 2008)

Where Q = volumetric discharge rate (L^3/t)

$\partial h/\partial l$ or i = hydraulic gradient (L/L) or slope of the potentiometric surface
A = cross sectional area (L^2)
K = hydraulic conductivity (L/t)

1.1.2 Importance of groundwater

Groundwater has many environmental, hydrological and agricutural uses. For instance, groundwater is a major source for both drinking and irrigation purposes, ecosystem management, and replenishment of stream and river flows (Nayak et al. 2006; Dor et al. 2011; Xie et al. 2012). Groundwater is the main source of water in arid to semi-arid regions of the world. However, groundwater is affected by agriculturally induced pollution which contributes to almost 70% of nitrates and around 30-40% of phosphorous which increases water treatment costs (Kay et al. 2012). Nitrates are one of the worst pollutants of water resources, and have seriously threatened its quality (Broers and Grift 2004). Nitrates and other pollutants end up in groundwater systems through leaching from agricultural lands and are transported by groundwater flow ending up at points such as drinking water supplies or groundwater dependent ecosystems (Visser et al. 2009). The water table beneath flood plains can be raised by increased inflows of groundwater into the floodplain from adjacent areas which are caused by changes in land management, especially because of development of agricultural infrastructure like irrigation schemes (Jolly and Rassam 2009). Because of this rise in groundwater levels, the area is subjected to soil salinization due to evaporation from a shallow water table.

1.1.3 Groundwater movement, monitoring and measurements

There are several ways of determining groundwater movement. The most common are the use of water balance methods, empirical equations, and environmental tracers (Blasch and Bryson 2007). For larger areas; coupled 2D surface water-groundwater models have been successfully utilised to study water balances, where researchers look at trends in water abstraction from water bodies for different uses. These models can be integrated with MODFLOW to simulate groundwater flow by observing recharge and evapotranspiration through the unsaturated zone using mass balance and an empirical relationship between evapotranspiration and water table depth (Jolly and Rassam 2009).

The key to understanding the hydraulic properties of an aquifer, requires asking many questions, such as time taken by water from the recharge area to reach a production well, or duration for a contaminant to move from and between marked points. It is important to know how far a cone of depression will reach once a well is activated, as well as knowing the effect on other production wells. This helps to atribute special hydraulic properties to the layers within the groundwater-flow model. Hence, it is necessary to perform pumping tests in order to answer such questions on the hydrogeologic formation (Weight 2008), one such equation is the Theis Equation below.

$T = \frac{Q}{4\pi S} W_{(u)}$ or $T = \frac{Q}{4\pi\,(ho-h)} W_{(u)}$ …………… (from Weight 2008)

Where T = transmissivity (L^2/t); which is the rate at which groundwater flows horizontally through an aquifer

Q = pumping rate (L^3/t)

$W_{(u)}$ =the well function; which is the relationship between the lowering of the piezometric surface and the duration and rate of discharge of a well using groundwater storage

s = drawdown (L), = $h_o - h$

In this research, wells in the form of piezometers were used, because wells provide a point of access to the water-bearing materials, and are one of the most important tools in groundwater studies. When properly designed and constructed, wells provide useful information about the characteristics of an aquifer (Weight 2008). The water level in a well, when no pumping is occurring, is known as the static water level (SWL) which reflects the total head at the midpoint of screened intervals of a well. If the well has no screen at the bottom, it is considered to be representative of the head at the bottom of the well. Typically, SWLs are measured from the top of the casing (TOC). Elevation surveys are then performed to determine the elevation of the TOC and the ground surface level (GSL). Once the reference level has been defined, the change in water level with time can be measured during a pumping or aquifer test to evaluate the hydraulic properties of an aquifer.

1.1.4 Irrigation effects on groundwater

Irrigation water causes the water table to rise in the soil, which dissolves minerals in the upper soil layers, leading them to leach down the soil profile. Water loss and/or water gain in an irrigation system is an important component of the water balance for planning and operation (Dor et al. 2011). There are more nitrates in groundwater associated with irrigation farming than in other aquifers, because farmers use nitrogen fertilizers for production (Schuman and Pahlow 2007; Pena-Haro et al. 2010). This results in more leaching of nitrates to groundwater (Nolan et al.1997).

1.1.5 Monitoring groundwater solutes

Methods to determine the velocity of solutes in groundwater system in order to ascertain how far they can be transported across an aquifer were described by (Freeze and Cherry 1979). They used the equation for steady-state flow through a saturated anisotropic porous medium (Pena-Haro et al. 2010). The equation for steady state flow is given below:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial H}{\partial z}\right)+W=0 \ldots \text{(from Freeze and Cherry 1979)}$$

Where Kx, Ky and Kz are the hydraulic conductivity values (L/T) in the x, y and

z directions;

H = hydraulic head (L)

W = the flux term (L/T) that accounts for pumping, recharge or other sources and sinks.

Stable isotopes can be used to study the origin of groundwater (Dor et al. 2011). The most commonly used stable isotopes are Oxygen-18 (18O) and Deuterium (2H). This leads to understanding the replenishment processes within sources, prediction of mix portions from components of the sources in question, and studying the hydraulic interconnections. Monitoring of groundwater solutes helps to quantify the threat of pollutants for present and future quality and thus protect groundwater from deterioration. It is, however, very challenging to determine mass transport, because the time taken for the water to flow from one point to another is extremely slow (Broers and Grift 2004).

1.2 Salinity problems in irrigation schemes

1.2.1 Classification and causes of salinity

Salinity is classified into three major categories, which are primary, secondary and fossil salinities (Lambert et al. 2002). Natural and fossil salinity are caused by naturally occurring phenomena usually from salt lakes, pans, flats or marshes. Secondary salinity occurs due to human activities, especially land and agricultural development (Barret-Lennard 2003). Examples are salinity due to irrigation resulting in rising water table or use of poor-quality water (Lambert et al. 2002). A major challenge in drier areas of the world where crop growing is dependent on irrigation, is soil salinity (Qadir and Oster 2004). Salinity causes major environmental damage that affects crop development and profitable productivity.

Irrigation is another source of groundwater salinization due to movement of dissolved salts (Abbas et al. 2013). This is a global challenge, especially in agricultural lands where irrigation water is poorly managed resulting in poor drainage. Salinization due to irrigation has affected 43 million hectares of agricultural land out of a total 77 million hectares which are damaged (FAO 2007; Qadir et al. 2009). The rate at which salinization is affecting farmlands on a global scale is very alarming, to an extent that almost 2 million hectares are lost annually (Stockle 2007; Abbas et al. 2013). Predictions show that around 30% of farm land in most countries where irrigation is practiced are badly damaged by salinity or likely to be affected shortly. This has forced farmers to abandon farmlands or lose livelihoods.

1.2.2 Effects of salinity in irrigation schemes

Irrigation development is done in areas with easy command, fertile and flat to gentle topography. These places are usually located on the bottom of the valleys or slopes and are common salt basins. Salts naturally move to these lower areas with erosion material, by seepage flows and by convection and diffusion. These salt movement mechanisms often continue to charge the irrigated areas with salt influxes from the various primary and fossil salt sources in the surrounding higher land and hill sites (Ammari et al. 2013). Salinity is expected to rise due to application of poor water quality due to effects of droughts which have caused low flows in rivers and also due to an increase in world population which will necessitate that more uplands are turned into irrigated agricultural lands for production of food to meet global food demand.

Irrigation induced salinization is more restricted to the semi-arid zone. Therefore, irrigation in these regions has to counter the highly natural saline landscapes and very high rates of evapotranspiration (Qureshi et al. 1993; Abbas et al. 2013). This ends up in increased annual salt concentration capacity of the arid zone. The concentrated salts emanate from the diluted salts in the irrigation water which was abstracted. As crops absorb only a fraction of the salt of the consumed water, irrigation causes these diluted salts to become concentrated. This salt concentration may lead to the deposition of precipitated salts in the soil, but mostly it will lead to the remaining soil water becoming more saline. Saturated gypsum in the soil also contributes to the soil salinity of the arid zone adding about 3 dS/m to the salinity per annum. Annual salt accumulation depends on the prevailing rainfall, over-irrigation and drainage conditions, as these conditions largely determine the leaching regime of the landscape (Ibrikci et al. 2015). It has been reported that when conditions are favorable, all salts can be leached and drained (Gill and Terry 2016).

Primary salts can also be mobilized through seepage and leakage from large scale irrigation areas (FAO 2007). This is because potential flow theory of groundwater mechanics predicts that long distance seepage flows are likely to pass through deeper strata and are therefore likely to mobilize salts stored in some of these strata. Water table elevation differences establish groundwater flow between higher and lower areas and between existing or newly created sources and sinks. In large irrigation schemes, studies have shown that annual common rates of salt mobilization are in the order of 1–3 tons per hectare (Ahmadi and Sedghamiz 2008).

1.2.3 Salinity measurement and monitoring

Salinity monitoring can be done using graphic explanations, field investigations, and laboratory examinations (Aza-Gnandji et al. 2013). However, the challenge is the availability of simple tools which can be utilized without difficulty to come up with realistic interpretations for appropriate decision making (Abbas et al. 2013). Salinity can be measured from samples in piezometers, soils or irrigation water. One of the simplest ways to measure salinity is with a pocket salinity sensor using a soil solution sample collected from a Full Stop Wetting Front Detector (Stirzaker 2011; Ibrikci et al. 2015).

1.3 Irrigation water management

1.3.1 Definition of irrigation water management

Irrigation water management is defined as the process of applying water to meet crop water demand in such a way as to limit water; soil and nutrient loss which could degrade the environment. Application amounts sould not only match the crop age, but also take into account the infiltration and uptake conditions of the soil so as to avoid soil erosion and eventually to aim at improving and maintaining water quality (USDA 1997; Panda et al. 2004; FAO 2016).

1.3.2 Importance of irrigation water management

Irrigation water management has several advantages when done correctly. The most common benefits are:

a) Reduced wastage of water during irrigation; i.e. over irrigation.
b) Less soil erosion and has the ability to cut labour demands since hours spent during excessive irrigation can be diverted to other agronomic areas.
c) Lower pumping costs (Evans et al. 1996). This is because, as energy costs are rising, an efficient water management system leads to saving money which would otherwise be used for pumping water
d) Sustain and sometimes improve groundwater quality and also that of downstream surface water
e) Increased yield and quality (USDA 1997).

1.3.3 Irrigation measurement and when to irrigate

It is important that the irrigation decision maker must understand the basic principle of applying an appropriate amount of irrigation water at an appropriate time, which includes an understanding of water use budgets, soil features, correct water delivery rates, existing soil water conditions and groundwater depth (USDA 1997; FAO 2009). Additionally, knowledge of crop features, especially how much water they use in a specific time, how they grow, expected yields and quality, the extent of root depth, and permissible water stress level and the effect of the water distribution calendar, are required. This can be achieved through correct flow measurements and field monitoring techniques in order to establish the frequency and quantity of irrigation.

In order to manage water application systematically for maximum productive potential, one can apply one of the most commonly used irrigation equations:

$Q = DA/T$ (from USDA 1997)

where Q is flow rate (l/s)

T time (s)

D depth (mm)

A area (ha)

The equation above helps to easily calculate how much water is being applied over a specific period, depending on known flow rates and area to which the water is applied (Merchán et al. 2015). There are many devices on the market which can be used to measure water flow rates in water canals or main water pipelines. Measuring water flows helps improve water management and one such irrigation water measuring device is a Cutthroat Flume (Figure 1.1). This device has vertical sidewalls with a level base and accelerates flow through contraction of the sidewalls until the flow reaches the throat (the narrow section) after which the area over which flow takes place is expanded Skogerboe et al. 1973; Samani and Magallanez 2000). This is the device which is used at Kasinthula at measuring points in all tertiary canals. For free flow measurements, discharge is given by:

$$Q = CH^{n}$$ (from Skogerboe et al. 1973)

And $$C = KW^{1.025}$$ (from Skogerboe et al. 1973)

Where Q is flow rate (l/s)

C is the free flow coefficient

W is the throat width (L)

K is the free flow length coefficient for the flume

H is the head at the point of measurement (m), and

n is the free flow exponent.

The primary point of measurement (Ha) is given by:

Ha = 2L/9 (Skogerboe et al. 1973)

Where L is length of the flume (m)

In these flumes, *n* and K vary with flume length.

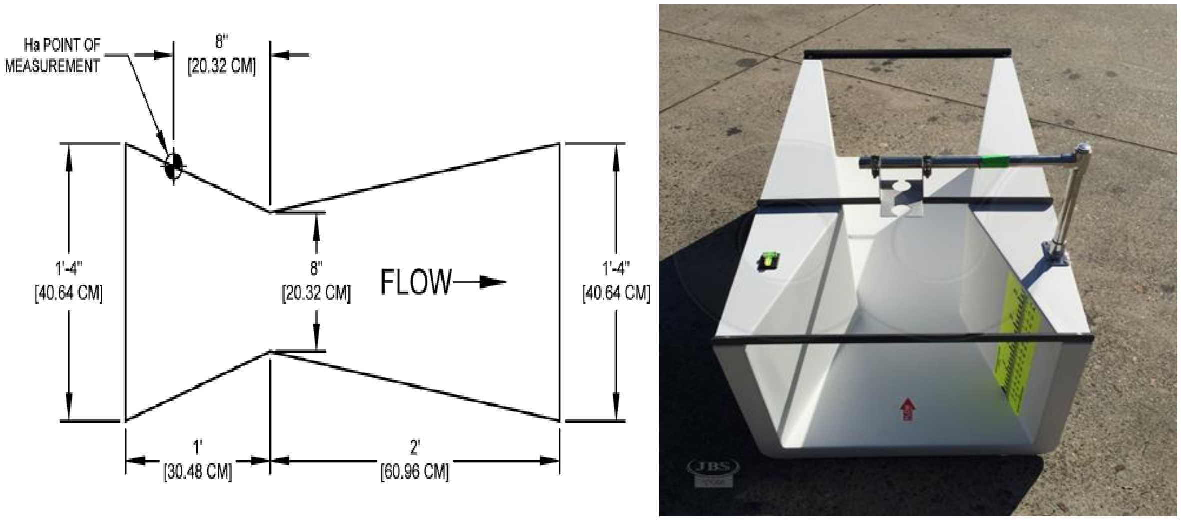


Figure 1.1 Cross section of a Cutthroat Flume and an image of a fabricated one

1.3.4 Factors to consider with irrigation water management

In order to carry out an appropriate irrigation water management schedule, one has to look at several factors ranging from the soil plant water balance to weather conditions of the area in order to make proper decisions.

This is enhanced by the ability to apply an understanding of soil and crop characteristics and ensuring continued monitoring of the variations in soil water content as well as the water stress levels, growth stage, root growth, and water usage. As such, water budgets can be used to plan irrigation schedules, while the water balance helps in estimating daily water availability and are vital irrigation water management tools (USDA 1997; FAO 2002; Merchán et al. 2015).

1.3.4.1 Soil

Soil bulk density, available water capacity, field capacity, water holding capacity, maximum allowed depletion, and wilting point are integral components that determine soil water uptake in plants (Wichelns and Qadir 2015). Therefore, improved water management should be guided by an understanding of these soil water characteristics. In brief, field capacity (FC) is defined as the quantity of water that is held in the soil when the rate of downward water movement has become negligible and surplus water has drained (Veihmeyer and Hendrickson 1931). Wilting point (WP) is defined as the level of soil water under which plants wilt as they cannot take water up, even in a humid environment when this demand is low, and will not recover without irrigation. Available water capacity (AWC) is defined as the range of water in the soil (FC-WP) that can be stored and is available for plant uptake (Richards and Wadleigh 1952; USDA 1997). This portion of AWC which is freely available for plant growth is termed readily available water (RAW). Maximum allowable depletion (MAD) is the soil water level which is expected before an irrigation event begins and is the percentage of available soil water or the depth of water that can be depleted in the rootzone. Providing irrigation water before MAD is reached, minimizes plant water stresses that could reduce yield and quality (FAO 2016).

1.3.4.2 Soil water content (SWC)

This is defined as an amount of water in a soil volume at a given depth. It is expressed in mm of water depth that is present in a depth of one m of soil (FAO 2016). The soil water content can be quantified using different tools. As such the quantity of accessible water to crops is given by the difference between SWC and WP. In order to decide when and how much water to apply, the change in soil water content is measured. In order to do this, several sites in the field are sampled at different soil depths like 15 cm, 30 cm, 45 cm and so on (FAO 2016). There are several commercial soil water content measuring devices on the market which display a numerical range of soil water content. The method used mostly at Kasinthula is qualitative, and amounts to feeling and looking at the soil, the so-called feel and appearance method. This is the most easily implementable method when determining soil water. However, it requires a lot of experience to make accurate decisions which do not affect crop growth. With this method, samples are collected and compared with charts that depict different moisture features for different soil textures (USDA 1997; FAO 2002; FAO 2016). It does not require sophisticated equipment, and most often irrigators only require shovels, augers or core samplers.

1.3.4.3 Gravimetric or oven dry method

This is a method where soil samples are collected in the field at the chosen depths using a core sampler or auger and weighed before being placed in an oven for 24 hours at 105 degrees Celsius in order to evaporate the soil water. It is important to weigh the soil samples before they dry out and also to avoid over heating during oven drying which could degrade soil organic matter (USDA 1997; FAO 2002). Using the differences in mass between the oven dried and the original soil sample, a percentage water content can be calculated which can also be computed to volumetric units by multiplying the mass percentage water content with the soil bulk density. Available soil water is calculated by subtracting percent total soil water at wilting point from this value.

1.3.5 Crop factors and crop characteristics

Irrigation water management is influenced by the type of crop one is growing as well as other crop characteristics. These include crop evapotranspiration factors, critical growth stages, root development and yield quality vs water use relationships (FAO 2002).

1.3.5.1. Crop evapotranspiration (ETc)

Accurate determination of crop evapotranspiration (Etc) is a key factor for irrigation (USDA 1997; FAO 2016). ETc is defined as the amount of water that is lost through a crop while involved in transpiration (T) which helps build plant tissue, and evaporation (E) from the soil or plant foliage surface. Local climatic conditions and growth stage help in determining the ETc. There are several equations that can be used depending on available climatic data and degree of intensity of the irrigation management programme which one may wish to use. The most commonly used is the Penman-Monteith (PM) equation which is an empirical formula used in determining standard reference evapotranspiration (ETo) which can then be multiplied with different crop factors to determine ETc (Chiew et al. 1995).

1.3.5.2 Critical growth periods

Plant growth and development is greatly affected by the amount of water that is available in a season. Almost every crop is very sensitive to water stress during critical growth periods for example during flowering in cereals, as such scarcity of water may result in no pollination which can affect yields drastically. This is more pronounced in vegetables and fruits, where inadequate water supply at the critical stage may render unmarketable produce because low water availability results in poor yield quality (Mastrorilli et al. 1995). Therefore, an understanding of how much water a crop needs during a specific growth period is vital in growing quality crops with subsequent high economic returns. Matching the correct crop factor with the correct growth stage is thus very important.

1.3.5.3 Root development

An understanding of the growth stage of the crop helps estimate the root depth. This has a bearing on plant water use. Too much water during the early growth stages when roots are still shallow leads to loss of nutrients and unnecessary expense of pumping. Many factors control development of roots, such as the crop growth stage, depth of exploitable soil, state of compaction of the soil and soil water content. Water application should be planned in a way to supply only that amount which the plant will be able to utilize (Mastrorilli et al. 1995; Evans et al. 1996; FAO 2002).

1.3.6 Irrigation scheduling

Irrigation scheduling is the decision of when to apply water to a field as well as determining the quantity to be applied. This is done in order to maximize time between irrigations through correct water application needed for soil water replenishment. It is a very economical tool as it saves water and energy (Brouwer and Prins 1989; USDA 1997; FAO 2016) if done correctly. It involves the use of monitoring tools that determine when water is needed. Irrigation scheduling techniques require information on the crop, the soil physical and chemical characteristics, the climatic conditions, the system of irrigation being used and water application methods. The most commonly used means to estimate irrigation requirements is by means of a soil water balance (Brouwer and Prins 1989).

2.0 Materials and methods

2.1 Area of study

The research was carried out at Kasinthula Irrigation Scheme in the southern part of Malawi from August 2017 to December 2017. Kasinthula is located in Chikwawa District as shown in Figure 2.1. It is a smallholder scheme comprising 1435 ha. The main crop grown in the scheme is sugarcane which is used as raw material for sugar production. The area has predominantly clay and clay loam soils. The area is fairly flat, with a gentle slope of about 0.5 %. The area around Chikwawa has an aridity index of 0.41 from data for the past 5 years, showing that the area is semi-arid because the aridity index for semi-arid lands ranges 0.2 to 0.5 (UNESCO 1979). The mean annual precipitation for Chikwawa is 700 mm while the mean annual reference ETo for the area is 1700 mm. Aridity Index is defined as the ratio of annual precipitation to annual reference ETo. This therefore necessitates use of irrigation for sugarcane production as the mean annual rainfall is insufficient for optimal production. The scheme has furrow and centre pivot irrigation systems. The research was conducted in the area where farmers irrigate using furrow irrigation, because it is the oldest section and it is the area where yields have been noted to have deteriorated considerably over time. The area has three distinct seasons, namely, the rainy (December to March), winter (April to July) and summer (August to November) seasons. Irrigation is required almost throughout the year, as dry spells are common even in the rainy season.

At Kasinthula; sugarcane is usually planted around June to October and harvesting starts after twelve (12) months. The major varieties grown are N14, N32, MN1, MN25 as well as 92F. Fertilizer application is done twice per growing season with 189 N distributed evenly using Sulphate of Ammonia which has 21% N. The harvesting is mainly done from May to November which are dry months to allow mobility of haulage trucks into the field. Harvesting is done by hand and the average ratoon age is eleven (11) months. Average sugarcane yield is around 120 ton/ha while the sucrose content ranges from 11% to 14%.

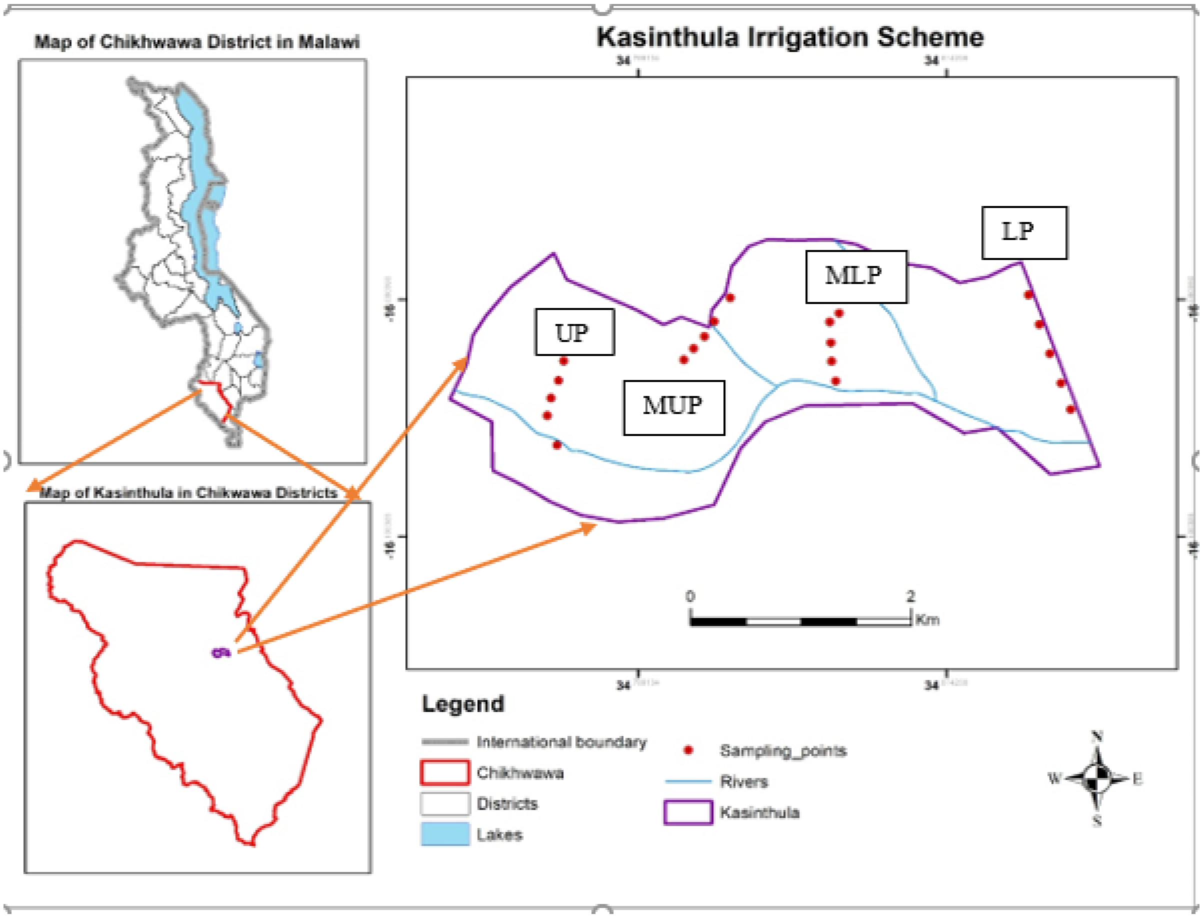


Figure 2.1 Map of Malawi showing Chikwawa District and Kasinthula Irrigation Scheme

Transects were used in the scheme for locating sampling points as determined by their elevation in the landscape. In this study the lowest elevation transect was labelled LP (Lower Piezometer). The adjacent transect was labelled MLP (Middle Lower Piezometer) with the following transect designated as MUP (Middle Upper Piezometer). The final and highest elevation transect was labelled UP (Upper Piezometer). Characteristics of these transects and numbered piezometers are presented in Table 2.1.

Table 2.1 Characteristics of transects and piezometers

Transect	Average distance between transect (m)	Piezometer Id	Reduced elevations for Piezometers (m)	Average reduced levels per transect	Distance between Piezometers (m)	Transect Length (m)	Piezometer max. Depth (d) (m)	Average Watertable Depth (m)
LP	0	LP1	79.9	79.74	0	1153	5	1.1
		LP2	79.8		290		5	2.0
		LP3	79.8		288		5	1.6
		LP4	79.7		297		5	1.2
		LP5	79.6		278		5	0.5
MLP	1218	MLP1	89.7	87.09	0	806	5	2.2
		MLP2	91.9		230		5	2.1
		MLP3	85.7		210		5	2.4
		MLP4	83.8		180		5	0.5
		MLP5	84.5		186		5	2.0
MUP	1022	MUP1	89.7	89.94	0	715	5	3.1
		MUP2	91.9		260		5	3.7
		MUP3	91.5		165		5	1.9
		MUP4	88.5		150		5	2.3
		MUP5	88.2		140		5	2.5
UP	1777	UP1	96.4	95.87	0	834	5	3.6
		UP2	95.4		196		5	2.8
		UP3	95.6		180		5	1.9
		UP4	95.9		160		5	3.6
		UP5	96.0		298		5	3.5

These transects were selected after noting declining trends in sugarcane yields which were considered to be caused by shallow groundwater tables after eliminating other factors such as compaction, pH, ratoon age and diseases especially smut and mosaic virus which were deemed not to have contributed significantly to the yield losses. Twenty monitoring points were identified where piezometers were installed. The fields were selected based on similar soil, crop, irrigation system, slope and crop stage, as presented in Table 2.2.

Table 2.2 Similarities in fields selected for monitoring points

Site physical characteristics	**Description**
Slope of the land	<3%
Crop grown	Sugarcane
Crop stage	1^{st} ratoon less than a month after harvesting
Soil types	Clay and clay loam soils
Irrigation type	Furrow irrigation method
Cane variety	N14 and N32

The following sections will describe the procedures followed in order to install equipment and collect the necessary data in the field and all the analyses that were carried out.

2.2 Water table fluctuation monitoring using piezometers

In order to obtain reliable data using the piezometers, FAO (1999) was used to determine the density of sampling points. In the guidelines, FAO advises that for a 50-ha area, five groundwater monitoring points are sufficient to give representation of the whole area. Based on this, each transect covered a total area of less than 35 ha. This was to ensure that the data collected would effectively represent the total area. In total, 20 sampling points were selected, and the total area covered was 104.6 ha.

The piezometers were installed in manually augured boreholes using a 65 mm diameter extensible soil auger to a depth of 5 m. Then, 40 mm internal diameter class 4 PVC pipes with narrow cut slots were lowered into each piezometer borehole. Slots were cut into the bottom 4 m of the pipes. The slots were made to allow free movement of water between the soil and piezometers in order to maintain the actual water table level inside the piezometers. Each piezometer was lowered to a depth of 5 m and a 0.5 m length was left above the ground surface so that surface runoff water was prevented from entering the piezometer. The sides of the pipes were back filled with sand to reduce clogging to depth of 4 m and sealed above this with 1m clay material up to the surface. Each piezometer was fitted with an end cup on the surface to ensure that no external materials were thrown into them and to maintain ambient salinities.

The ground elevation at points where piezometers were installed was collected through surveying using a theodolite, and referenced to benchmarks of the main canal. From this data, reduced levels were calculated. These levels were used to generate a digital elevation map of the scheme as seen in Figure 2.2.

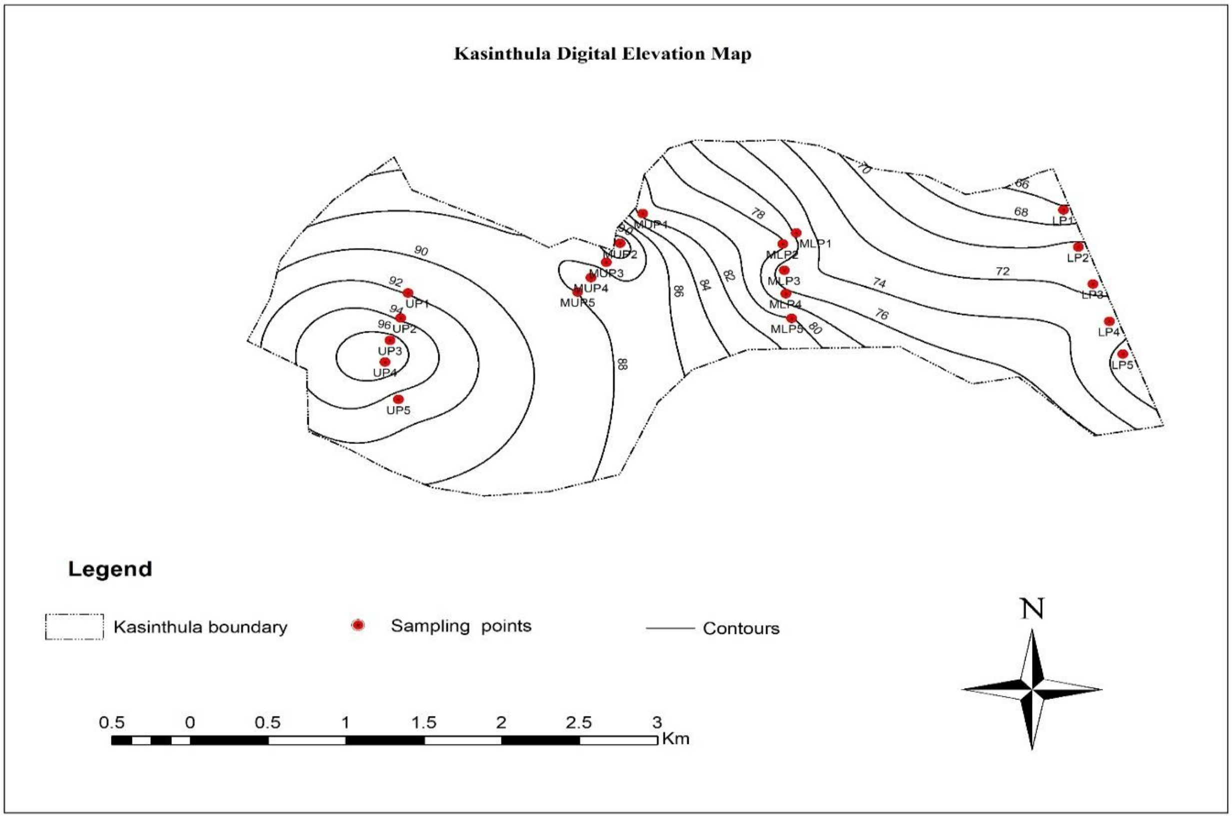


Figure 2.2 Kasinthula Digital Elevation Map (DEM) showing monitoring points

Water table depths (WTDs) of each piezometer were measured and recorded using a battery powered Solinst Water Level Meter (WLM) with a resolution of ± 0.05 cm by lowering its electronic end slowly down the piezometer until it touched the water surface and a light is displayed and a sound emitted. The piezometers were installed between the 2nd and 5th August 2017, and were used to start collecting WTD data on 10th August 2017 after allowing almost a week for all piezometers to fully equilibrate with surrounding groundwater conditions.

This was also a period when sugarcane production was predominantly dependent on irrigation since it was the beginning of the dry season. WTDs were recorded every week until the 16th of December 2017, which was the beginning of the rainy season.

After the monitoring season, average WTDs of each piezometer from the surface were calculated and using the specific latitudes and longitudes for the piezometers which were collected using a hand-held Garmin Etrex 30 GPS, a Microsoft Excel sheet composed of XYZ (latitude, longitude and average WTD) values was created.

The WTDs of each piezometer were deducted from the reference levels of each piezometer for groundwater level calculations. Actual groundwater levels were calculated by subtracting reduced surface levels of each piezometer from the WTD levels which were recorded during the research period and were used to develop hydrographs of each piezometer for the duration of the study. The reduced groundwater levels were used to generate sampling day maps in Surfer 13 by Kriging the grid data and then volumes of water as contributed by irrigation or rainfall which were measured throughout the study period. Similarly, maps showing volume changes of water in the soil were also generated in Surfer by subtracting different pairs of maps for different dates.

When the piezometers were installed, pumping tests specifically using the ‘bail out test’ method were performed in all piezometers to determine hydraulic conductivity of the surrounding soil. This was done by dipping a 35 mm external diameter water bailer into the piezometer and withdrawing water so that the water level was lowered as measured from the surface. Thereafter, another level reading was taken after a measured time interval. Using the level differences and time taken together with the diameter of the piezometer, the hydraulic conductivity of soil around each piezometer was calculated using a steady state flow equation (Hooghoudt 1940; Weight 2008).

$$\boldsymbol{k = \frac{3600a^2}{[d+(10a)+2-\left(\frac{y}{d}\right)\times y]} \times \left(\frac{\Delta H}{\Delta t}\right)} \qquad \text{(Hooghoudt, 1940)}$$

where K = hydraulic conductivity (m/day)

a = radius of the piezometer

d = depth of piezometer below the static ground water table (m)

ΔH = rising ground water table over time (t) in metres

Δt = time measurement of rise of ground water table in seconds

y = average distance from static ground water table to the water table in the piezometer

2.3 Soil sampling

Soil samples were collected in August 2017 to help understand factors that would influence water table prevalence and salinity distribution within the scheme. This was necessary because besides elevation difference influence, groundwater movement is also affected by soil physical and chemical characteristics. The samples were collected from three points at about 3 m around each piezometer in all transects. This was done to help understand the soil variability around each piezometer.

Samples from six depths, that is 0-10, 10-20, 20-30, 30-40, 40-50 and 50-60 cm were collected and analysed for bulk density, particle density and particle size distribution, while textural classes were determined using the USDA classification system as described by Warrick (2002). This was augmented by in situ soil classification using the Munsell Soil Colour Chart obtained from Kasinthula Research Station. This was used to determine the conditions of the soils under review and determine their composition (Warr 2015). There were 10 segments of 10 cm each which were core sampled for determining soil water holding capacity using the Hilgard Soil Cup method. The soil bulk density was measured using the gravimetric method with soils collected using volumetric rings. Soil particle density was measured using the pycnometer method.

Nitrates in soil water were monitored using Nitrate Test Strips which were dipped into soil solution collected from wetting front detectors which were placed at 30 mm and 60 mm depths on each side of piezometers. The colours obtained were matched to corresponding colour codes and the amount of nitrogen in the soil water deduced and recorded (Stirzaker 2011). This was monitored to ascertain whether there was sufficient or inadequate nitrogen for cane production. However, just a few months into the data collection campaign, vandalism of equipment resulted in loss of all the

WFDs. Therefore, data collection for solute determination was halted midway into the research period.

2.4 Salinity monitoring

It was planned to monitor salinity and soil solutes using three sources, namely groundwater salinity in the piezometers, soil salinity and solute levels using installed wetting front detectors (WFD) and also irrigation water salinity. However, a few months after installation most WFDs were vandalised, therefore monitoring of soil salinity and solute levels with these tools was abandoned midway through data collection. Fortunately, the monitoring of groundwater salinity using water drawn from piezometers continued uninterrupted until the end of the data collection period. Therefore, this section will detail processes that were carried out to monitor groundwater and irrigation water salinities.

An effort to understand soil salinities in the scheme was done through soil samples which were collected on three spots around each piezometer. Each soil level was mixed with soils from all pits around each piezometer and a representative sample of 200 g was placed in a sampling bag ready for testing. They were then placed in plastic containers where 0.8 l distilled water was added to make a 1:4 soil water suspension. This was then allowed to equilibrate for 24 hours, after which the solutions were filtered and the respective EC was determined using an EC meter through dipping the electrodes into the water after calibrating the meter with the HI 7031L conductivity calibration solution (Malota and Senzanje 2016). The depth increments were chosen because Hurst et al. (2004) and Malota (2012) reported that the top 60 cm depth constitute 60% of sugarcane roots. Then the EC was converted to ECe using conversion factors calculated from the particle and bulk densities for each soil type and ratio of water which was used to dilute the suspension. First, soil porosity was found using

$$\theta = 1 - \frac{\rho b}{\rho}$$

Where θ is porosity, ρb is bulk density and ρ is particle density.

Then gravimetric water content (ωg) was calculated using

$$\omega g = \frac{\rho b}{\theta}$$

Since the soil suspension was in a ratio of 1 to 4 where 100 g of soil were mixed with 400 g of water, then the converted ECe was calculated using

$$ECe = \omega g * 40 * EC$$

Groundwater salinity in the piezometers was measured weekly using an EC meter on water obtained through a water bailer which was used to draw water from each piezometer. In order to maintain the salinity in the piezometer as close as possible to that of the groundwater, each piezometer was fitted with a top cap to stop rainfall entering and also stop evaporation losses (Northey et al. 2006). Similarly, irrigation water salinity was tested weekly by just collecting water from the canals using a tumbler and testing it using the EC meter.

2.5 Yield response to salinity

Sugarcane yields from 2001 to 2017 from all fields that were sampled were collected from Nchalo Sugar Mill owned by Illovo Sugar Group where Kasinthula farmers crush their cane. Average groundwater salinity graphs for groups of piezometers were produced using Excel software and were compared to the published threshold salinity of 1.7 dS/m for sugarcane production and a slope of 5.9% was used to estimate potential yields under saline conditions (du Plessis et al. 2017).

Average field salinities and average yields were plotted in scatter graphs to determine their correlation. This was done to estimate the relationship between yield response to salinity and water table fluctuation which was measured; thus; the yield response to salinity was developed for the scheme. This was done because it is known that crop water use is heavily affected by salt tolerance of crops (Ayars et al. 2006). The salinity response was then compared to Maas and Hoffman (1977) plant salt tolerance relationships which were developed based on yield loss caused by increased salinity in the rootzone. The Maas and Hoffmann Response to Salinity Function provides a reasonable basis for considering the potential crop water use from shallow groundwater. The yield averages were also compared with each other using scatter plots to evaluate effects of water table and salinity on sugarcane yields.

Surfer 13 software was used to produce yearly yield maps by Kriging (Ayers et al. 2006) yield data of each year and producing contours of yields across the scheme. Then, subtracted yield maps for different years were also generated using the same procedure in Surfer 13 software and losses or gains in yield were plotted as contours. A subtracted yield map depicts yield changes between years compared in Surfer 13.

2.6 Water application and use

In order to calculate water application and crop water use, all necessary weather data were collected from Nchalo Illovo Estate weather station which is some 16km away as the one at Kasinthula Research Station which is very close had stopped data collection. The data that was obtained from Nchalo included total monthly rainfall and rain days, cumulative monthly and average ETo, total monthly radiation, average monthly radiation, total and average monthly sun hours, average maximum and minimum monthly temperatures and wind speed for the past 5 years. Irrigation water application rates were obtained by use of Cutthroat Flumes each time irrigation took place (Samani and Magallanez 2000). The Cutthroat Flumes were built permanently in both the main and tertiary canals in all fields.

Kasinthula receives an average of 700 mm of rainfall (Malawi Meteorological Services 2006) but from Cropwat estimates, sugarcane around Kasinthula requires 1850 mm of water per growing season (Doorenbos and Pruitt 1977; FAO 2002; Liu et al. 2015). Thus, these growers require 1150 mm of irrigation water to supplement the rainfall for an optimum crop yield in a year.

During the monitoring period, on average, farmers would irrigate 725 mm (since it is the peak evapotranspiration period) but the area received about 203 mm of rainfall. Irrigation water measurements were done in feeder canals that were linked to the transects of piezometers in order to understand the relationship between water table fluctuation with amount of water applied after considering the return flow at the ends of the flooded fields.

The water content of the soil was monitored using a chameleon reader which was able to connect to 20 chameleon sensors arrays (Stirzaker 2011) which were installed at a depth of 30 cm, 45 cm and 60 cm next to each piezometer. Chameleon sensors use electrical resistance principle which display colour changes as the soil water changes (Steyn 2016). The colour change interpretations are presented in Table 2.3. Farmers can easily use the colour changes to know and determine when they must irrigate. Unfortunately, this water-use monitoring did not last, as the same problem of vandalism also occurred with these devices. The soil water balance was calculated using the Penman-Monteith equation to overcome the problem of vandalised equipment meant to monitor water-use.

Table 2.3 Chameleon sensor colours, matrix potential ranges and interpretations (Steyn 2016)

Chameleon Colour Display	**Matrix potential range (kPa)**	**Interpretation**
Blue	0-25	Soil is "wet"
Green	25-45	Moderate soil moisture
Red	>45	Dry soil

3.0 Groundwater dynamics and salinity

3.1 Overview

Irrigation often results in increased soil salinity and waterlogging that causes irrigation schemes to fail (Dandekar and Chougule 2010; Malota and Senzanje 2016). In most schemes high salinity and waterlogging problems are caused by poor drainage (Hirekhan et al. 2007), more especially in Africa which accounts for more than 90 % of poorly drained irrigation systems (Wood 2008). Increased irrigation water application in poorly drained schemes causes lands to be perpetually waterlogged and can trigger salinization from deep lying salt. When an area has proper drainage and practices good water management, it is easier to prevent groundwater from appearing on the surface, which in turn can also reduce salinization and thus boost crop production (Fouss et al. 2007).

In Malawi, some schemes like Kasinthula pump their water from Shire River, which is more expensive than gravity fed systems. Despite water being pumped, a large area of the scheme has shallow groundwater. The presence of shallow groundwater has both positive and negative impacts on agricultural production. Shallow groundwater can be utilized as a major source of irrigation water either through pumping it to the crops or using drainage discharges as potential water sources for downstream users if it is not saline (Ayars et al. 2006).

Shallow groundwater is often associated with salinity increases in fields. However, in-situ use of shallow groundwater with moderate levels of salinity has been known to be an effective water source for crops in many studies (Ayars et al. 2006). Therefore, farmers whose fields have high prevalence of shallow groundwater can benefit from using the water table as a water resource and can therefore reduce the need for pumping of water.

Several factors must be considered when farmers want to use shallow groundwater for their crops. These include depth to groundwater, salinity levels, crop growth stage, crop salt tolerance, application depth, irrigation frequency and whether or not the crop is seasonal or perennial. Below is a description of the factors that determine crop water use from shallow groundwater reserves.

3.1.1 Soil water flux

Crop water use is affected by the distance between the shallow groundwater surface and the bottom of the root zone, as this is the distance water must cover to be available to crops (Ayars et al. 2006). The unsaturated hydraulic conductivity determines the flux of water to the root zone. This is usually controlled by soil type and soil matric potential. Darcy's law is often used to determine the soil water flux as shown below.

$$z = \int_0^{hz} \frac{dh}{1+\frac{q}{k(h)}} \qquad \text{(from Ayars et al. 2006)}$$

Where z is distance between a water table and a position in the soil profile with a constant flux of q and k is the hydraulic conductivity given as a function of matric potential (h). As stated earlier, soil type greatly affects hydraulic conductivity, which in turn determines flux from a water table to plants. A root zone that is closer to the water table tends to increase potential crop water use (Ayars et al. 2006).

3.1.2 Roots

Although the extent of roots in the soil is rarely used to predict crop water use, it represents the most important component which coordinates plant vegetative growth and soil water in the vicinity. There is little literature pertaining to root development and crop water use in shallow groundwater areas (Ayars et al. 2006). However, there could be no meaningful shallow groundwater use by plants if roots do not develop close to the shallow water table. In this case, plants with a more extensive and deeper root system have a bigger chance of utilizing shallow groundwater reserves over extended periods than do shallow rooted crops.

One equation by Borg and Grimes (1986) relates root development (in relation to growth period and period) to reach maximum growth of roots and number of days after planting as shown below

$$RD = RM_m\ [0.5 + 0.5\ \left(3.0 * \left(\frac{DAP}{DTM}\right) - 1.47\right)] \qquad \text{(from Borg and Grimes 1986)}$$

Where RD is the root depth, RM_m is maximum rooting depth, DAP is number of days after planting and DTM is number of days to maximum rooting depth. The data from this equation can be utilized alongside soil data and water table depth to calculate potential water use from shallow groundwater (Hurst et al. 2004; Ayars et al. 2006)

3.1.3 Crops

Different crops extract water of different salinities from groundwater reserves. Several factors contribute to a crop's ability to abstract shallow groundwater. These include salt tolerance, duration of growing season and extent of the root system (Ayars et al. 2006; Askri et al. 2014). Of the many factors, salt tolerance is crucial to crop water use from shallow groundwater reserves. Shallow groundwater leads to capillary rise which also brings salts to the root zone which sometimes causes salinization, therefore, a good understanding of groundwater dynamics and its effects on salinity in irrigation schemes is important to ensure sustainable use of agricultural lands (Northey et al. 2006; Ayars et al. 2006; Fouss et al. 2007).

This research attempts to describe water table dynamics of Kasinthula, and to ascertain how this affects soil salinity and crop yield in the scheme. The objectives of the study were to investigate the effect of irrigation and rainfall on the variation of water table depth in space and time, and to understand how the water table influences sugarcane yields and salinities. The next sections provide the characteristics that determine groundwater dynamics and salinity.

3.1 Soil characteristics of Kasinthula Irrigation Scheme

This section presents the soil physical and chemical properties as measured and tested in the laboratory as well as hydraulic conductivity values obtained from bail out tests. Table 3.1 below shows the soil characteristics such as bulk density, particle density, electrical conductivity, soil pH and soil types for the sample sites. Also presented is the saturated hydraulic conductivity values of the aquifer which guide groundwater flow which were calculated from the pumping tests data.

Table 3.1 Soil and aquifer characteristics of Kasinthula Irrigation Scheme

Field	**Depth**	**Soil pH**	**1:4 Soil:Water Electrical Conductivity (EC)**	**Converted Electrical Conductivity (ECe)**	**Textural Class**	**Bulk Density (BD)**	**Particle Density (PD)**	**Saturated aquifer hydraulic conductivity (integral of 1-4 m depth) (*k*)**
	(cm)		**(dS/m)**	**(dS/m)**		**(g/cm^3)**	**(g/cm^3)**	**(m/day)**
LP1	0-60	7.25	1.13	7.22	Clay Loam	1.48	2.4	0.04
LP2	0-60	7.53	1.23	8.50	Clay	1.41	2.43	0.03
LP3	0-60	7.22	0.83	5.53	Clay	1.45	2.45	0.04
LP4	0-60	7.13	0.7	4.42	Clay Loam	1.51	2.48	0.03
LP5	0-60	7.23	0.9	5.73	Clay Loam	1.51	2.52	0.03
MLP1	0-60	7.07	0.83	5.50	Clay Loam	1.47	2.53	0.03
MLP2	0-60	7.07	0.75	4.89	Clay Loam	1.48	2.49	0.03
MLP3	0-60	7.22	0.73	4.69	Clay Loam	1.49	2.47	0.03
MLP4	0-60	7.05	0.82	5.34	Clay Loam	1.48	2.49	0.03
MLP5	0-60	7.03	0.73	4.79	Clay	1.48	2.53	0.03
MUP1	0-60	7.1	0.33	1.88	Clay Loam	1.59	2.43	0.06
MUP2	0-60	6.02	0.4	2.28	Clay Loam	1.59	2.44	0.06
MUP3	0-60	7.03	0.5	2.95	Clay Loam	1.59	2.54	0.06
MUP4	0-60	7.1	0.47	2.96	Clay Loam	1.5	2.43	0.03
MUP5	0-60	5.02	0.43	2.74	Clay Loam	1.49	2.44	0.04
UP1	0-60	7.1	0.43	2.36	Clay Loam	1.59	2.34	0.06
UP2	0-60	7.12	0.3	1.64	Clay Loam	1.59	2.34	0.06
UP3	0-60	7.22	0.35	2.26	Clay Loam	1.48	2.44	0.03
UP4	0-60	7	0.4	2.60	Clay Loam	1.48	2.47	0.03
UP5	0-60	7.23	0.37	2.20	Clay Loam	1.54	2.39	0.05
Standard Deviation	N/A	0.54	0.27	1.92	N/A	0.05	0.06	0.013

From soil pits it was observed that the upper layer of the profile (0 to 60 cm) had a quite uniform clay loam texture, and deeper layers (60 – 100 cm) were typically more clayey. The saturated k values obtained during bail out tests are consistent with a group of aquifers with low permeability like clay and clay loam aquifer formations (USDA 1997; Weight 2008). The soil pH values for

MUP2 and MUP5 are outliers because these points are lying just below a hill which has high weathering which could explain the low soil pH.

3.3 Shallow groundwater dynamics

In order to understand the shallow groundwater dynamics of Kasinthula, the reduced levels were used to generate a longitudinal cross-sectional profile for the scheme. Below is an example from one point in the scheme from the UP transect to the LP transect as seen in Figure 3.1. This indicates that there is an elevation difference of 23 m and an average slope of 0.5%.

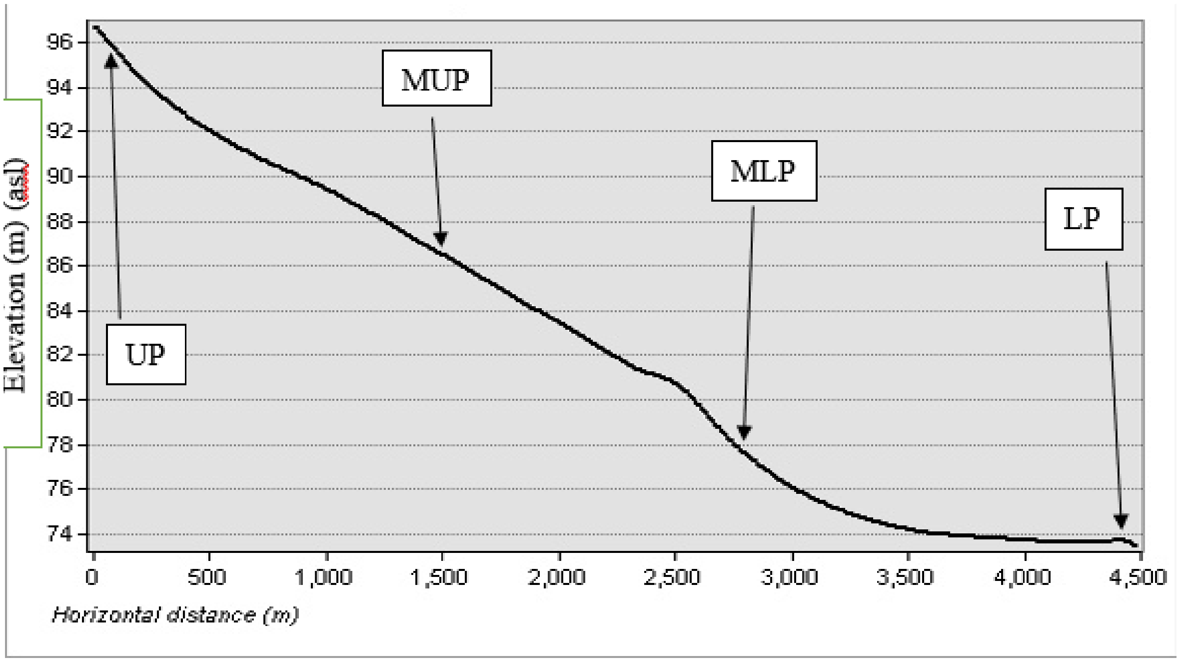


Figure 3.1 Longitudinal cross section of Kasinthula Scheme

After generating the representative longitudinal cross-section profile, a vector map (Figure 3.2) was generated to show groundwater flow directions. In the diagram, the arrows are pointing from the left to the right with a downward west-east general flow of water which corresponds with the longitudinal profile. Points of diversion of arrows are canals which are on high ground.

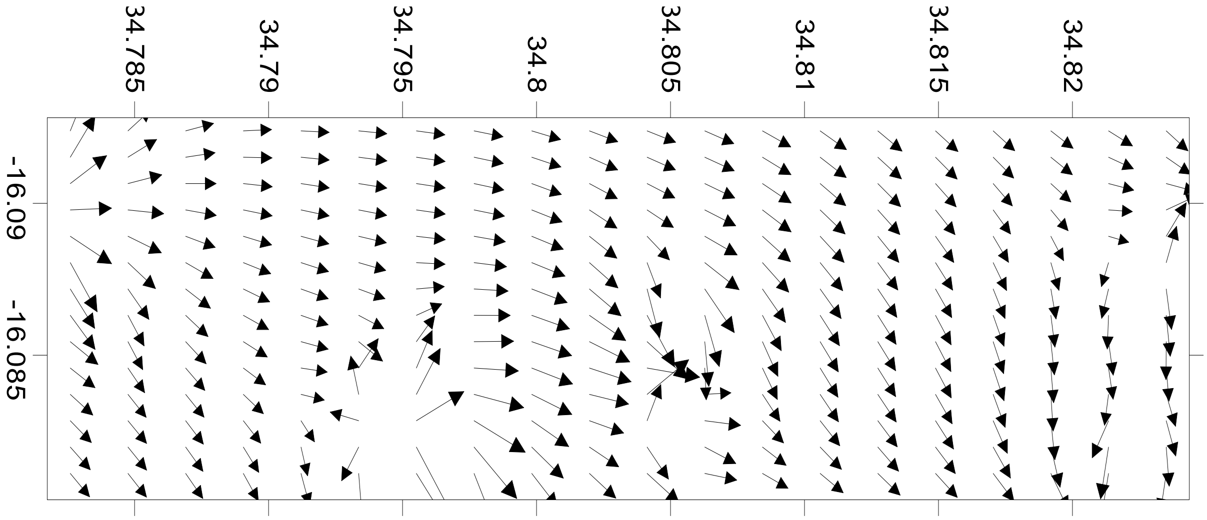


Figure 3.2 The Vector Map for the area showing water flow paths

Crop water requirement (CWR) as estimated from Cropwat software, as well as rainfall and irrigation water are shown in Figure 3.3. Only January had a CWR that was met by rainfall, while in all the other months, irrigation was needed to meet the CWR for sugarcane for the year 2017 growing season.

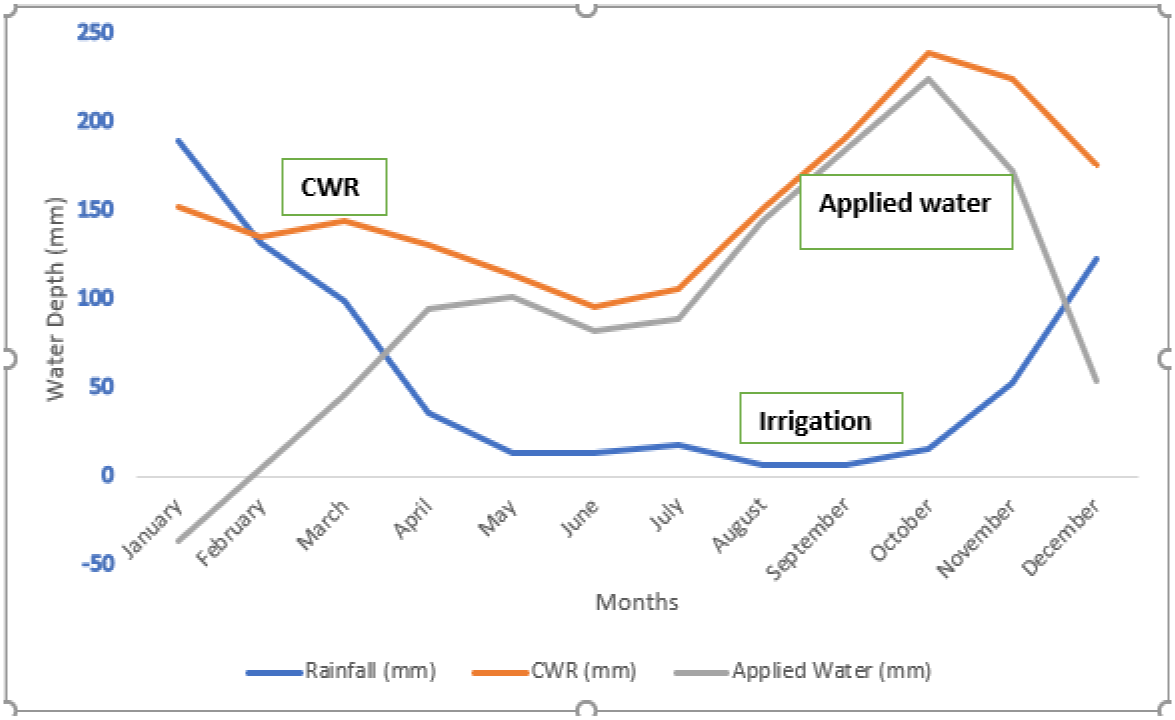


Figure 3.3 Kasinthula crop water requirement (CWR), irrigation (I) and rainfall (R)

Water table depth measurements were taken once every week. Water table graphs were then generated to depict how shallow groundwater behaved during that period. Figure 3.4 below is an average of five piezometers for each transect plotted together to depict the variations across the scheme at various elevations. From the graphs, it is seen that all transects exhibited similar trends in water table rise and fall during the observation period, indicating a uniform aquifer response to water use and application in all areas. The trough in all hydrographs relates to a period when irrigation was stopped due to an electricity failure in the area.

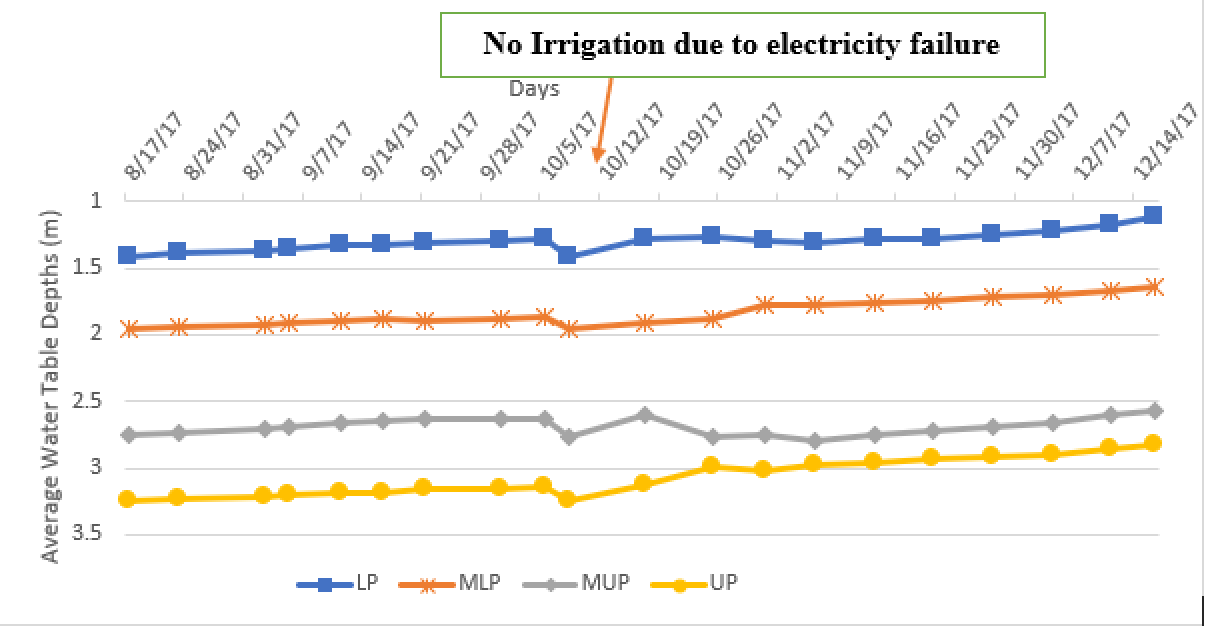


Figure 3.4 Average transect water table fluctuations over time at Kasinthula

Figures 3. 5 to 3.8 below provide hydrographs from each transect, whilst Tables 3.2 to 3.5 present rainfall and irrigation amounts for Fields LP1, MLP3, MUP4 and UP2. On average, water tables rose from the beginning to the end of the trial by 0.3 m for LP1, 0.4 m for MLP3, 0.2 m for MUP4 and 0.42 m for UP2. In Figure 3.5, the graph suddenly rises towards the end of the monitoring period due to the heavy rains which were received around Kasinthula especially the heavy downpour of 156 mm on 27th November 2017 which followed an irrigation event of 63 mm on 22nd November 2017.

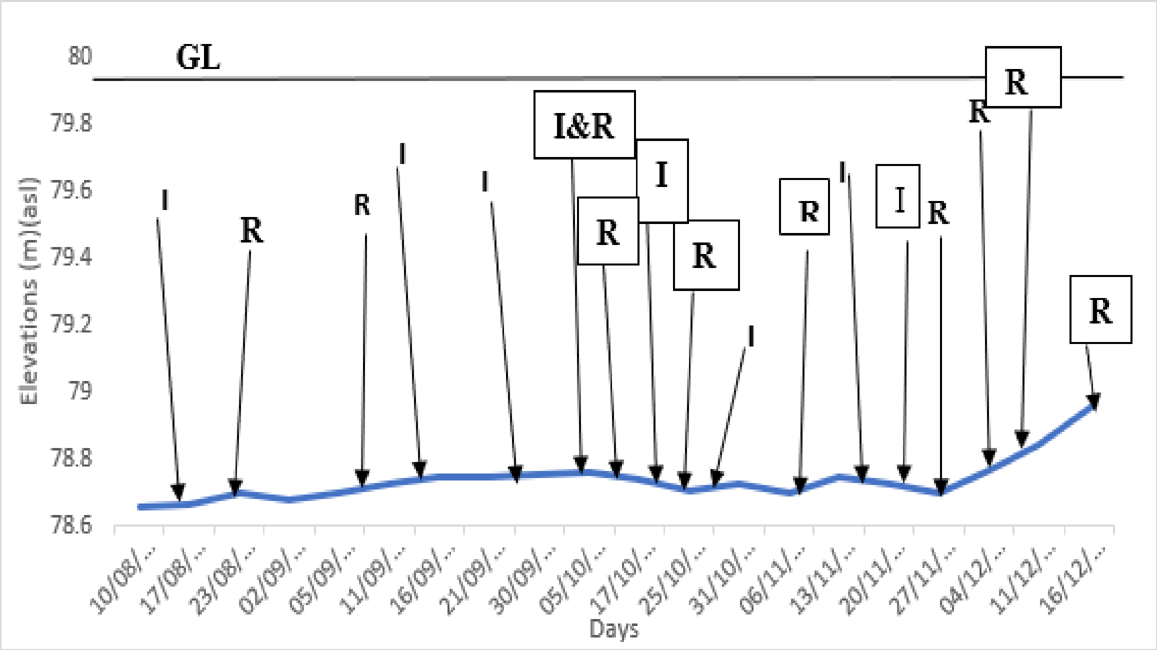


Figure 3.5 Water table graph for Piezometer LP1 showing days of irrigation (I) and rainfall (R), ground level (GL)

Table 3.2 Measured irrigation (I) and rainfall (R) event amounts for LP1 for the dates monitored

	Field			Field			Field	
Date	LP1	Remark	Date	LP1	Remark	Date	LP1	Remark
15/08/2017	63.0	I	30/09/2017	7.0	R	10/11/2017	60.0	I
19/08/2017	2.0	R	05/10/2017	11.0	R	22/11/2017	63.0	I
05/09/2017	5.0	R	14/10/2017	64.0	I	27/11/2017	34.00	R
12/09/2017	62.0	I	17/10/2017	4.0	R	04/12/2017	83.0	R
23/09/2017	65.0	I	25/10/2017	62.0	I	09/12/2017	16.0	R
30/09/2017	62.0	I	08/11/2017	19.0	R	14/12/2017	23.0	R

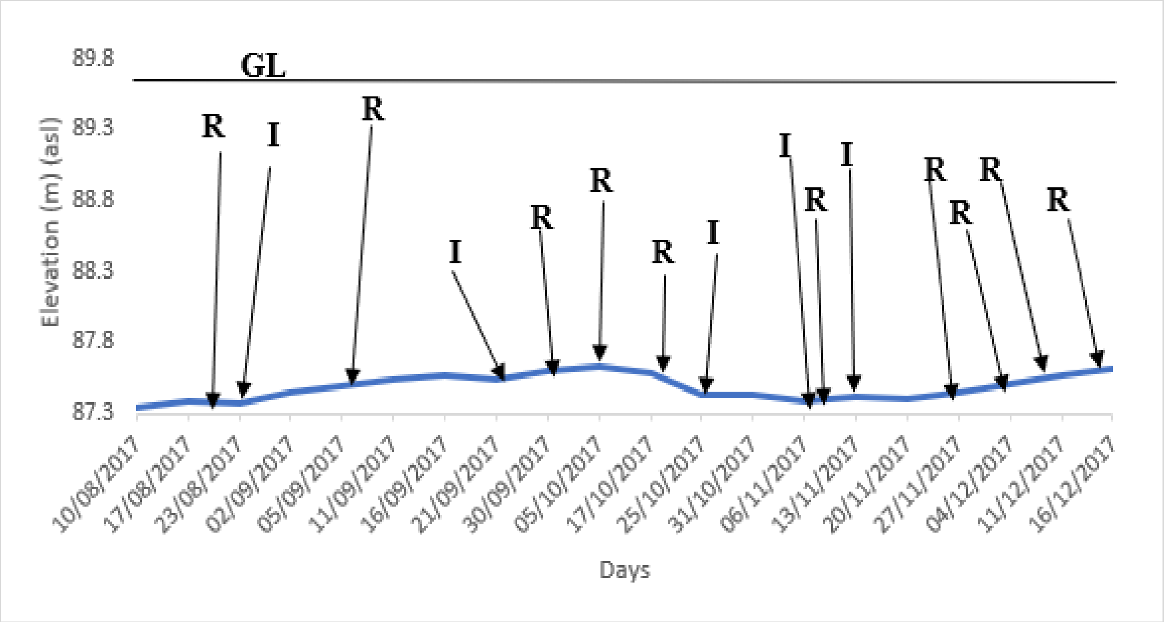


Figure 3.6 Water table graph for Piezometer MLP3 showing days of irrigation (I), rainfall (R) and ground level (GL)

Table 3.3 Measured irrigation (I) and rainfall (R) event amounts for MLP3 for the dates monitored

	Field			Field			Field	
Date	MLP3	Remark	Date	MLP3	Remark	Date	MLP3	Remark
19/08/2017	2.0	R	05/10/2017	11.0	R	13/11/2017	60.0	I
23/08/2017	62.0	I	17/10/2017	4.0	R	27/11/2017	34.0	R
05/09/2017	5.0	R	25/10/2017	61.0	I	04/12/2017	83.0	R
21/09/2017	59.0	I	06/11/2017	59.0	I	09/12/2017	16.0	R
30/09/2017	7.0	R	08/11/2017	19.0	R	14/12/2017	23.0	R

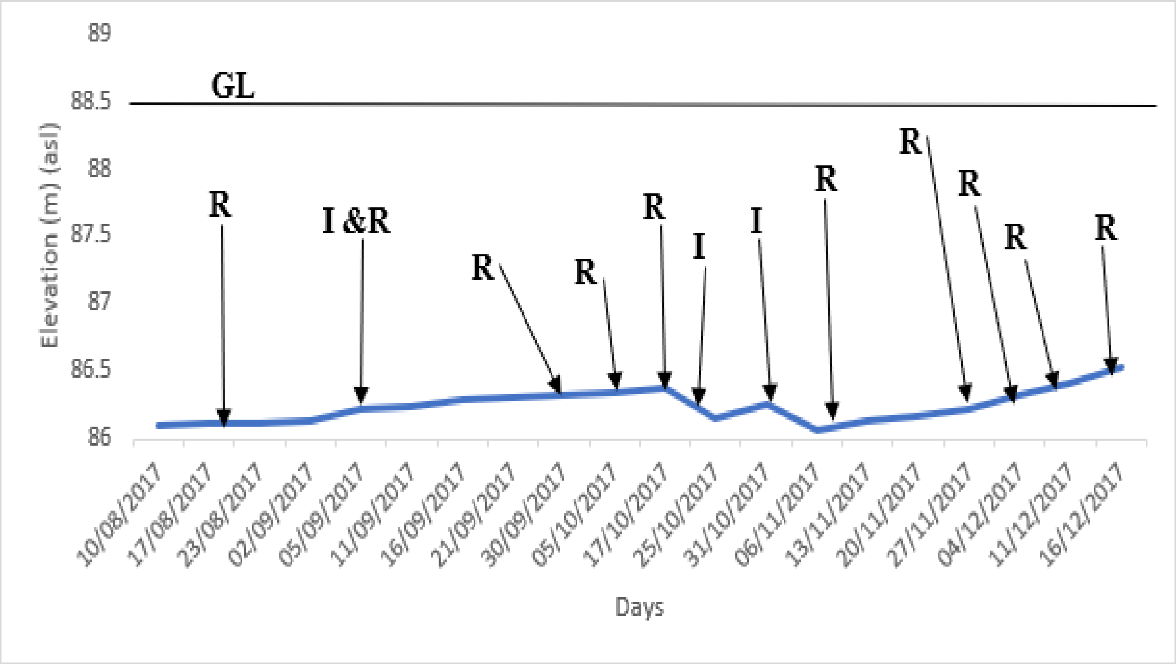


Figure 3.7 Water table graph for Piezometer MUP4 showing days of irrigation (I), rainfall (R) and ground level (GL)

Table 3.4 Measured irrigation (I) and Rainfall (R) event amounts for MUP4 for the dates monitored

	Field			Field			Field	
Date	MUP4	Remark	Date	MUP4	Remark	Date	MUP4	Remark
19/08/2017	2.0	R	17/10/2017	4.0	R	04/12/2017	83.0	R
05/09/2017	57.0	I	21/09/2017	61.0	I	09/12/2017	16.00	R
05/09/2017	5.0	R	31/10/2017	60.0	I	14/12/2017	23.0	R
30/09/2017	7.0	R	08/11/2017	18.00	R			
05/10/2017	11.0	R	27/11/2017	34.0	R			

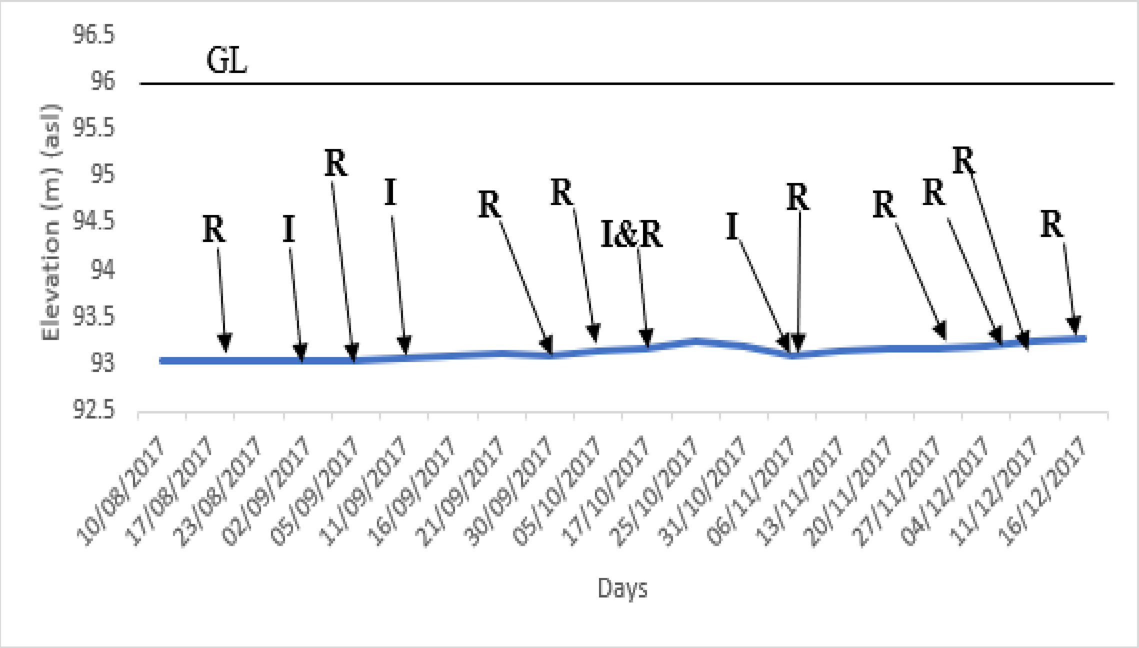


Figure 3.8 Water table graph for Piezometer UP2 showing days of irrigation (I), rainfall (R) and ground level (GL)

Table 1

Table 3.5 Measured irrigation (I) and Rainfall (R) event amounts for UP2 for the dates monitored

	Field			Field			Field	
Date	MUP4	Remark	Date	MUP4	Remark	Date	MUP4	Remark
19/08/2017	2.0	R	05/10/2017	11.0	R	27/11/2017	34.0	R
02/09/2017	63.0	I	17/10/2017	64.0	I	04/12/2017	83.0	R
05/09/2017	5.0	R	17/10/2017	4.0	R	09/12/2017	16.0	R
11/09/2017	61.0	I	06/11/2017	62.0	I	14/12/2017	23.0	R
30/09/2017	7.0	R	08/11/2017	19.0	R			

The correlation between the rise in the hydrograph and irrigation and rainfall events are presented in Figure 3.9. LP1 was chosen because it was monitored more often during irrigation events than the others were, and as such, the scatter plot for correlation was established. The data shows no correlation between irrigation and rainfall amounts relative to water table rise or fall, partly because water table monitoring was done once every week which could have missed the water table response. This could have been because the soils have very low hydraulic conductivity values which caused water flow in the soils to be very slow. Furthermore; this could have happened because one set of rainfall figures were used for all locations and that not all irrigation applications were not measured. This is shown in a fall of the water table even after recording irrigation events the previous week. However, over the whole monitoring period, water tables in each transect rose by 0.3 m in LP1, 0.4 m MLP3, 0.2 m MUP 4 and 0.42 m in UP2. This is not a large rise considering the rainfall and irrigation over the period.

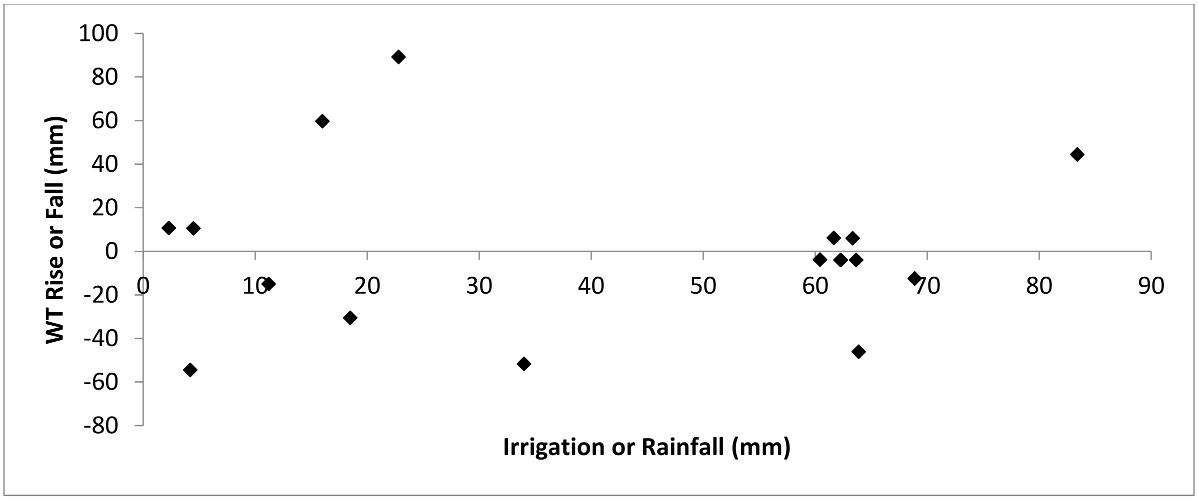


Figure 3.9 Scatter plot of LP1 showing water table rise or fall with amount of water received through irrigation or rainfall

Water table maps for each data collection day across the entire scheme were also generated by interpolation. The water table maps presented are for the first day of data collection (12-08-17), Figure 3.10, and the last day (16-12-17), Figure 3.11. Also presented is the subtracted map for these dates to see how much groundwater was gained or lost (Figure 3.12). When these maps were subtracted from each other using the Surfer13 program to determine water level differences, it was observed that there were large elevation changes, with up to 0.68 m rise in measured water table level.

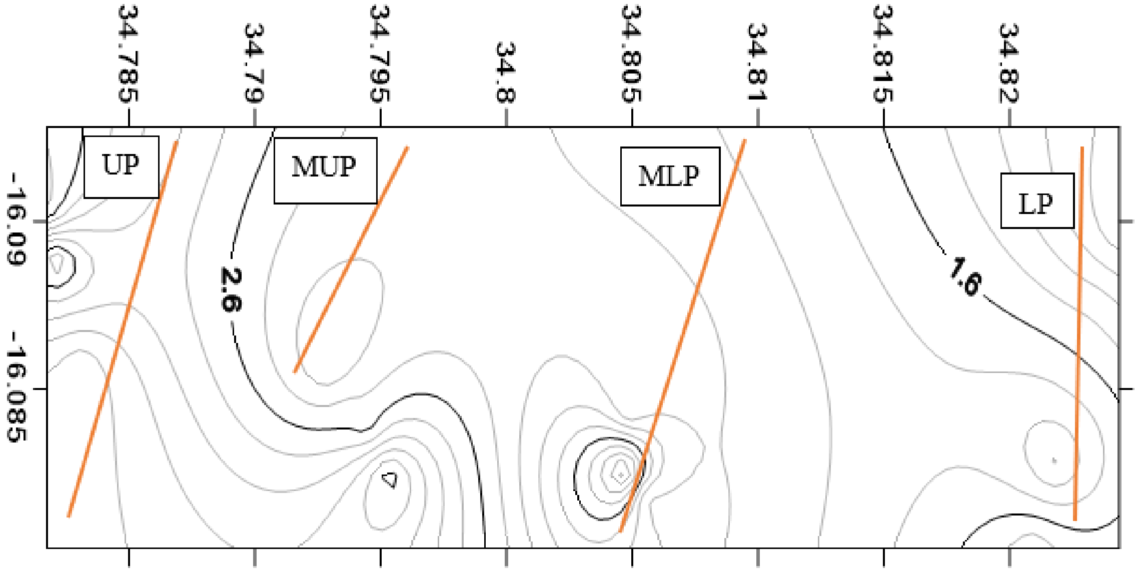


Figure 3.10 Water table map for 12th August 2017 showing depth of water table surface from the soil surface and positions of transects

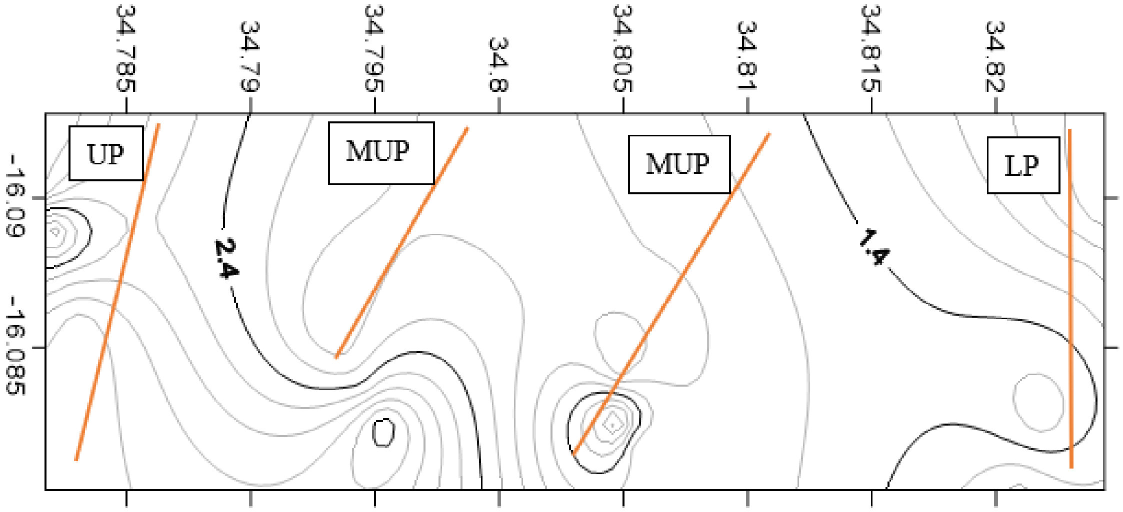


Figure 3.11 Water table map for 16th December 2017 showing depth of water table and positions of transects

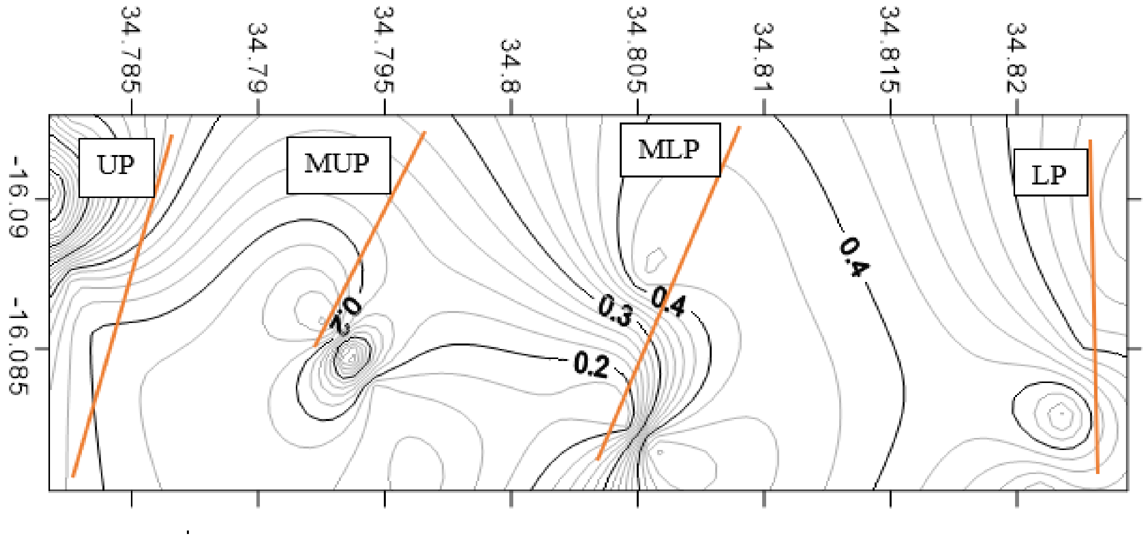


Figure 3.12 Water table change map for 16th December 2017 from 10th August 2017 showing change in depth of water table and positions of transects

From these differences in elevation a calculation of volume changes of water were done by multiplying the average elevation rise or fall with 10 % which is the typical drainable porosity for clay soils and recharge rates were calculated using average elevation rise and number of days between successive dates subtracted as shown in Table 3.6. Drainable Porosity (P_d) was calculated using Skaggs (1978) equation below.

P_d (%) = (drainable pore water (mm) x 100) / (h (mm)) (Skaggs et al. 1994)

Where h is groundwater level change over time

Table 3.6 Observed water table differences from subtracted maps, volume changes of water and net recharge rates with rainfall and irrigation data and estimated drainable porosity

Dates	**Spatially averaged WTD Difference (m)**	**Volume water (mm)**	**Number of days**	**Net Recharge/Discharge rate (mm/day)**	**Rainfall (mm)**	**Irrigation (mm)**	**Rainfall+irrigation (mm)**	**% I+R net recharge**	**Remark**
10-08-17 16-12-17	0.68	68	128	0.53	204	502	705	0.1	Whole period
10/08/2017									
17/08/2017	0.05	5	7	0.71	2	0	2	2.17	Difference between each date
23/08/2017	0.08	8	6	1.33	0	63	63	0.13	
02/09/2017	0.075	7.5	10	0.75	0	0	0	0	
05/09/2017	0.07	7	3	2.33	5	62	66	0.11	
11/09/2017	0.085	8.5	6	1.42	0	0	0	0	
16/09/2017	0.045	4.5	5	0.9	0	65	65	0.07	
21/09/2017	0.08	8	5	1.6	0	62	62	0.13	
30/09/2017	0.07	7	9	0.78	7	64	70	0.1	
05/10/2017	0.05	5	5	1	11	60	72	0.07	
17/10/2017	0.055	5.5	12	0.46	4	0	4	1.31	
25/10/2017	-0.45	-45	8	-5.63	0	0	0	0	
31/10/2017	-0.22	-22	6	-3.67	0	0	0	0	
06/11/2017	0.13	13	6	2.17	0	63	63	0.21	
13/11/2017	0.115	11.5	7	1.64	19	0	19	0.62	
20/11/2017	0.06	6	7	0.86	0	62	62	0.1	
27/11/2017	0.07	7	7	1	34	0	34	0.21	
04/12/2017	0.1	10	7	1.43	83	0	83	0.12	
11/12/2017	0.105	10.5	7	1.5	16	0	16	0.66	
16/12/2017	0.11	11	5	2.2	23	0	23	0.48	

3.4 Groundwater, soil and irrigation water salinities

The observed groundwater salinities across the scheme showed lower salinity than expected dilution capacity. The graphs below show how groundwater salinities varied for each transect. When these salinities for individual piezometers were plotted together for the same transect, it was observed that there were also variations for each piezometer as shown in Figure 3.13 and Figure

3.14. The decreasing trends for the graphs across the scheme are as a result of increased irrigation activities and rainfall which was experienced in the area which washed away salinity sources from the soils.

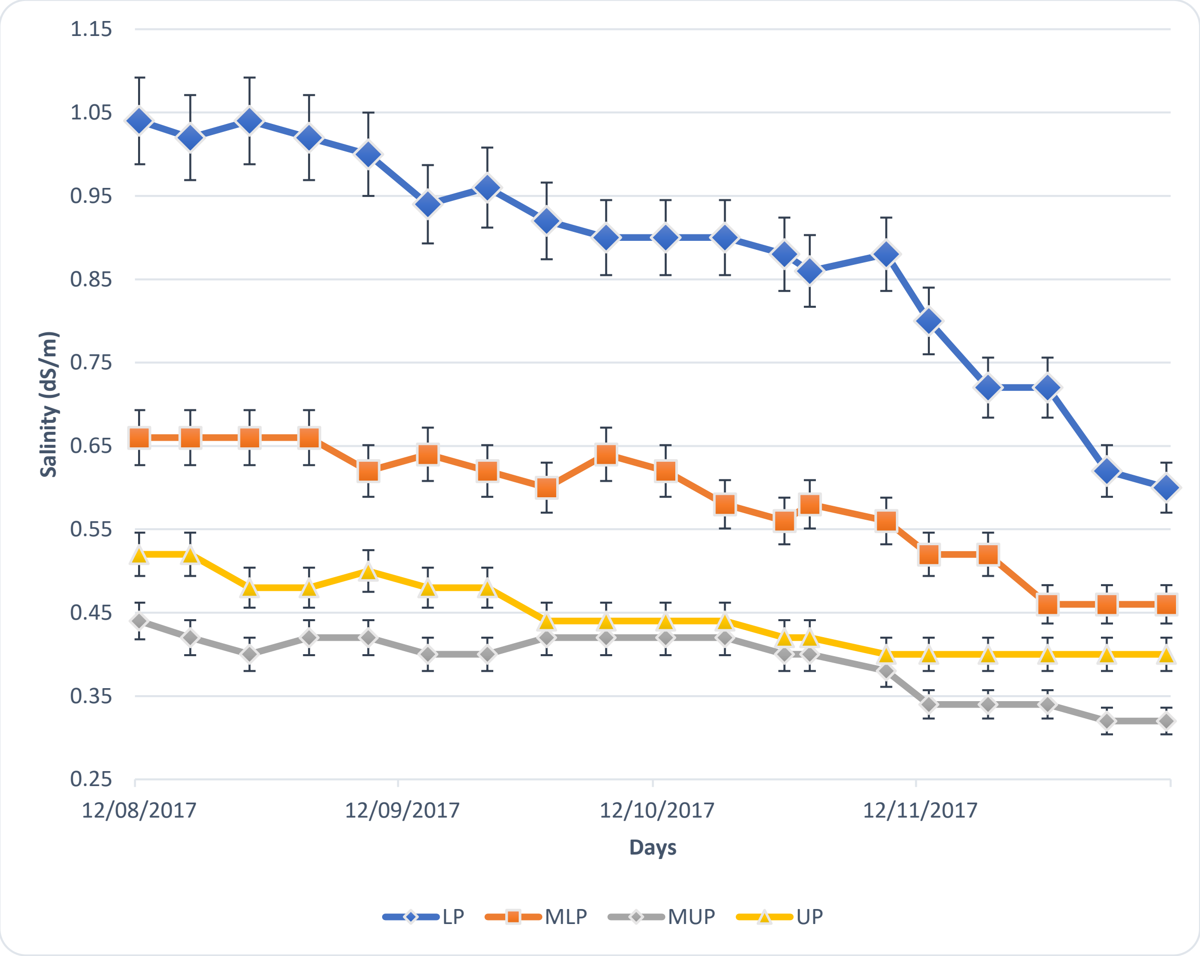


Figure 3.13 Average groundwater salinities for each transect showing error bars

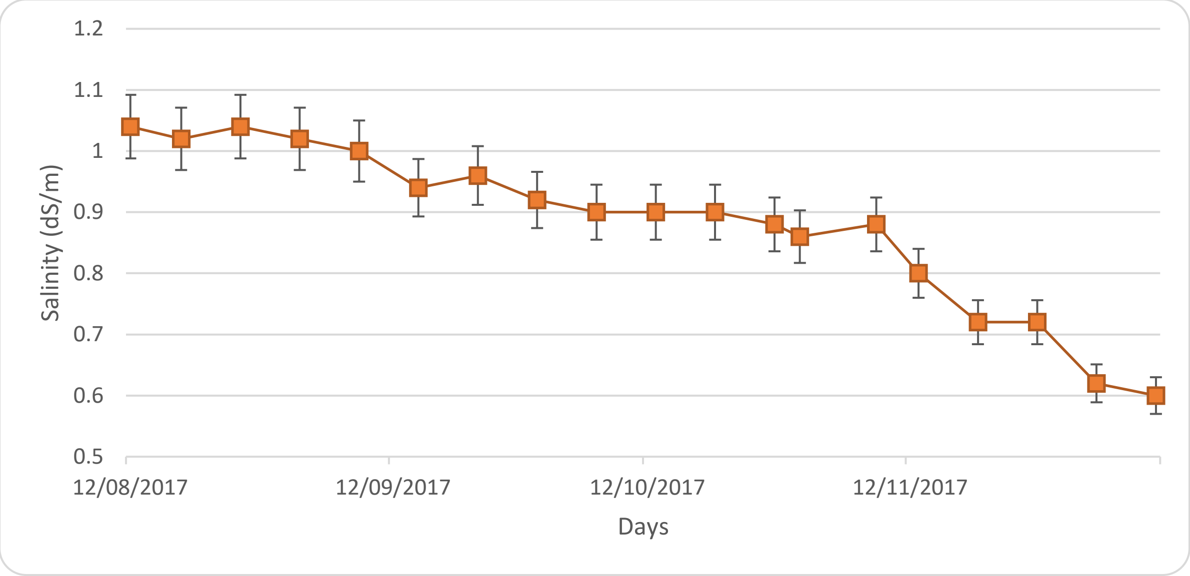


Figure 3.14 Average groundwater salinities for LP transect

Similarly, the salinity of irrigation water from Shire River was tested weekly by collecting water from the canals using a tumbler and tested using the EC meter as presented in Figure 3.15. From this data, it is observed that the irrigation water salinities were well below the sugarcane 1.7 dS/m ECe salinity threshold levels (Malota and Senzanje 2016), which means that the water was safe for irrigation when drainage is good, otherwise poor drainage could quickly raise soil salinity to unwanted levels.

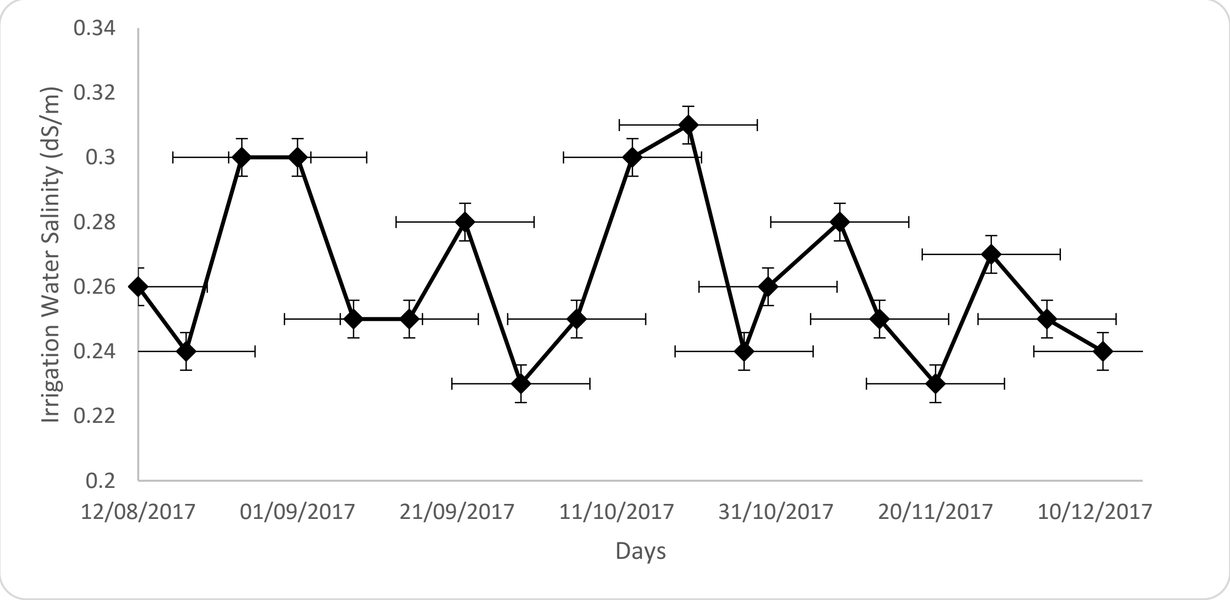


Figure 3.15 Irrigation water salinities measured at Kasinthula

Soil salinities observed for Kasinthula were found to be higher than sugarcane threshold salinities. Figure 3.16 shows the soil salinities generated after converting the 1:4 soil water solution salinities with conversion factor values calculated using the relationship between bulk and particle densities to develop the relationship with ECe. It must be pointed out that the conversion factors obtained of 5.3 to 6.9 were very similar to those presented in literature tables for different soils (Shaw 1988). The area has highest soil salinity of 8.5 dS/m while the lowest was 1.64 dS/m with mean salinity at 4 dS/m. From the data, it was observed that the lower transect had very high soil salinity levels, unlike the upper transect. Despite this, even in the upper transect, salinity levels were higher than sugarcane threshold levels.

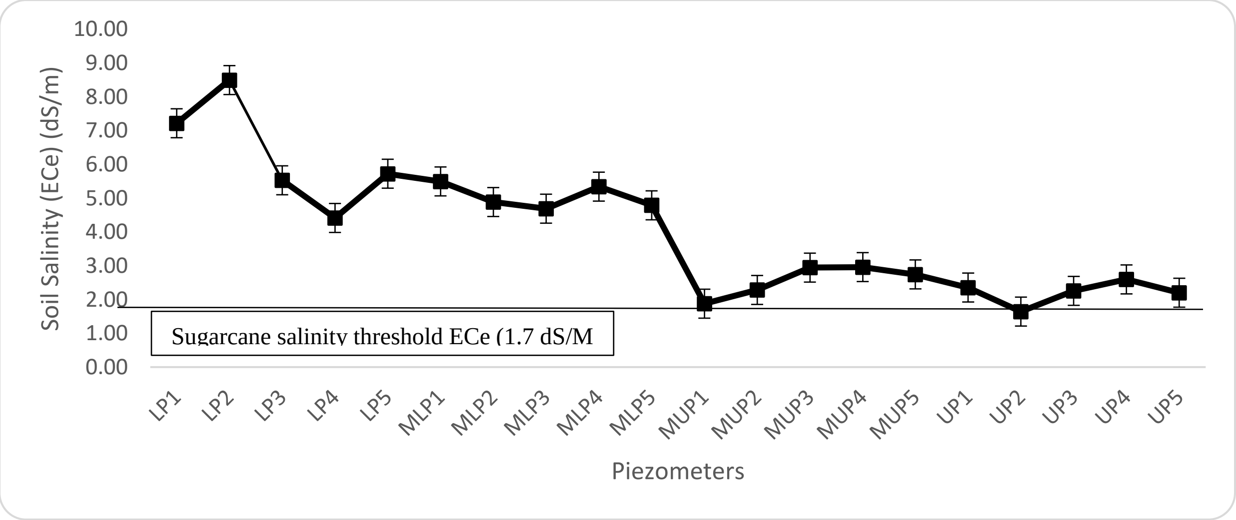


Figure 3.16 Saturated paste soil salinities calculated from measured 1:4 EC values obtained at Kasinthula

3.5 Discussion

This section will discuss the results based on the data collected. It includes calculations and output from various software packages used for analysis. Emphasis will be given to interpretation of results relative to various other published studies.

3.5.1 Soil characteristics

From the observed data, the soils around Kasinthula exhibited two distinct layers in the profile. The top layer extends from the surface to around 60 cm and is usually clay to clay loam in texture as shown in Table 3.1. The deeper layer which extends beyond 1 m to almost 5 m, is predominantly clayey, as observed from soil samples collected during installation of the piezometers.

The top layer has bulk densities which range from 1.4 g/cm^3 to 1.6 g/cm^3, while the particle densities range from 2.3 g/cm^3 to 2.5 g/cm^3 as shown in Table 3.7 below. From this table it can be deduced that there are no statistically significant differences in bulk densities and particle densities across the area because the CVs are 3.51 % and 2.28 %. These CV values are far less than 35% which Wilding (1985) reported as cut off points.

The maximum hydraulic conductivity (K_{sat}) and minimum K_{sat} calculated from the piezometer bail out tests were 0.06 m/day and 0.03 m/day respectively, with a CV of 31.21 %. These K_{sat} values are typical for clay and clay loam soils which are alluvial deposits (Freeze and Cherry 1979), which are the dominant soils across the scheme. Similarly, pH in the area shows little variation since its CV of 7.74 % is also far less than the 35 % Wilding (1985) benchmark. However, a look at ECe shows a CV of 43 % indicating a high variability over the scheme.

Table 3.7 Descriptive statistics of soil characteristics in the top 1 m and aquifer characteristics of Kasinthula Irrigation Scheme up to the 5 m depth

Statistic	Bulk Density (g/cm^3)			Particle Density (g/cm^3)			pH			ECe (dS/m)			K (m/day)
Depth (m)	**0.0-0.3**	**0.3-0.6**	**0.6-1.0**	**0.0-0.3**	**0.3-0.6**	**0.6-1.0**	**0.0-0.3**	**0.3-0.6**	**0.6-1.0**	**0.0-0.3**	**0.3-0.6**	**0.6-1.0**	**0.0-5.0**
Minimum	1.41	1.42	1.41	2.31	2.34	2.29	6.81	6.53	5.04	1.83	1.64	2.85	0.02
Maximum	1.62	1.63	1.64	2.57	2.52	2.59	7.51	7.34	7.52	5.92	8.52	8.13	0.06
Mean	1.51	1.51	1.52	2.45	2.41	2.45	7.14	6.95	6.91	3.28	4.02	4.67	0.04
Standard Deviation	0.06	0.05	0.06	0.07	0.06	0.07	0.24	0.29	0.54	1.27	1.92	1.93	0.01
CV (%)	3.93	3.31	3.95	2.84	2.51	2.86	3.44	4.17	7.23	38.71	47.63	41.38	25.24

Saturated hydraulic conductivities are directly linked to soil bulk densities, as well as least limiting water ranges. They are usually affected by textural classes and management systems in place such as tillage practices. The bulk densities that were found for all textural classes of soil around Kasinthula seem to correlate with what literature defines as typical bulk densities of clay and clay loam soils (Arshad et al. 1996). Since the average value obtained (1.52 g/cm^3) is within the ranges of the soils mentioned above, their effect on limiting root development is not severe in sugarcane (Harris and Bezdicek 1994). Non-limiting soil density is below 1.75 g/cm^3 (Daddow and

Warrington 1983), hence the sugarcane at Kasinthula have all the soil physical conditions that would allow healthy growth.

It is known that soil porosity is affected by the bulk density which also influences hydraulic conductivities of different soils. The results from Kasinthula show that the hydraulic conductivities of 0.06 m/day are higher for clay soils than those reported in literature (Harris and Bezdicek 1994). This could be attributed to tillage practices which take place yearly after harvesting where all fields have the furrows between ridges ripped to allow improved water infiltration in the subsequent ratoon. Strudley et al. 2008 and Wallor et al (2018) in their different studies concluded that continued tillage practices in cultivated lands tend to increase K_{sat}.

Groundwater salinities for the scheme were observed to be lower than the published salinity threshold for sugarcane. For example, lower groundwater salinity of 0.3 dS/m was observed in the upper transect, while higher salinity values of between 1.0 to 1.2 dS/m were recorded in the lower transect. However, soil salinities were very high, and when presented in a scatter plot against water table depths, it was observed that there was a negative correlation with depth to water table. Shallow water tables exhibited higher soil salinity levels, unlike deeper water tables as seen in Figure 3.17. The high soil salinities can be attributed to crop root water uptake which results in salts accumulating in the root zone. There also would be more concentration of salts further down the slope (cumulative effect).

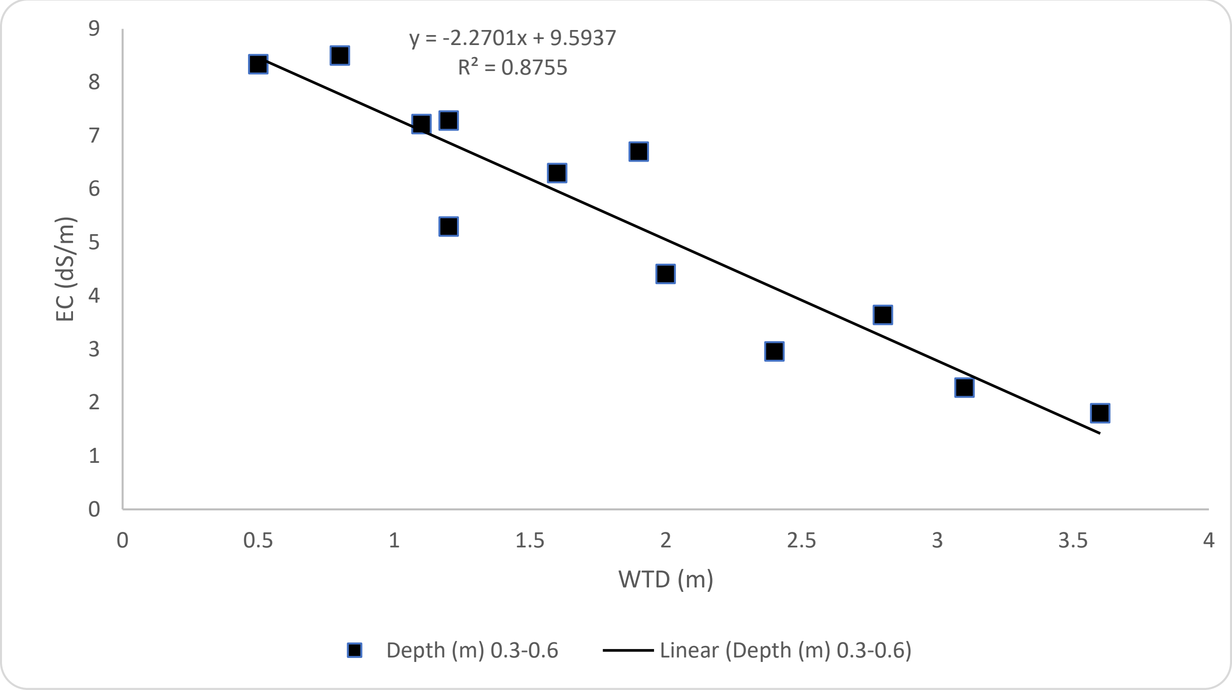


Figure 3.17 Scatter plot of average soil salinities against water table depths

3.5.2 Shallow groundwater dynamics

Variable water table fluctuations were observed in the different fields. Water tables rose considerably with irrigation or rainfall events. For instance, on the 17th of August 2017, when 64.5 mm of water was applied in LP2, the water table rose by 30 mm within 7 days. This indicates that the soil could not recharge and discharge fast enough with any amount of water the area receives. The rise registered was very small considering during this seven-day period, but the small values observed could be due to the monitoring frequency which was done once every week. Probably if the monitoring was done daily, the recharge observed could have been much higher as shared by what Fouss et al. (2007) reported on groundwater replenishment when they were studying water table control systems in almost similar soil conditions as Kasinthula. In this study almost 50% of the drainage flow was from irrigation water which had risen barely 24 hours after an irrigation event. During our scheme observation period, it was noted that there were periods of net discharge, especially when there was no power to run the pumps, with the whole scheme registered falling water tables of up to 0.45 m in almost 21 days. This tells us that water table depth can be controlled by adjusting irrigation intervals. Over-irrigation can lead to leaching of N and pay a penalty in yields.

The water table in the lower transect piezometers was closest to the surface at almost 0.5 m, while the upper transect had the deepest shallow water table which was around 3.5 m from the surface. The difference in elevation between these transects was almost 20 m. This essentially means more water was supposed to flow down gradient, but a water table of only 0.5 m on the lower section was recorded. Although groundwater in the upper section flows downwards to the lower sections (Ibrakhimov et al. 2011), it is, however, guided by geological formations, especially alluvial depositions, impermeable layers and topography (Sophocleous 2002). Kasinthula Scheme has clay loam soils in the upper section and clay soils in the lower sections which could affect flow of water downwards since clays have lower hydraulic conductivities which can impede flow. The piezometers were drilled to a depth of only 5 m, and there is a possibility that below this depth soils could be sandy which could act as an aquifer conduit path with least resistance, resulting in limited water table rise, as more water will drain down the soil profile into the Shire River, the main source of water for the scheme.

Table 3.8 presents aquifer characteristics for the Kasinthula Irrigation Scheme There is another possibility of an impermeable layer lying horizontally at Kasinthula which could divert water to the edges of the scheme. Alternatively, since Kasinthula is in a faulted area, and considering the map of Kasinthula (Figure 2.1), minor rivers are seen within the scheme which were trained during construction but would drain the water from the upper section before reaching the lower section, thus, leaving the slope of the water tables to be uniform (Sophocleous 2002; Sehatzadeh 2011).

Table 3.8 Aquifer characteristics of the Kasinthula Scheme for top 5 metre soil depth

Aquifer characteristics	**Description**
Type of material	Generally, clay to clay loam
Hydraulic conductivity (k)	0.06 m/day
Porosity	54%
Storativity	0.015
Depth of aquifer	>5 m
Flow direction	Vertically downwards
Average hydraulic gradient	0.005
Unit flow rate	0.3 mm/day/m^2

From Table 3.8 above, we see that the aquifer around Kasinthula has a very low conductivity of around 0.06 m/day. This means that no matter the hydraulic gradient, very little water can flow through the system. For example, the vertical elevation difference between the LP and UP transects is about 20 m and the horizontal distance is 4000 m which gives the hydraulic gradient (i) of 0.005. When Darcy's equation (Q = kiA) is used to calculate unit flow rate, we obtain 0.0003 m/day per m^2 cross section area or simply 0.3 mm/day. This water does not cease flowing towards the LP position as it continues to flow down towards the river. This is why in all areas the response of all piezometers is very similar; there is not a bigger rise in the low-lying areas relative to higher lying areas because groundwater flow in the whole system is very slow and continuous.

When we look at the poor correlation between irrigation or rainfall and water table rise or fall in Figure 3.9, a general trend of water table rise across the scheme over time is noted. As this rise over time is very similar across the scheme it can be said that the aquifer appears to be quite uniform in its nature and also that it appears that the rate of recharge and discharge is very similar across the scheme. It is noticeable that when all irrigation is stopped due to pump failure the water table dropped everywhere. This indicates that the whole area is similarly affected by recharge from irrigation. This is clearly noticeable when the trends of LP and UP are compared. Trends are very similar, which indicates that the aquifer responds in a very similar way everywhere. This probably means that the water table drop was due to the general aquifer discharging down gradient towards the river system.

A closer look at different fields which exhibited near waterlogging conditions, and those that showed none, indicates that fields that were on the lower end of groundwater flow were more prone to water being near the surface, unlike others that were at a higher elevation. This also supports the school of thought that water flows from higher to lower elevation, especially driven by hydraulic gradient (Dandekar and Chougule 2010). For instance, in the Upper Transect, UP3 had a rising water table, unlike UP4 and UP5 which happen to be on a higher elevation than UP3. The same situation was observed in MLP where MLP1, which is on the lower end, had a water table closer to surface. These observations were also noted in all transects where piezometers with lower elevations had shallower water tables than those with higher elevations in the same transect. For instance, when the ground level cross section of MLP in Figure 3.18 is considered, where arrowheads are the tops of piezometer positions, it is observed that MLP2 is on a higher elevation than MLP1 which had water closer to the surface throughout the study duration.

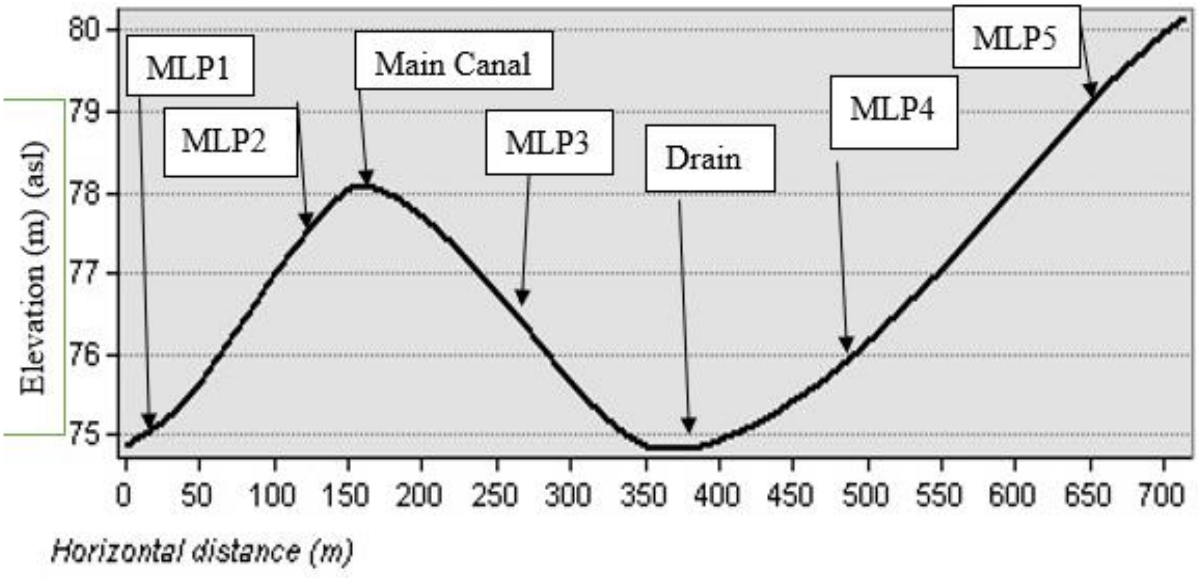


Figure 3.18 Cross section of MLP showing crests for feeder canals and troughs for drains

3.5.3 Soil, irrigation and groundwater salinities

The soil salinities observed at a depth of 0.3 to 0.6 m, which is the depth of most roots of sugarcane, are considered higher than threshold salinities for sugarcane to thrive. The tests on soil salinities indicated a highest salinity level of 8.5 dS/m recorded in LP, while the lowest of 1.64 dS/m was recorded in UP. When these values are compared with allowable stress-free salinities of sugarcane of 1.7 dS/m, it can be deduced that the area has very high salinity problems. Even a comparison of cane yield in the UP was found to be higher than that of LP. Although the lowest salinity recorded is close to the threshold, it is assumed to be high enough to have an effect on yields. If different times of the year are considered, salinity could rise above threshold levels, especially deep in the summer months when the area has low rainfall and only depends on irrigation. Furthermore, Northey et al. (2006) explained that the top of the water table can exhibit varying salinities due to changes in interactions of groundwater, soil water and irrigation water entering the soil profile which may lead to salinity stress at short intervals due to fluctuating water tables which could still be detrimental even during rainy seasons.

The high soil salinities which are mostly way above the Maas Hoffmann sugarcane salinity threshold could explain the decrease in yields per hectare over the years. This could have been caused by irrigation water which could cause salts to rise to the surface and as roots abstract the water could have led to salt build up in the upper soil profile. Another reason could have been salt rise using the faults from the salt bearing geological formations underneath the area. (Sehatzadeh 2011). A look at soil salinities from individual transects shows that the lower transect registered higher soil salinities than the upper transect. This could have been caused by lateral downward transport of salts form higher areas to the lower areas in the scheme. On the other hand, soil salinities within the same transect from individual piezometers showed variations which could have been attributed to differences in elevations between individual piezometers which caused water from higher areas to flow towards low areas and in the process transporting salts dissolved in them.

When groundwater salinities between individual fields within a transect are considered, it was observed that the fields had varying salinities which could explain the differences in yields of individual fields. For instance, the groundwater salinity in MLP1 kept dropping with time, unlike for MLP2 as shown in Figure 3.19. As seen in the previous section where it was observed that groundwater tended to be closer to the surface in MLP1 than in MLP2, the continuous flow of water may have helped wash away the salts in the profile of MLP1 due to drainage. The yields of lower lying fields in the same transect were comparatively lower than those in higher lying fields. For some reasons, MLP2 groundwater salinity values remained the same throughout the monitoring period, unlike all other monitoring points in the scheme. It was difficult to detect the main reason for this behaviour, but MLP2 is very close to the earth main canal (about 20 m), which supplies water from a storage reservoir to all fields, and it could have experienced seepage from the main canal to affect the salinity of the groundwater around MPL2.

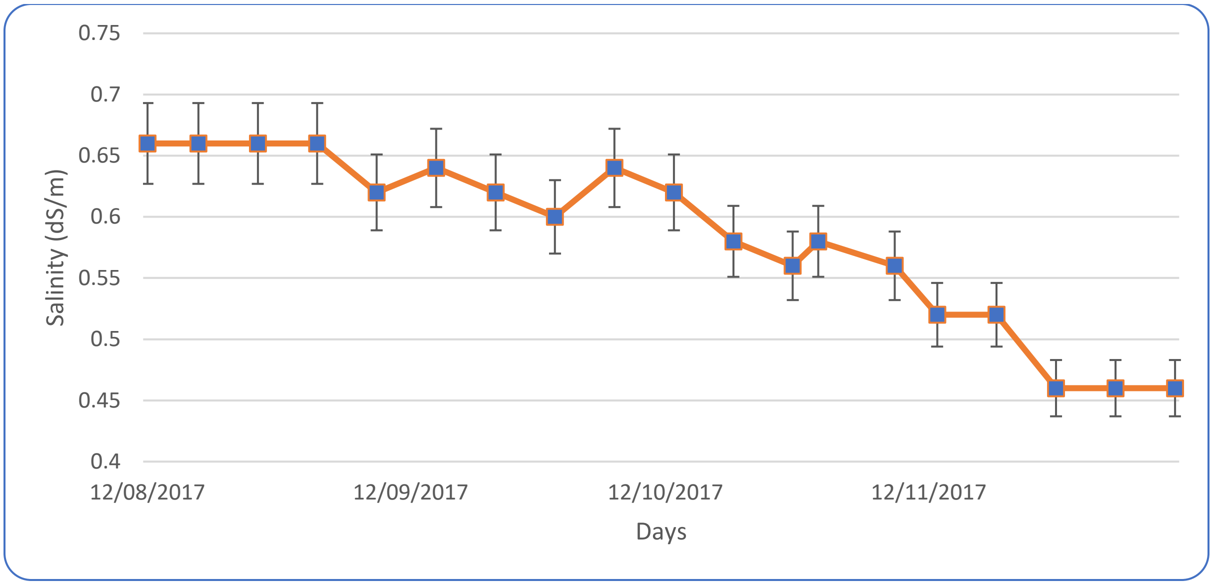


Figure 3.19 Average groundwater salinity variations across different piezometers in MLP

Kasinthula is underlain by highly saline strata due to the presence of fault lines (Sehatzadeh 2011) which puts the area at risk of salinization due to capillary up-flow if irrigation is not properly managed (Northey et al. 2006). Therefore, to reduce the high soil salinity of the area, the farmers' water management practices must consider improving drainage as it was observed that not all fields had proper drainage systems which caused temporary water logging conditions immediately after irrigation or rainfall, as seen in Figure 3.20 and that yields in fields with drainage were higher over the years as compared to the yields in fields without proper drainage system. They can also improve their irrigation management practices which would be much cheaper since the data showed that when the water was disrupted due to power outage, the water table receded significantly and they can also use agriculture lime to redress the salinity issues in the short-term period since the soils are very rich in sodium (Na).

Figure 3.20 A field showing signs of temporary waterlogging at Kasinthula, and a piezometer with a white cap

4.0 The effect of salinity and water table depths on sugarcane yields

4.1 Overview

The problem of salinity in irrigation schemes has been present since time immemorial (Askri et al. 2014). Salinity in irrigation schemes can arise from applied water, inorganic inputs and sometimes underlying geological formations on the site (Fouss et al. 2007). Water that is applied onto farms has certain amounts of salt which can eventually lead to salinization, even though water of salinity less than 0.3 dS/m is considered safe with good drainage (Fouss et al. 2007).

Soil or water salinity is known for limiting growth of crops, leading to loss of production (Shomeili et al. 2011). When salinity exceeds tolerance levels, crop production is adversely affected (Ayars et al. 2006). Maas and Hoffman (1977) led the process of characterising plant salt tolerance through linking yield loss as affected by rootzone salinity increases. This function also helps to adjust potential crop water use from shallow groundwater resources (Ayars et al. 2006) but the threshold values must be used in correlation with other factors such as the amount of irrigation water to be applied which can increase salt accumulation and water logging because Maas (1990) reported that plant salinity tolerance varies with growth stages and crop species.

Sugarcane is one of the crops considered to be in the medium salt tolerance category (du Plessis et al. 2017). It is widely grown in tropical and sub-tropical areas around the world (Shomeili et al. 2011). The crop thrives well when the soil salinity is less than or equal to 1.7 dS/m measured in a saturated soil extract. Other studies, have reported that sugarcane yields are less affected in rootzone soil salinities of up to 3 dS/m with a yield decline of only 10%, however, when the salinities rise above this up to 5 dS/m, the yield is negatively affected and yield losses can be up to 25% (Shomeili et al. 2011). Higher yield losses have been reported when rootzone salinities rise above 5 dS/m (Malota and Senzanje 2016). However, some cultivars are said to withstand rootzone salinities of up to 10 to 15 dS/m where yield losses are 35%; above which serious yield losses are encountered which makes farming sugarcane uneconomical (Rozeff 1995; Soltani et al. 2008; Shomeili et al. 2011). This is because higher soil salinities affect biomass production and juice quality, which in turn affect sucrose content and yield (Lingle and Wiegand 1997).

Soil salinity has an indirect impact on yields due to reduced water uptake because of decreases in osmotic potential. Water table depth also affects how a plant uses soil water. Shallow water tables have a potential to increase salinization through capillary effects (Fouss et al. 2007) which if left unattended could jeopardize profitable crop production. However, shallow water tables can also be used to supplement irrigation requirements to crops if the crops have roots that are deep enough to be in proximal contact with the upper layer of the water table (Northey et al. 2006). In such cases, the shallow water table can be used to reduce irrigation pumping costs, improve plant growth and in turn improve yield through readily available water which would otherwise be left without use.

Many studies have linked the importance of shallow water tables to agricultural productivity. Ayars et al. (2006) presented a list of literature which explained how different crops have been studied utilising shallow water table as supplement to irrigation. In the studies cited, it was reported that among the many factors that affect shallow water table utilisation, soil type and the crop being grown are key, which in turn, determines how much irrigation can be reduced as the crop uses the shallow groundwater (Escolar et al. 1971; Ayars et al. 2006).

For the utilisation of shallow groundwater to be effective and minimise yield loss to over-irrigation and salinity, water managers must ensure that the rootzone is close enough to the shallow water table and that groundwater salinity EC ratio in the Maas- Hoffman threshold to yield is less than 2 so that it matches the salt tolerance of the crop. The water managers should also ensure that the ratio of duration for maximum root development to total growth days is less than 0.5 so that the crop has enough time to use the shallow ground water and that the ratio of maximum rooting depth and mean water table depth, should be more than 0.5 and that ratio of effective water extraction depth to water table depth should be less than 0.4 when the Meyer equation Z_r/Z_{max} is used (Ayars et al. 2006). The Meyers Equation describes that the top one-third of the root zone is the one that has maximum root density and directly contributes to significant water uptake.

At Kasinthula Irrigation scheme, sugarcane yields have been noticeably declining for the past 20 years. On average the ratoon age is between 10 to 12 months and plough out happens usually after 8 to 10 years. For some reasons, cane varieties are changed when planting is done after plough out, but the main varieties for the scheme still remain MN1, N14 and N32 (Isyagi and Whitbread 2002). Kasinthula receives an average rainfall of 700 mm per annum. The objective of the research was to attempt to ascertain if salinity and water table depths played a role in the declining yields and to try to provide management strategies which farmers could employ to improve yields and thereby return profitability to the scheme. The next section will present yield results which will be discussed in relation to salinity and water table depth effects on yields.

4.2 Sugarcane yields

Yield data from 2001 to 2017 were obtained for the scheme from the mill where Kasinthula farmers deliver their sugar. Average annual yields per ha are presented in Figure 4.1.

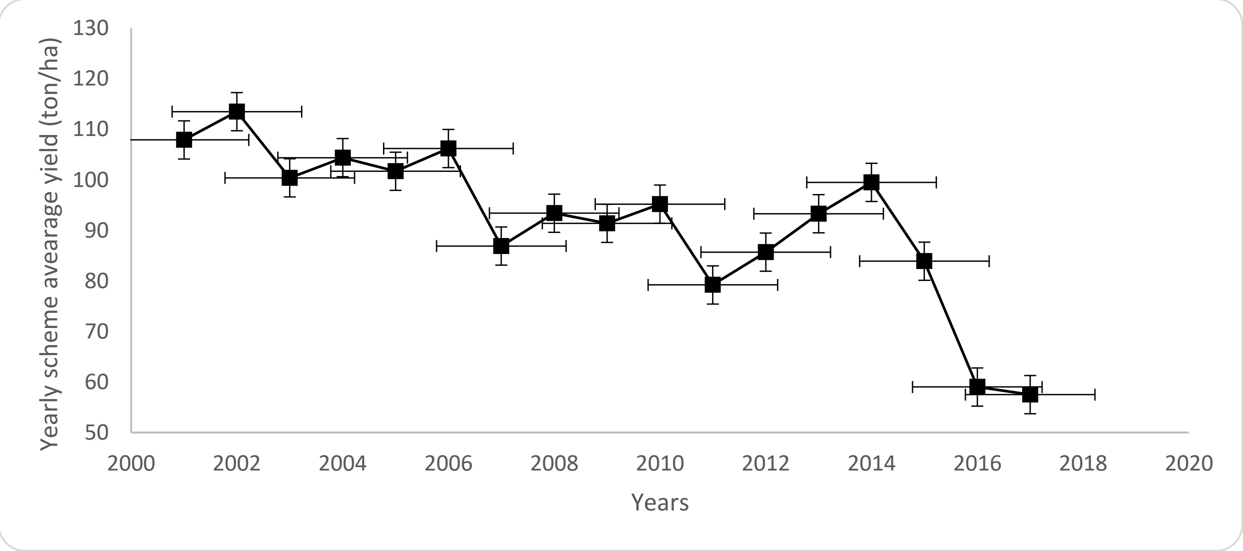


Figure 4.1 Average annual scheme yield for Kasinthula

Scheme annual yields were used to produce yield distribution maps using Surfer 13 software as seen in Figure 4.2 where the axes are geographic coordinates. For example, in 2001, the highest yield recorded was around 145 ton/ha while the lowest was around 65 ton/ha while in Figure 4.3 for the year 2017 the highest yield was 105 ton/ha with the lowest being 25 ton/ha. The yield losses are very worrisome considering that production input prices are increasing every year. It can be observed that from 2010 – 2014 yields increased every year, mainly because of new fields that were developed under centre pivot irrigation system and the replanting activities that were undertaken in some furrow irrigated fields. However, there was a sudden huge yield drop in 2015 and 2016 which may be attributed to higher soil salinity, but not water table fluctuations. It may also be due to agronomic factors such as low fertiliser use, disease pressure or lack of irrigation water in those years.

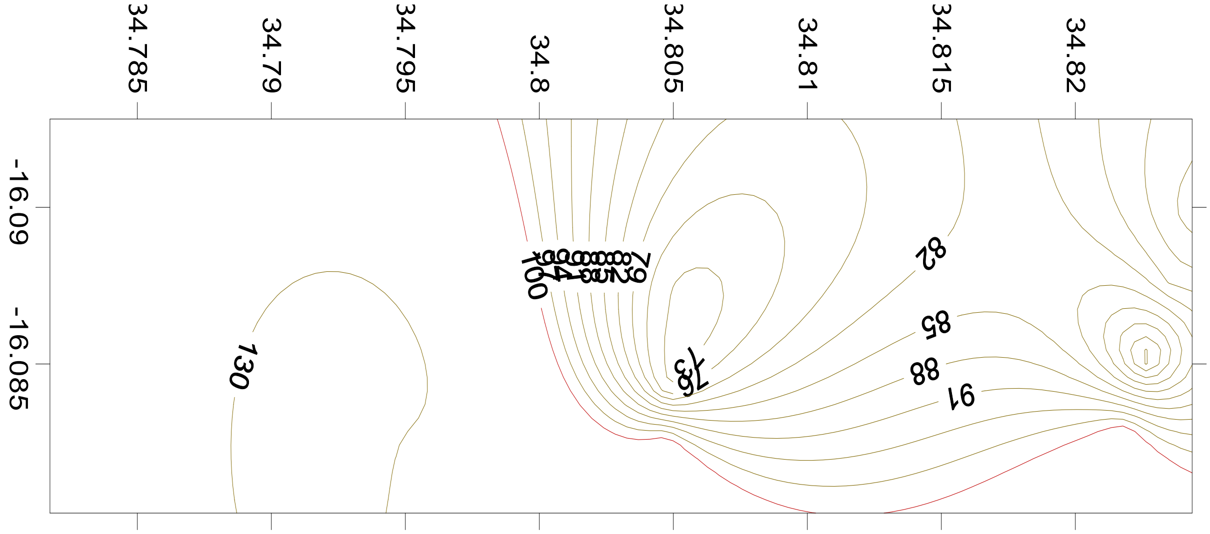


Figure 4.2 2001 Yield (ton/ha) map for Kasinthula Scheme

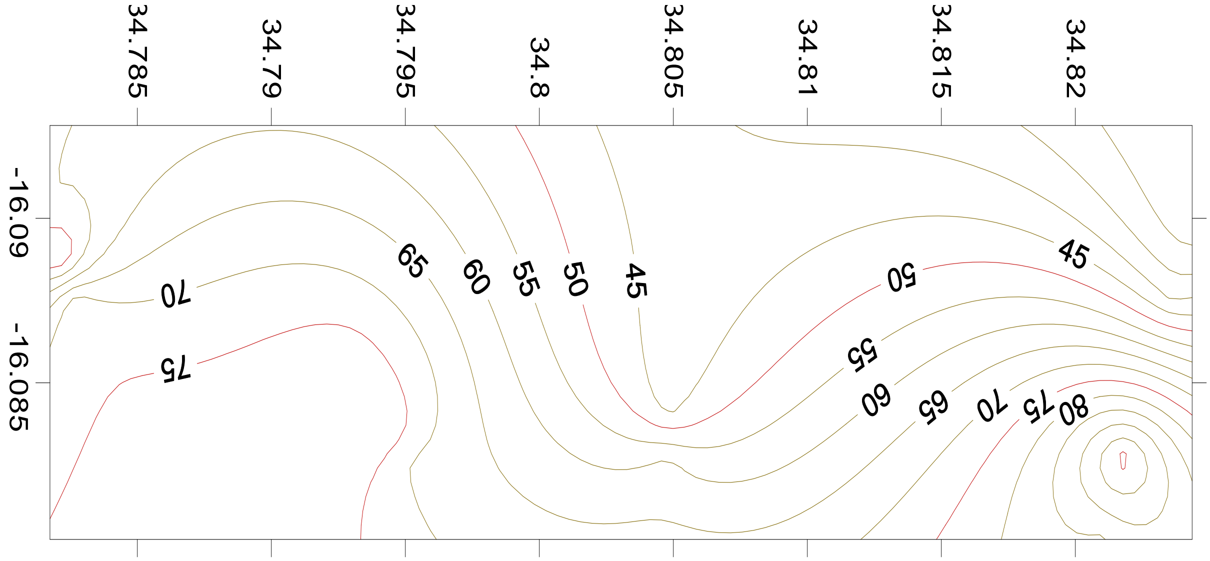


Figure 4.3 2017 Yield (ton/ha) map for Kasinthula Scheme

A closer look at yield map for 2001 shows that most fields had yields ranging from 80-100 ton/ha, except in a small area that has very high yield of more than 130 ton/ha. This could be an area with a few very high yielding fields which makes the map display more contours in a specific area than the other. The 2017 yield map shows almost the same yield (75 to 80 ton/ha), irrespective of elevation differences. It should be stated that the whole area was under sugarcane production and the map interpolation represents the actual yield recorded.

The subtracted yield maps for different years were also generated using the same software as seen in Figure 4.4, depicting subtracted yields of 2001 and 2017. This was used to calculate the amount of yield that was either lost or gained in the subtracted years per hectare for the scheme. Some parts in the upper section of the scheme have lost up to 70 ton/ha, while the lower section registered 60 ton/ha as highest sugarcane yield losses. This does not support the expectation that yield losses would be largely affected by elevation difference which contribute to water table rise and salinity in the lower sections. In fact, in some areas of lower elevation, the smallest yield losses of as low as 5 ton/ha over the years were registered, while the mid elevation regions exhibited yield losses of between 35 to 55 ton/ha.

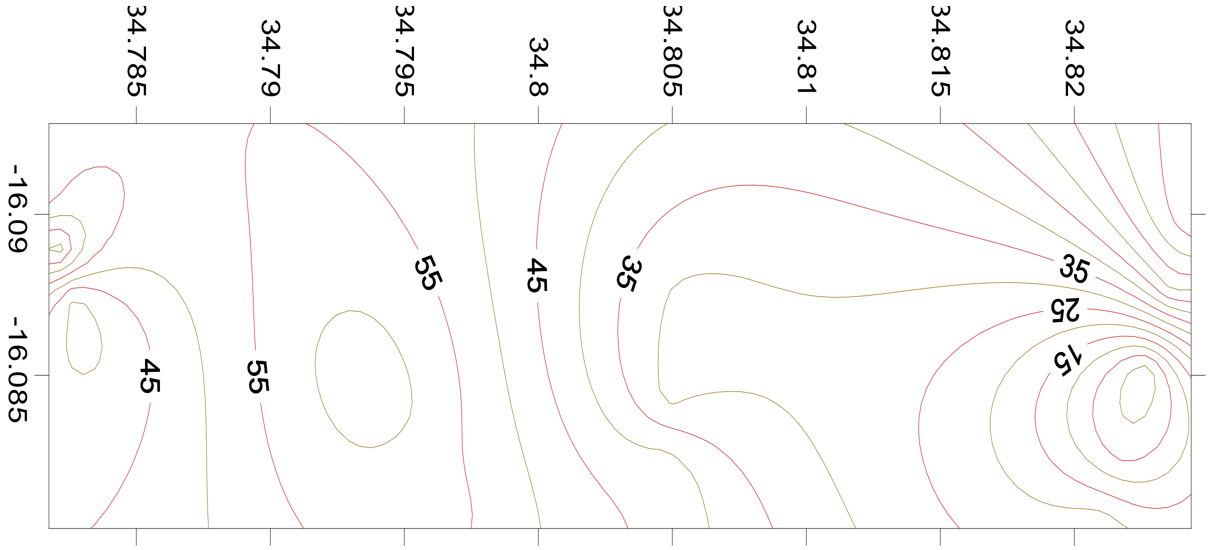


Figure 4.4 2001 and 2017 Subtracted yield map for Kasinthula Scheme

When yield changes for each transect were compared for the different years, it was observed that yields exhibited a dwindling trend in all transects with increase in ratoon age. Figure 4.5 to 4.8 show graphs of different fields in each transect. It is clear from all transects that yields continued to drop year after year except when the fields had new plant cane. However, it does not take long before yield declines are again observed.

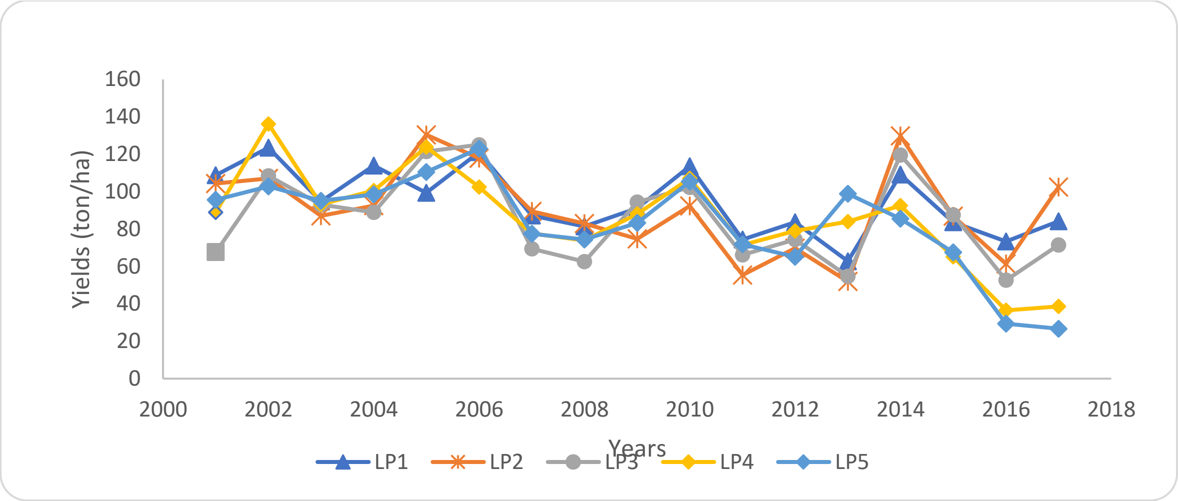


Figure 4.5 Yields of fields in LP from 2001 to 2017

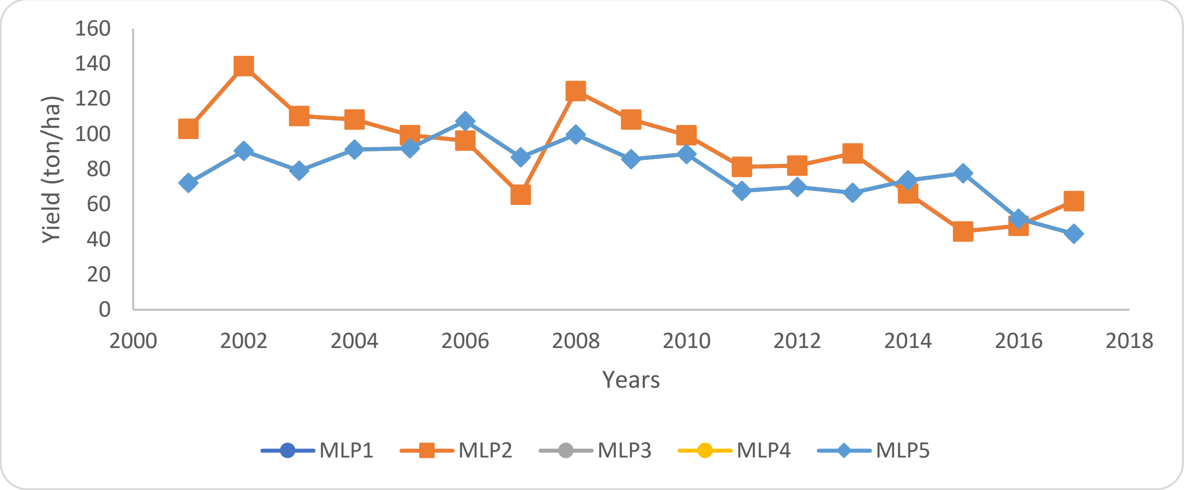


Figure 4.6 Yields of fields in MLP from 2001 to 2017 where MLP1 falls directly under MLP2 while MLP3 and MLP4 fall under MLP5

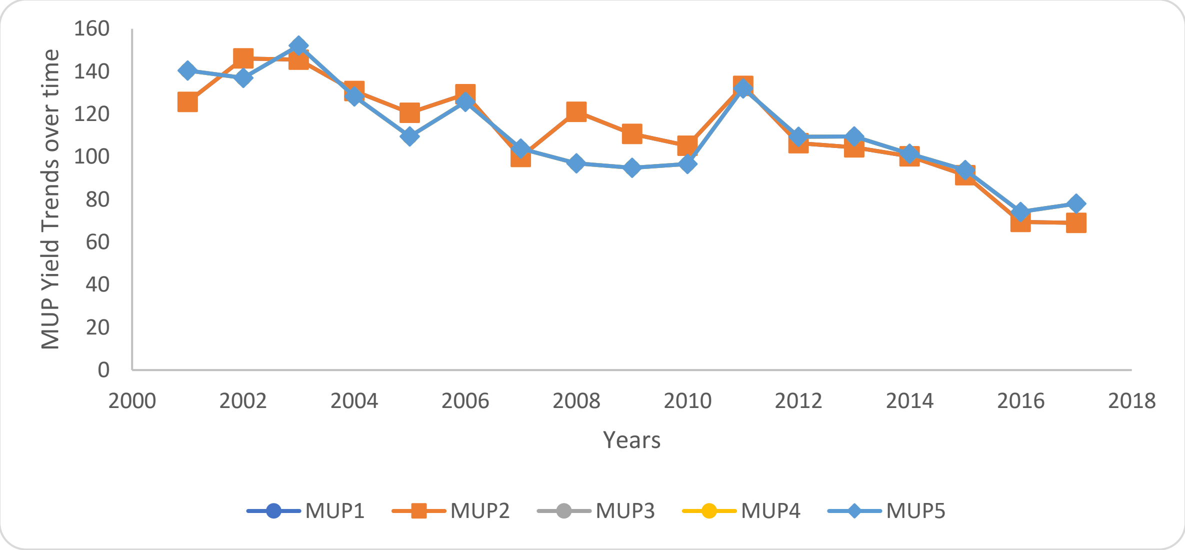


Figure 4.7 Yields of fields in MUP from 2001 to 2017 where MUP1 falls directly under MUP2 while MUP3 and MUP4 fall under MUP5

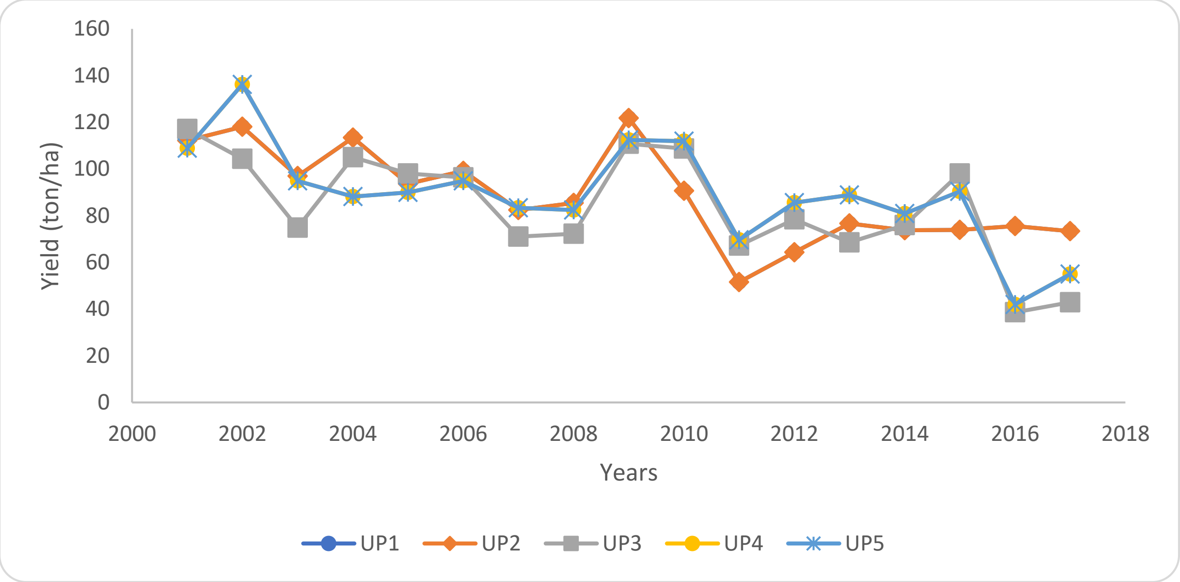


Figure 4.8 Yields of fields in UP from 2001 to 2017 where UP1 falls directly under UP2 while UP4 falls under UP5

Yearly average yields for individual transects are presented in Figure 4.9 below. As earlier alluded to, the yield losses declined at similar rates over time. MUP is observed to have characteristically higher average yields in most years than the other transects, while UP and LP have very similar yields year in and year out which does not support the expectation that yields will be affected by elevation difference.

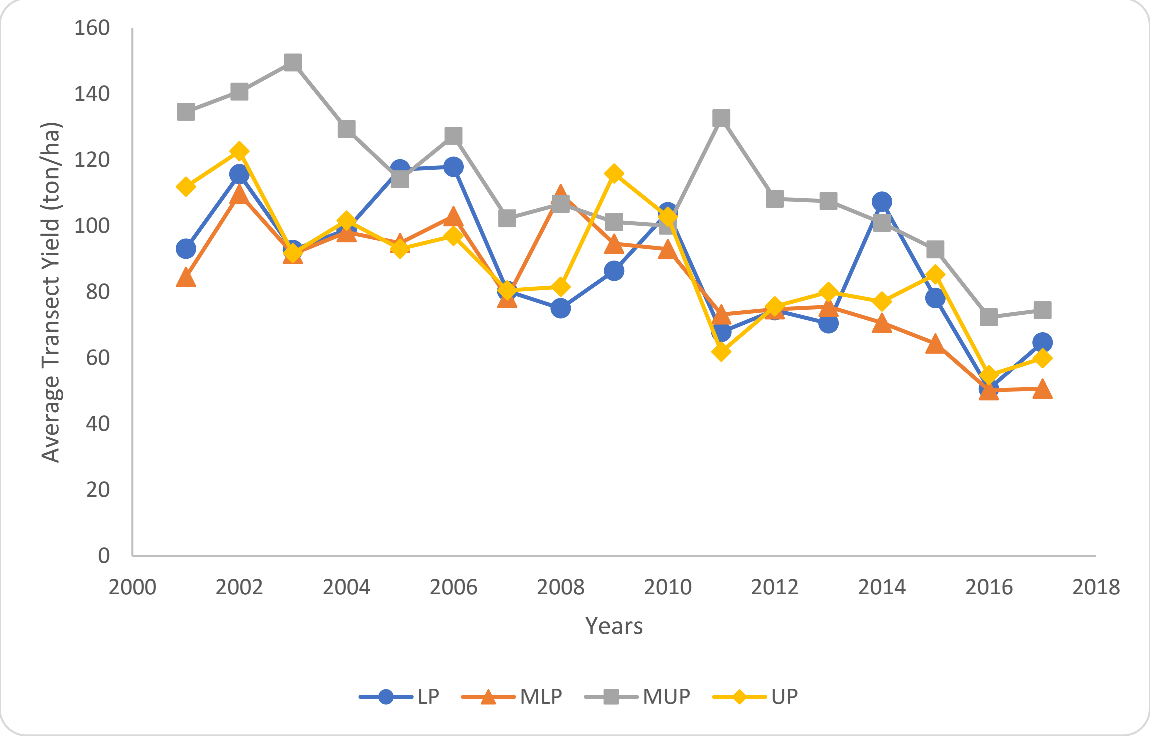


Figure 4.9 Yearly average yields for individual transects at Kasinthula from 2001 to 2017

4.3 Discussion

The yield maps that have been presented above clearly show a trend of dwindling yields across all fields in the scheme. The descriptive statistics for yields for the years 2001 and 2017 are presented in Table 4.1.

Table 4.1 Descriptive statistics for yields in 2001 and 2017

Statistic	2001 Yield (ton/ha)	2017 Yield (ton/ha)
Mean	105	62
Minimum	67	26
Maximum	140	102
Standard Deviation	22	18
CV (%)	21	29

When individual transects were considered for yield loss over years, it was observed that in LP yields dropped from around 120 ton/ha to around 60 ton/ha representing 50% drop, except in a few fields which registered lowest yields of between 25 and 40 ton/ha representing between 79% to 67% drop. For MLP a drop from 140 ton/ha to 60 ton/ha representing 57% drop was observed, and MUP showed a yield decline from 145 ton/ha to around 80 ton/ha which is a 45% drop. UP exhibited yield decreases from 140 ton/ha to 55 ton/ha (61%) drop. The yield decline had no statistical correlation with elevation as explained previously, with all sections registering considerable yield losses and even greater losses were recorded in higher lying elevations than lower parts of the scheme over the 17 years of data recording.

A closer look at individual fields revealed that most recorded very low yields compared to average expected yields of sugarcane of the same varieties and with good management, with considerable variation, from the LP to the UP transect fields (Figure 4.10). For example, in 2017 within the LP transect, it was observed that LP5 yielded 26 ton/ha while LP3 produced three times this yield (72 ton/ha). Again, in the MLP transect, it was observed that MLP3 produced 43 ton/ha while MLP1 delivered 62 ton/ha. Similarly, in the MUP transect it was observed that MUP2 registered 69 ton/ha while MUP4 registered 78 ton/ha. This was also observed in UP where UP1 had 73 ton/ha while UP3 had 43 ton/ha. The yield disparities do not correlate with water table depth because average water table depths were at 1.3 m for LP, 1.8 m for MLP, 2.7 m in MUP, and the deepest at 3.1 m for UP. This shows that some fields in lower sections of the scheme had lowest yields while others had relatively better yields and the trend was similar in all transects. This counters the argument that yield losses would have been higher in lower transects because of water table rise, but certainly the high soil salinity had an effect all over the scheme on top of other factors related to agronomic and water management practices.

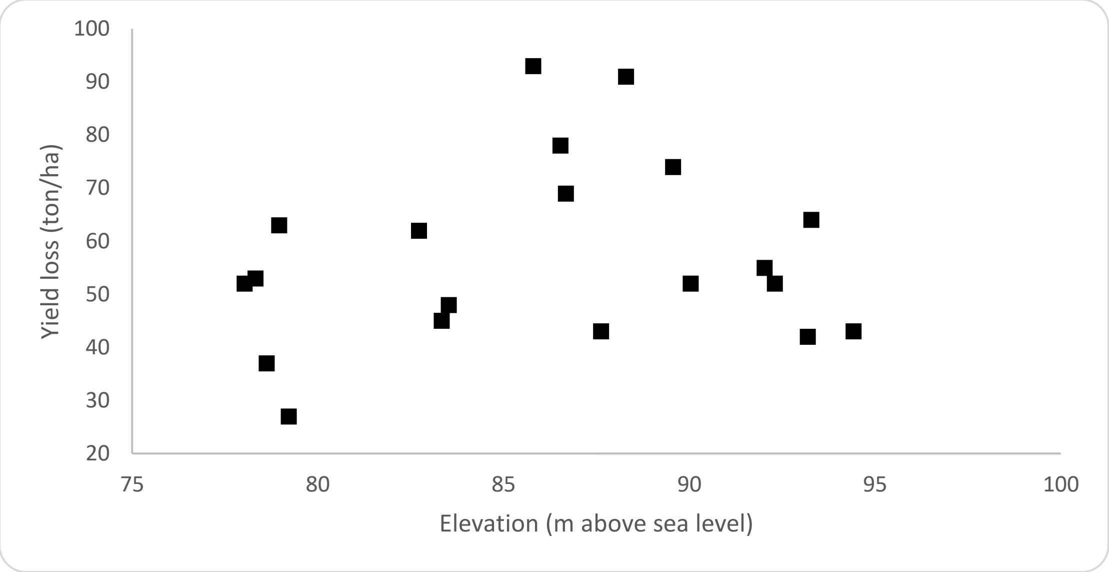


Figure 4.10 Scatter graph of average scheme sugarcane yield losses in relation to field elevation above sea level over the 17 years

The scatter graph above shows no correlation between elevation and yield losses. Similarly, the high-water tables observed during the data collection period had no direct link to historical yield losses at Kasinthula as there was no correlation between water table depth and yields recorded over time. The assumption made was that water tables have remained fairly constant over the years. However, when 2017 yield data was plotted against water table depth, it was observed to have a slight link to yield losses because soil texture slightly changes as we move up the slope from heavy clay to clay loam, although not quite statistically significantly (Figure 4.11).

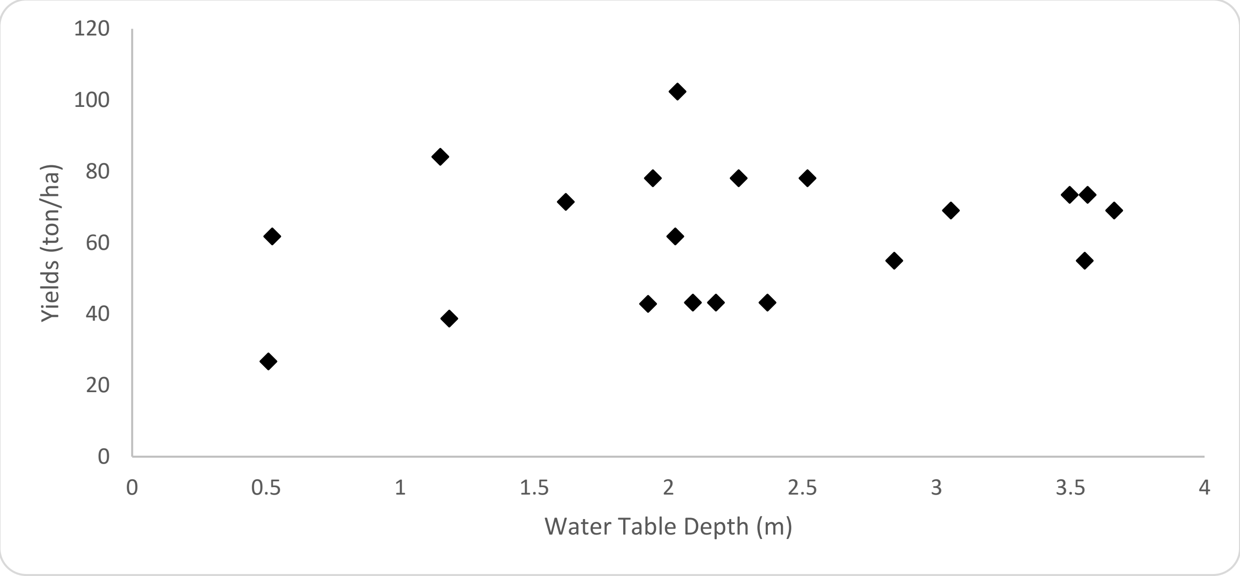


Figure 4.11 Scatter plot for 2017 yields and water table depths

As stated earlier, the dwindling sugarcane yields can also be attributed to poor agronomic management practices, on top of soil salinity variations. For instance, when one of the managers was asked on the yield loss trends, the response given was due to low fertilizer application as they now apply 110 kg/ha N instead of the previously applied level of 156 kg/ha N. When asked why they decided to do this, the manager stated that financial challenges the scheme is facing resulted in them not being able to afford to apply the recommended rate. An N level of 156 kg/ha can produce a yield of 120 to 140 ton/ha under smallholder farmer conditions. Therefore, through simple proportion assuming the response is linear, the 110 kg/ha N should be able to produce between 88 to 102 ton/ha. Hence, this is insufficient explanation for the observed yield decline because the level of N applied could only reduce the yields by 27 %. This then means that there is a combination of factors which need to be looked at holistically. Figures 4.12 presents a scatter plot of the relationship between 2017 yields against average soil salinities. It was observed that there was very little correlation as well.

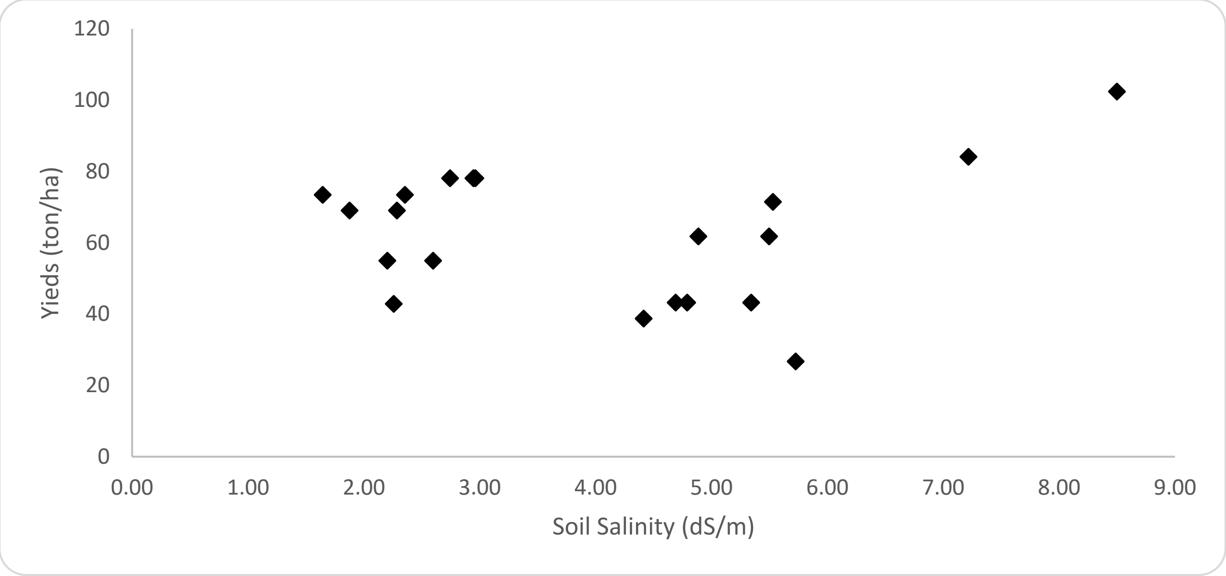


Figure 4.12 Scatter plot for 2017 yields and soil salinity (ECe)

A comparison of effect of average groundwater salinities and water table depths on historical yields changes also resulted in no correlation as seen in scatter plots presented in Figures 4.13 and 4.14. It was observed that more data points were concentrated in the median ranges of water table depth and groundwater salinity with the extremes exhibiting few occurrences. For example, high yield changes were more pronounced in groundwater salinities between 0.4 dS/m to 0.8 dS/m which was also found in soils with water table depth of between 0.5 m to 2 m.

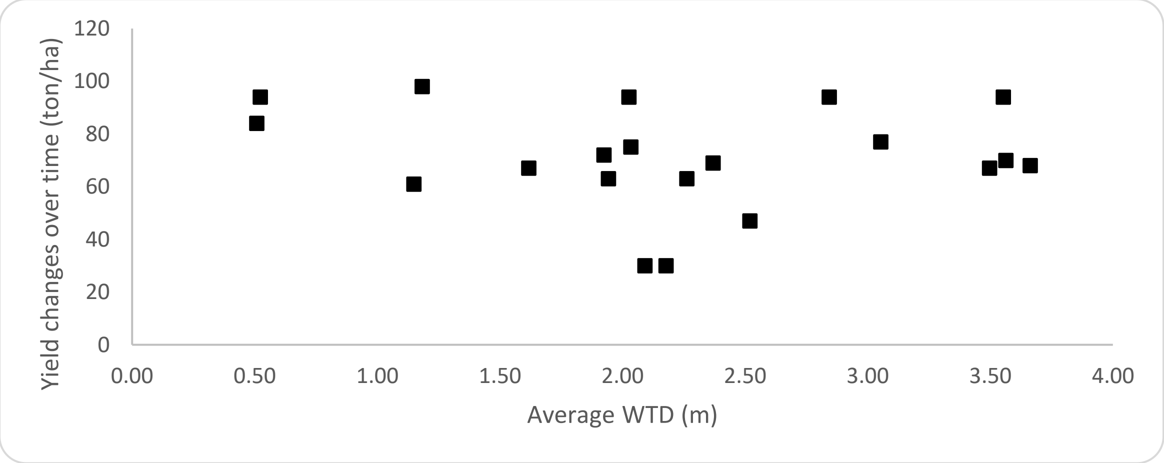


Figure 4.13 Scatter plot for yield changes over time and water table depths

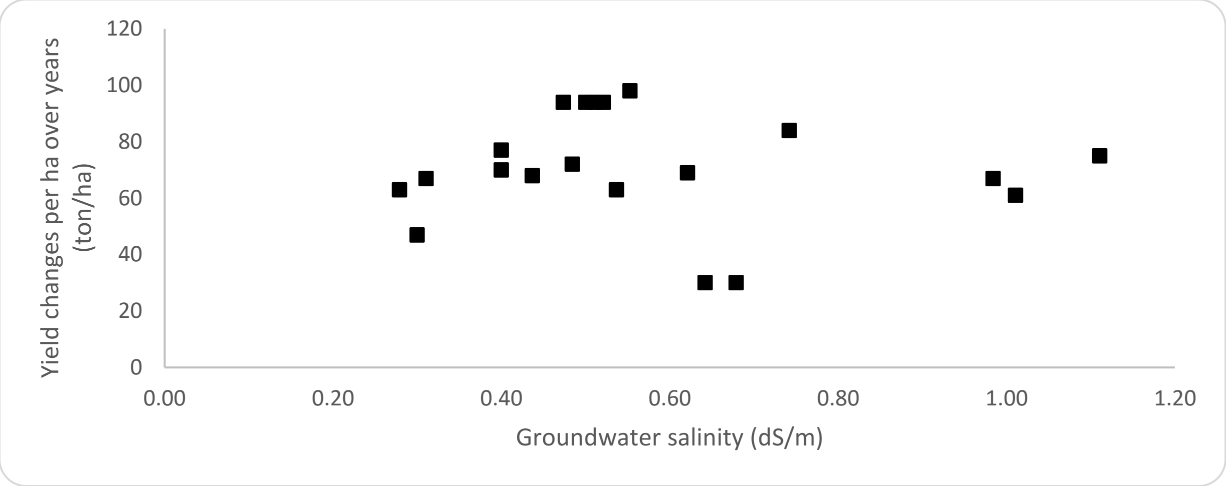


Figure 4.14 Scatter plot for yield changes over time and groundwater salinity

The Maas and Hoffman salinity threshold and yield decline response were used to compare yields obtained at Kasinthula with expected losses. In this function it is stated that once soil salinities go beyond 1.7 dS/m there would be an expected drop of 5.9 % yield for every unit increase in ECe measured in dS/m (Maas 1990, du Plessis et al. 2017). Therefore, the expected yield can be calculated through calculating first the difference between the threshold and actual registered salinity and multiply it with the 5.9 % and subtract that from potential yields. Since smallholder farmers can realise sugarcane yields of up to 120 ton/ha, it was calculated that the highest yield loss which could have been expected from Kasinthula could have been 40 ton/ha at the highest soil salinity of 8.5 dS/m (Figure 4.15). Thus, the expected 2017 yield could have been 80 ton/ha (Figure 4.16); however, data obtained show that at 8.5 dS/m, the 2017 yield was almost 102 ton/ha while the lowest salinity value of 1.64 dS/m could have given yields higher than 120 ton/ha. Instead, at that soil salinity level, the yield obtained was 73 ton/ha which is a yield decline from expected yields of 47 ton/ha.

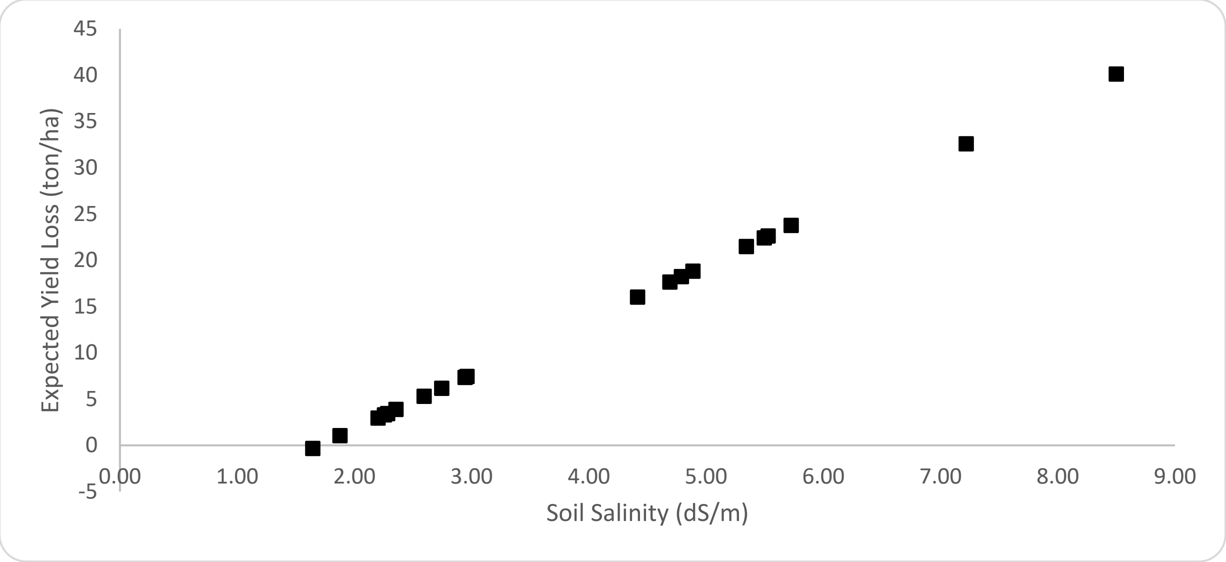


Figure 4.15 Expected sugarcane yield loss at different salinity levels above salinity threshold for Kasinthula

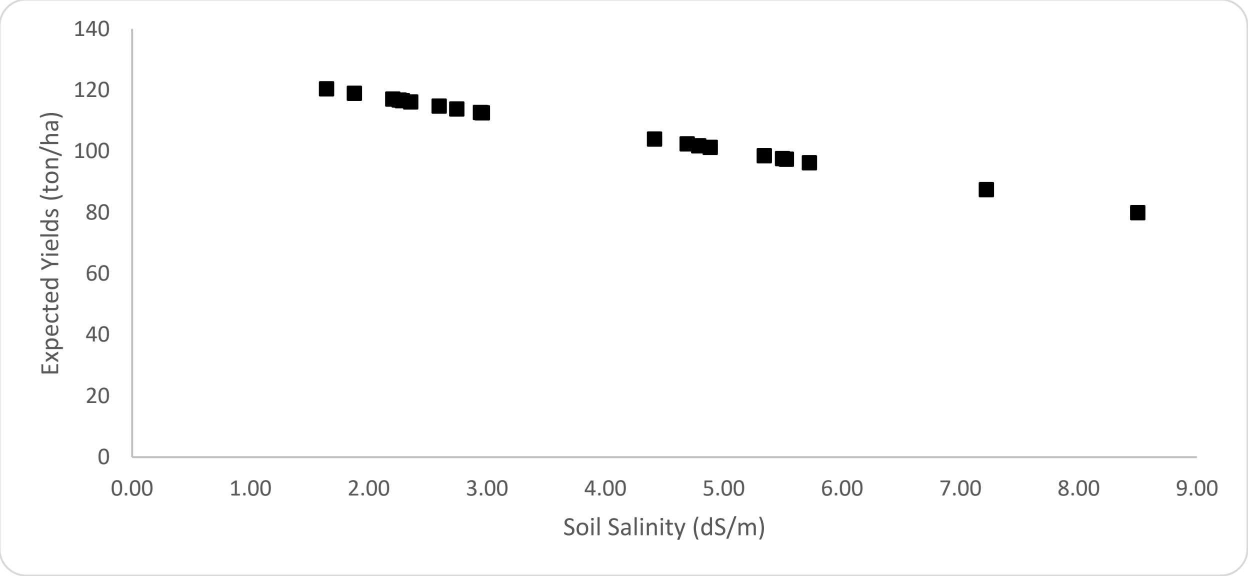
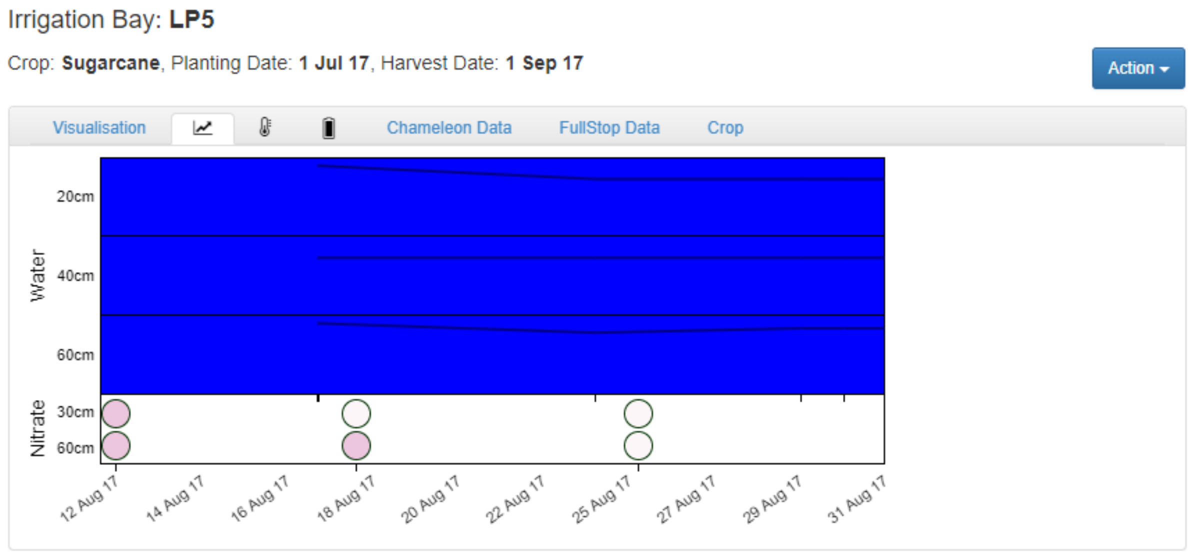


Figure 4.16 Expected sugarcane yields at different salinity levels above salinity threshold for Kasinthula

However, Hurst et al. (2004) explained that shallow water tables could be used to supplement irrigation without yield loss and potentially minimize waterlogging conditions and improve nutrient up keep in the rootzone. Irrigation management could play a role in declining yields as some fields especially LP2, MLP2 and MUP3 and UP1 were irrigated 60 % more times than others during the same period of study due to their proximity to night storage reservoirs which could be the reason some fields had high water table which could affect sugarcane growth because most nutrients were leached down the soil profile (Stirzaker 2011). For instance, the chameleon sensor visualisation for LP5 in Figure 4.17 shows one of the fields always blue, indicating the soil profile was very wet which could cause leaching of nutrients that would affect yields (Stirzaker 2011) and its 2017 yield was only 26 ton/ha. Farmers can use nitrogen test strips which detect changes in soil nitrates from water samples which can be collected from the ground, for example by Wetting Front Detectors (Stirzaker 2011; Ibrikci 2015). This simple tool can help farmers realize when they are losing more nitrates down the soil profile.

When the colour patterns were compared with the nitrate strip values, it was observed that all nitrates in the upper soil profile had washed down the soil profile to where roots cannot actively abstract nutrients because the top 60 cm soil profile registered 25 ppm N on 12th August to less than 10 ppm N soon after that. Farmers apply fertilizers twice in a growing season for sugarcane. The colour patterns displayed in the two fields as well as the nitrate strip readings correlate with the yield for respective fields.


Irrigation Bay: **LP5**

Crop: **Sugarcane**, Planting Date: **1 Jul 17**, Harvest Date: **1 Sep 17**

Figure 4.17 The visualisations from the Chameleon Sensor readings for LP5 showing nitrate readings (https://via.farm/visualisefarm/138/past/2017/)

This is in contrast with Figure 4.18 for the drier LP3 whose Chameleon Sensor readings showed more green and the nitrates looked to persist in the rootzone for a long time; its 2017 yield was 72 ton/ha. This indicates that if water application is properly managed, plants can have nutrients available for a much longer period.

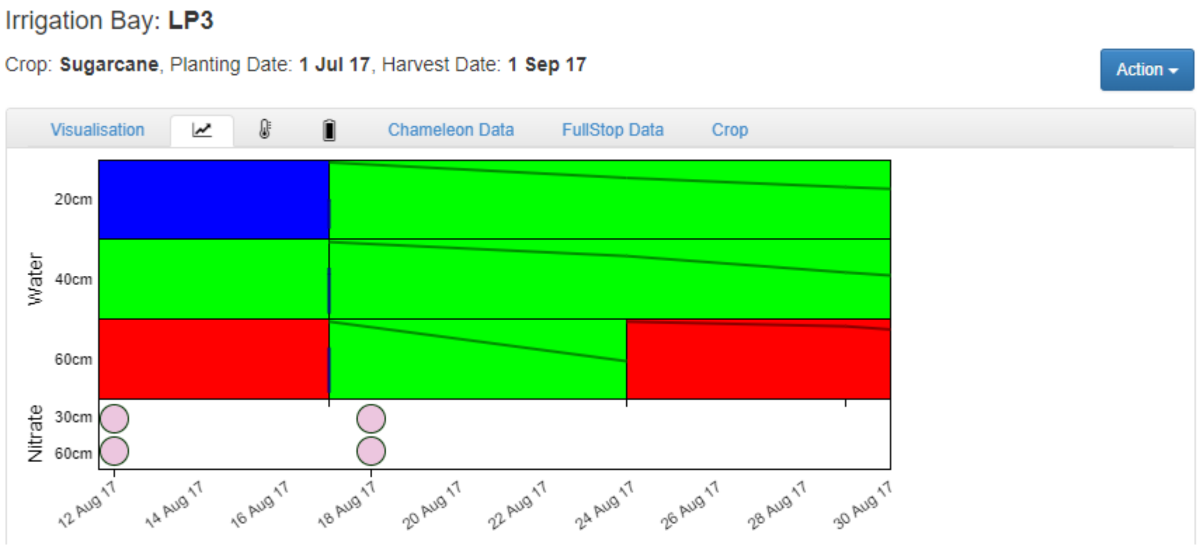


Figure 4.18 The visualisations from the Chameleon Sensor readings for LP3 showing nitrate readings (https://via.farm/visualisefarm/138/past/2017/)

Many studies have shown that when water tables are close to the surface in sugarcane fields, most crop water demands could be provided by the shallow water table. Omary and Izuno (1995), for example, reported that shallow groundwater in sugarcane fields provided between 20% to 106% of the ET when the water table fluctuated between 0.4 to 1 m from the surface. This means that the expected outcome could have been higher yields in the areas with shallow water table, but the results were completely different. However, Escolar et al. (1971) suggested that some varieties perform badly when the water table is closer to the surface like up to 50 cm eg PR 1059, while others such as PR 980 and PR 1028do well (Ray et al. 2009). This could lead to lower yields in the areas of shallow groundwater tables unlike other places. However, the varieties grown at Kasinthula are N32, N14 and MN25 and their susceptibility to shallow water tables has not been ascertained.

5 Determination of the water table depth threshold for action

5.1 Overview

Shallow water tables can provide sugarcane crops with water through capillary up flow (Hurst et al. 2004), if they don’t cause salinization or impede crop growth due to waterlogging conditions which would ultimately result in yield losses. Many studies have shown that shallow water tables can be utilised to supplement irrigation or sometimes eliminate irrigation completely if managed properly (Escolar et al. 1971; Ayars et al. 2006; Fouss et al 2007). The appropriate utilization of shallow groundwater could lead to reduction in incidences of waterlogging and leaching of nutrients down the soil profile (Hurst et al. 2004), provided there is an understanding of soil hydraulic factors, crop characteristics such as root growth depth towards the water table and the depth of the water table itself (Thorburn et al. 2003).

Shallow water tables are common in sugarcane fields of Iran, India, Columbia, USA and Pongola in South Africa (Malota and Senzanje 2016; Omary and Izuno 1995) and in Malawi, sugarcane is grown predominantly along the western shores of Lake Malawi and the Shire Valley, using furrow and pressurised irrigation systems (Chinsinga 2017). Most schemes, however, do not monitor groundwater levels and this makes it impossible to determine how much water can be supplied to crops from shallow water tables. It is essential to adjust irrigation management based on potential water contribution from shallow water tables (Hurst et al. 2004). This can be achieved through the use of plant-based water measurements where pan-based factors are adjusted to consider contribution from shallow water tables (Grimes et al. 1984).

Many studies show that shallow groundwater has contributed immensely to sugarcane production. In Columbia, when the water table was maintained between 1.2 to 1.5 m, no yield improvements were recorded if irrigation was applied (Torres and Hanks 1989). In Florida (USA), sugarcane was grown in different constant water tables in lysimeters and yields were not negatively affected (Glaz and Morris 2010). This means that the rest of the additional applied water was either lost through runoff, direct evaporation, drainage and lateral flow since the more irrigation water applied was more than the crop water use (T). In India two studies were carried out, one in sandy loam soils where it is reported that the water table contributed almost 65 % of total evapotranspiration

(Hunsigi and Srivastava 1977). The other study was also conducted in similar sandy loam soils, where it was observed that shallow water tables contributed up to 91, 86 and 55 % of total sugarcane evapotranspiration when the water tables were maintained at 0.2, 0.4, and 0.6 m respectively. However, in this study, it was discovered that the yields were significantly reduced at water table depth of 0.2 m, possibly as a result of waterlogging conditions in the field (Gupta and Yadav 1993). Similarly, Omary and Izuno (1995) reported that shallow groundwater contributed between 20 – 106 % of potential pan evaporation when water tables were between 0.4 to 1.0 m in sugarcane fields. These results suggest therefore, that sugarcane can readily utilize shallow groundwater if the water table is closer to the surface than 1.5 m (Hurst et al. 2004) depending on soil texture.

The objective of the section is to investigate the potential improvements in water management that would lead to reduced irrigation water use and to increase cane yields through determination of the water table depths which farmers must monitor in order to manage waterlogging and keep salinity to the lowest levels. This can be achieved through use of simple tools such as monitoring floating flags in shallow piezometers which show different paint colours as the water table rises to the surface. A floating flag is a simple device that is inserted into a piezometer and as the water table rises the floating rod pops out showing different colours that are demarcated on it. The aim is to have the floating flag change colour when a specific water table depth is reached so that farmers can easily see and know the implication, thereby prompting them to adjust water application.

5.2 Materials and factors to be used

Monitoring water table variations can be done using water level meters which can be inserted in piezometer and the reading recorded. However, the problem with this manual method is that only a few people would be able to know what is happening in the field or would also require someone to transmit that information to fellow farmers which may be difficult to accomplish. Furthermore, not everyone would be willing to believe that the information being given is a true reflection of the situation on the ground because many people easily understand things when they see for themselves other than being told stories. It is from this background that a floating device is being proposed so that all farmers see for themselves through the colour changes. In this way, the farmers can easily interpret levels of groundwater and thus, can easily change their water application. However, the main challenge lies in determining the water table depth that satisfies the crop water needs and also knowing the depth at which water table contributions become negligible.

Chameleon sensors are already in use to help farmers determine soil water availability, but these require a portable hand-held device to be mounted on the sensor array in order to determine the amount of water in each soil layer being monitored which may be faulty due to installation errors. Sometimes the chameleon reader can be affected by low battery power which would affect inference of moisture in the soil. But a floating flag will determine the changes in water table depth by displaying different visible colours above ground which will automatically inform the farmers or all those surrounding on what depth the water table is and how they can change their irrigation frequencies and volumes. Therefore, the use of chameleon sensors may help farmers to know when the fields require water but cannot help change irrigation frequency in order to utilize the shallow groundwater available as is the case when they will be using floating flags.

Much as chameleon sensors can be installed at different depths but they cannot directly inform the farmers the contribution of shallow groundwater to the crops while based on the water table depth displayed by the floating flags, farmers will know what contribution the shallow water table is providing to their crops through the simple explanation which will be given when they are installing the device and hence provide an adaptive water management system. Since water table fluctuation in a farm occurs over a larger area, one floating flag can be useful to farmers within a particular area of the same elevation and can be installed at one point which has constant security whereas chameleon sensors need to be installed in as many fields as possible to make meaningful decisions where they can be vandalised as has been experienced already.

The floating flags will be useful to manage waterlogging as when the water table rises to critical points, irrigation can be reduced or postponed such that the sugarcane uses groundwater and help lower the water table. It will, however, be difficult to manage soil salinity but the understanding of shallow groundwater can easily be linked to managing soil salinity as the waterlogged soils tend to allow salts down the soil profile to rise through capillary action into the rootzone which would affect crop growth as reported by Hurst et al. (2004) and Ayars et al. (2006). The other thing is the understanding of possible changes to irrigation management that would result in improved irrigation water use efficiency or crop response to irrigation when water tables lie within extremes (Hurst et al. 2004).

When water table is below 1.5 m depth, the sugarcane yields have never been affected in most reported cases (Escolar et al. 1971; Hunsigi and Srivastava 1977; Gupta and Yadav 1993). The following depth ranges of 0-0.5, 0.5-1.2 and 1.2-1.5, therefore, these will be used in the painting of the flag as the cut off points for indicating a dangerous situation if the water table would be allowed to rise closer to the surface. However, since different soils have different hydraulic conductivities which would allow for differences in recharge and discharge rates, the soil types found at Kasinthula will be assigned different cut off depth for action.

As already explained above, it is highly difficult to delineate the floating flag to monitor soil salinity apart from linking water table depth to soil salinity proliferation based on salt transfers. However, the depths of action for water table were developed based on what other studies across the world recommended as levels which could contribute to crop water uptake with least effect on yields while also reducing irrigation requirements (Escolar et al. 1971; Hunsigi and Srivastava 1977; Gupta and Yadav 1993, Hurst et al. 2004). Based on these studies, which happen to have environmental and soil types similar to Kasinthula, the colour depths were selected. Table 5.1 shows the delineation depths for colour changes for different soils as found in different studies as described below.

a. WTD from 2m to 1.5 m sugarcane grows normally (Kahlown et al. 2005).

b. WTD from 1.5 m to 1.2 m there is 20% contribution of ETc from water table and will be marked **green.**

c. WTD from 1.2 m to 0.6 m there is 65 % contribution of ETc from water table and will be marked **yellow** because as it is contributing to Etc, the water table is rising to dangerous levels which could lead to soil salinity and waterlogging.

d. Water table which is less than 0.6 m there is 86 % contribution of ETc from water table and will be marked **red** because the water table has reached dangerous levels which could lead to soil salinity and waterlogging and require action to stop irrigation and improve drainage.

Table 5.1 Colour delineation depths for action (Sources: Escolar et al. 1971; Hunsigi and Srivastava 1977; Gupta and Yadav 1993; Hurst et al. 2004)

	Colour Depths		
Soil Type	Red	Yellow	Green
Clay	≤ 0.6 m	0.6 - 1.2 m	1.2- 1.5 m
Clay loam	≤ 0.5 m	0.5 - 1.0 m	1.0 - 1.5
Sandy loam	≤ 0.4 m	0.4 - 1.0 m	1.0 -1.5 m

The lessons learnt from chameleon sensor patterns correspond very well with water table depths indicated in Table 5.1. Sugarcane yields were low in fields which showed constant blue from the top 20 cm to 60 cm unlike in areas where the chameleon sensors showed a lot of green and red in the lower soil profile. Therefore, understanding the water table depth will be used to adapt irrigation management so that the fields have just enough water for crop growth rather than leaching down nutrients as observed in fields whose chameleon sensors showed more blue colours.

Shallow water tables can lead to soil salinity as well as waterlogging which is dangerous for crop growth. That is where the wetting front detectors and chameleon sensors are equally useful on farms. But if farmers can manage the shallow water tables to reduce irrigations and allow groundwater to supplement irrigation, there would be low incidences of soil salinity and waterlogging. This is because as farmers make use of shallow water table to supplement water requirements for crops, plant water abstractions will eventually lower down the water table to less dangerous levels.

The floating flags will have to be installed in shallow piezometers which will be dug to a depth of 2 m. The 2 m depth has been chosen because studies have shown that sugarcane can utilize groundwater at depths of up to 2 m without problems and hence it was felt that this be selected as the threshold for concern (Kahlown et al. 2005). The piezometers will have to be protected with PVC pipes which will have cut slots to allow free entry of water to act as float housings. The floats will be made from foam rods similar to the ones in wetting front detectors. When installing the floating flags, after inserting the PVC pipe, the section painted red on the foam float will be lowered first into the piezometer. This will allow to show green colour first then yellow colour and finally red colour. A hand-held soil auger will be the device used to excavate a piezometer where the PVC pipe will be installed. The opening of the pipe on the surface will be made level with ground level so that any colour changes can easily be seen by farmers.

5.3 How will it be used

From the figures in Table 5.1, the floating flags will be made so that when the water table is between 1.2 m to 1.5 m, depending on soil type, the flag will show the green colour and when the water table rises to within 0.5 m to 1.2 m the flags will show the yellow colour which will mean that the water level is rising dangerously and must be checked. Finally, when the water table is between 0.0 m to 0.5 m, the flags will show the red colour indicating that the water table has reached undesirable levels and serious action needs to be taken to lower it especially stopping irrigation completely. The floater will only be 1.5 m long which will allow for normal irrigation when the water table is at 2 m and when it rises to 1.5 m the green colour will be seen. This will also mean the water table is at favourable depths which will help the farmers know that groundwater is contributing to total evapotranspiration of the sugarcane. This will help farmers to change their scheduling as sugarcane will be using more of the groundwater reserves on top of the irrigation water (Escolar et al. 1971; Hunsigi and Srivastava 1977) as shown in Figure 5.1.

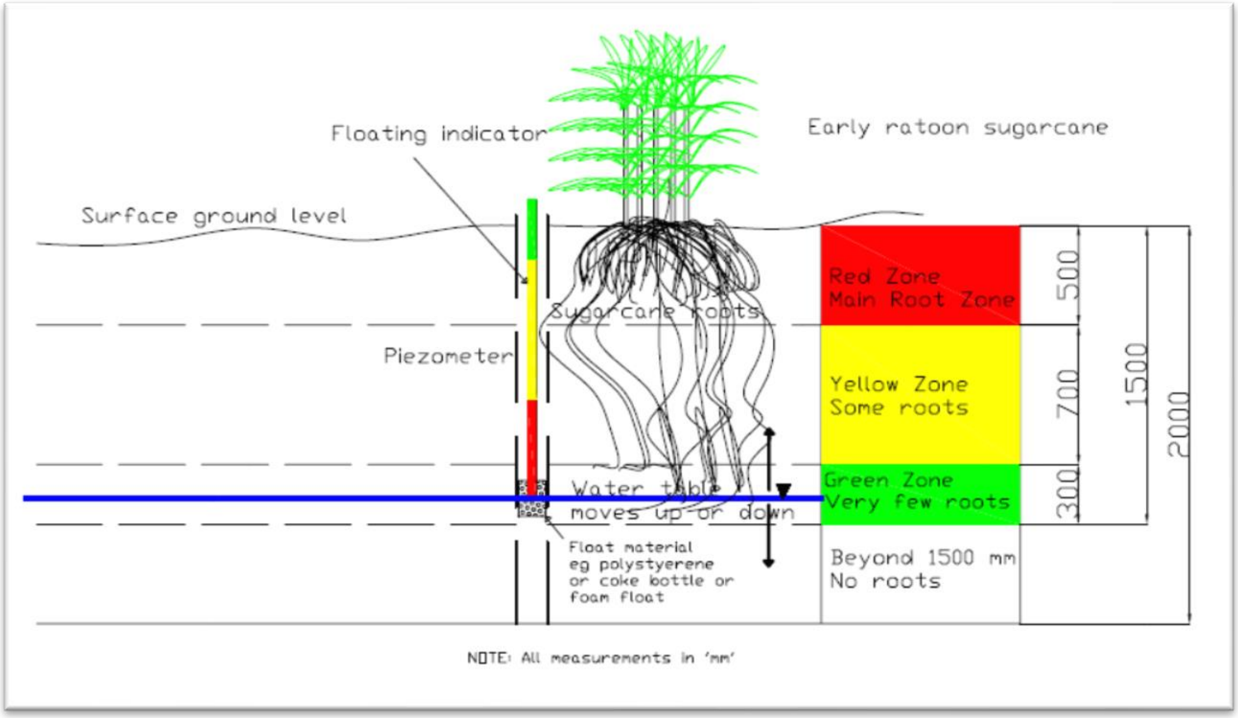


Figure 5.1 Schematic representation of a floating flag installed in the ground

The irrigation water management manual for Kasinthula states that farmers are required to apply 48 mm for an irrigation cycle of 7 days for a fully-grown cane (peak ET) which is slightly above 50% of the analysed readily available moisture of 78 mm/m. But through the measurements taken when the actual irrigation was happening and eventual calculations revealed that they were applying up to 62 mm per irrigation event. Thus, the revised irrigation scheduling will be calculated based on the designed water application of 48 mm per irrigation event.

For example, at 0.5 m, the water table contribution to evapotranspiration will be 86 % (Escolar et al. 1971; Hunsigi and Srivastava 1977), therefore, irrigation frequency will be increased to 50 days without affecting the crop yield. When the water table is at 1.2 m to 0.5 m, the contribution of water table to total evapotranspiration is 55 % (Gupta and Yadav 1993), thus the farmers will be able to reschedule the irrigation every 15 days. While if the water table is at 1.2 to 1.5 m, the contribution to evapotranspiration will be 20 % (Hurst et al. 2004), and the farmers will have to schedule irrigation frequency to 8 days intervals as seen in Table 5.2.

Table 5.2 Water table depths and revised irrigation frequencies when the floating flags will be used

Water table Depth (m)	Irrigation Water Requirement (mm)	Irrigation Frequency (days)	Water Table Contribution (%)	Water Table Contribution (mm)	Irrigation Contribution (mm)	Revised Irrigation Frequency (days)
≤ 0.5	48	7	86	41.28	6.72	50
0.5 - 1.2	48	7	55	26.4	21.6	15
1.2 - 1.5	48	7	20	9.6	38.4	8

The calculations for Table 5.2 were based on class A pan evaporation basin; the crop factor for sugarcane of 0.85 when the crop has reached full canopy cover (Brouwer and Prins 1989; FAO 2002), and that Chikwawa has a maximum of 7.5 mm/day of evapotranspiration (FAO 2016), thus, the ETc was calculated to be 6.4 mm/day, which means, farmers or management will have to decide on the crop factors depending on crop stage and pan evaporation This way, they will be able to reschedule irrigation activities correctly. In order to mitigate risks when the floating flag idea is introduced, it will be necessary to carry out soil moisture tests in the fields that are practising the new schedules so that the crops are not adversely affected and when it is certified that the method is adequately working, farmers can be allowed to use it on their own.

When there is a rainfall event, it will be advisable for the farmers to take into consideration the amount of rainfall and adjust their irrigation schedule accordingly. In case the rainfall has been heavy so that the red section of the flag is seen, one way would be to stop irrigation as it is normally practiced and ensure that the drainage system is fully functional. Furthermore, the use of other devices like the chameleon sensors will help farmers understand how much effect the rainfall has had.

5.4 How will farmers benefit

The introduction of the floating flags will enable farmers to visualise the groundwater situation through the colour displays from the floats. This will enable them to know what the water table situation is and can easily interact with fellow farmers on ways of improving water application so that the situation is corrected. In terms of water application, the rescheduled irrigation intervals will mean more money saving as the scheme will be applying water at lower frequencies than normal as the crop will be utilizing the groundwater resource. The monitoring device will be made from cheap materials and can last many years if properly taken care of. It should be mentioned here that one of the challenges at Kasinthula is vandalism of monitoring equipment. When the equipment is finally installed, there must be proper sensitization and also improved to secure long-term use of the equipment while also ensuring that spare floats are available for replacement.

There is a high probability that if the monitoring devices are installed, Kasinthula Scheme can improve yields through the utilisation of groundwater instead of just pumping water which is costly and results in waterlogging conditions. The labour costs of irrigation can dramatically decrease, thus, revenue at the scheme can be directed to other areas such as inputs. Of course, Kasinthula will act as a pilot scheme, but eventually more schemes can learn from them and thus implement the method elsewhere to improve overall irrigation water management.

6 Discussion

The soils around Kasinthula are predominantly clay and clay loam soils with aquifer hydraulic conductivity of 0.06 m/day which can provide good conditions for sugarcane production. These soils and hydraulic conductivity regulated water table fluctuations with irrigation or rainfall events. The water table in the lower transect piezometers was closest to the surface while the upper transect had the deepest shallow water table because the scheme has a downward gradient from west to east. However, the water table rise did not correlate with the elevation difference between the highest and lowest transects partly because groundwater flow is moving laterally influenced by soil types, impermeable layers and topography. The clay loam soils in the upper profile and clays in the lower profile constitute a very low conductivity aquifer which allows vertical downward and then lateral flow of water into the Shire River, thus reducing shallow groundwater rise at the lowest transect and hence the whole area responded quite similarly with irrigation or rainfall events because the whole area has similar geological characteristics. However, elevation differences within the scheme resulted in water table variations, supporting the fact that water flows from higher to lower elevation under the influence of a hydraulic gradient and it follows topography.

The soil salinities for Kasinthula are very high compared to threshold salinities for sugarcane and could have an effect on yields. Kasinthula lies in a fault area which could easily have led to higher soil salinities registered due to capillary rise of salts into the rootzone or through salt deposits from irrigation activities. This is also caused by the heavy clays found around the scheme coupled with the low hydraulic conductivities registered. This means the salts mobilised from the deep lying layers or through irrigation water seldom drain away, hence causing the root zone to be very saline. The salt problems can be minimised through improved drainage system and flushing of the salts through the surface water application. Therefore, the yields are lower than potential sugarcane yields because of agronomic factors being practiced, such as the huge reduction in nitrogen application as well as the salinity challenges faced.

Similarly, yield losses were observed from the historical data that was collected from Nchalo Mill over the years. The losses were observed in all areas within the scheme irrespective of elevation difference, water table depth and salinity ranges. This seems to contradict the notion that shallow groundwater could have been used to supplement irrigation because many studies have supported that idea. It also contradicts the idea that high water table depth and higher soil salinities will cause low yields in lower transects. However, it must be noted that some fields had shallow groundwater which caused nutrients to be leached down the soil profile. But again, poor agronomic practices in the course of sugarcane production could have led to dwindling yields. It is for these reasons that management at Kasinthula must consider analysing the many challenges that could have led to low yields holistically in order to address this and bring it to its full production potential, although the results are not conclusive.

Shallow water tables have been known to be used to supplement irrigation and, if properly managed, they can help reduce yield loss and potentially minimize waterlogging conditions and improve nutrient up keep in the rootzone. An analysis of the relationship between yield changes over time against average water table depths and soil salinities did not show any correlation because more yield changes were concentrated in the median ranges of water table depth and soil salinity. This supports the idea that the yield losses could have been triggered by poor irrigation water management and agronomic practices other than the water table depths within the scheme. The chameleon sensor visualisation provide evidence to the suggestion made above because the sensors kept showing blue signifying an abundance of soil moisture, but farmers still irrigated such fields. There was also an indication of a reduction inorganic fertilizer application due to financial challenges which led to yield losses.

In order to understand shallow water table fluctuations, a floating flag is being proposed as an ideal monitoring tool. It will work on the principle of colour changes that will be displayed as the float pops out due to shallow groundwater rise or fall. There are cut-off points where colours will change have been designated according to soil types. This can easily be used alongside the chameleon sensors which monitor soil moisture in the rootzone and wetting front detectors for solutes in the soil. The floating flag will provide farmers with knowledge on how much the groundwater is contributing to crop water requirements and hence they will be able to schedule irrigation based on those recommendations.

Although vandalism of equipment is a major problem at Kasinthula, that should not prevent an attempt to introduce this novel intervention that should be able to improve water management for prosperous crop production. The responsibility will be on management, farmers and the entire community to ensure that there is enough awareness so that, when the equipment is installed, it is safe. The prospects of making Kasinthula viable are high and can easily become a model scheme where farmers from other schemes will learn from.

When farmers understand the interpretation of floating flag colour patterns, they can easily know and determine when they must irrigate. On top of using colour patterns from chameleon sensors to manage irrigation, wetting front detectors can help understand rootzone solutes which are essential for crop growth. A properly managed field can have plants with enough nutrients while also reducing water demands through utilisation of shallow water tables. Since Kasinthula is underlain by highly saline geological formations due to presence of fault lines, good water management can reduce the risk from salinization. One way of doing this is the improvement in the drainage system.

Since a shallow water table acts to maintain the moisture at the bottom of the rootzone, it will be ideal for the farmers to utilize both the chameleon sensors and floating flags to maximise water use because a chameleon sensor at say 60 cm will remain wetter when there is a shallow water table than a sensor where there is no shallow water table. Therefore, the sensor can effectively signal that there is moisture available from a shallow water table. One drawback may be that sensors will need to be installed deeper e.g. 1 m to measure changes there and record the root extraction of water.

It is expected that farmers will still use chameleon sensors to provide information on moisture levels in designated soil layers while the floating flag will provide farmers with information on groundwater dynamics while wetting front detectors will help understand solute levels in the soil. The floating flags will help farmers schedule irrigation depending on the understanding of whether groundwater is contributing to crop water requirement while the chameleon sensors will show when the upper soil layers have low soil moisture for plant abstraction and thus inform farmers if irrigation is required or not. This can be done through installation of the chameleon sensors in the top 60 cm while the floating flags help farmers know what’s happening below 60 cm. Therefore, using a combination of chameleon sensors, wetting front detectors and water table flags may be the best option but, considering the pros and cons of these equipment, it can be concluded that use of floating flags would be a good simple starting point.

7 Conclusions and recommendations for future research

7.1 Conclusions

Objective 1

To investigate the effect of amount of applied irrigation water on water table fluctuation.

- ✓ During the study period, approximately 700 mm of irrigation and rainfall occurred and the water tables increased by about 400 mm, with approximately the same increase in water tables in the higher and lower lying areas. It seemed that either little rainfall and irrigation water was reaching the water table or that the groundwater was draining away the water. The hydraulic conductivity of the aquifer was found to be low, approximately 0.05m/day.
- ✓ Water table was not affected by irrigation and rainfall water in the scheme during the study period because the shallow aquifer was found to be a heavy clay with low hydraulic permeability resulting in slow lateral movement of groundwater.
- ✓ However, the hypothesis that groundwater table will rise to within 2 m of the soil surface in the low elevation land due to irrigation activities as compared to the high elevation land within the irrigation scheme was accepted as the lower transects had an average water table depth of 1.3 m

Objective 2

To estimate the effect of soil salinity on sugarcane yield in the scheme.

- ✓ Irrigation water and groundwater salinities in the Kasinthula Scheme were lower than sugarcane threshold salinity and it was observed that they had no correlation with yield losses, however, soil salinity was found to be very high which could explain the main reasons behind the low yields being experienced in the scheme.
- ✓ The higher yields in low salinity areas were found to be around 120 ton/ha while the highest yields in the higher salinity areas were found to be around 60 ton/ha which is almost half of the yield from low salinity areas.
- ✓ The hypothesis that sugarcane yields would be depressed in areas with higher soil salinity in the rootzone (whose saturated paste extract ECe was above the sugarcane threshold of

1.7 dSm^{-1}), while higher yields were expected in areas of low salinity was proved because the soil salinities in the whole scheme were well above the 1.7 dS/m threshold and yields were less than potential yields smallholder farmers were supposed to be producing.

Objective 3

To estimate the effect of amount of applied irrigation water on the yield produced in the scheme.

- ✓ The amount of irrigation water was not found to contribute to yield variation in the scheme. But there was evidence of over irrigation in some areas from Chameleon sensor data and of leaching out of nitrates from the rootzone from the wetting front detectors.
- ✓ The hypothesis that sugarcane yields in the scheme will be depressed when the water table rises above 2 m from the surface was disproved because yield losses were observed all over even in those areas where water table was recorded at 3.2 m from the surface.

Objective 4

To estimate the effect of amount of applied water on soil salinity levels in the scheme.

- ✓ The soil salinity distribution within the scheme could not be linked directly with irrigation water applied since the whole scheme had higher than optimum soil salinities of less than 1.7 dS/m ECe which is the threshold for sugarcane. However, the lower transect had the highest salinity levels compared to the rest of the scheme.
- ✓ Therefore, the hypothesis that groundwater and soil salinities will increase from higher lying areas to lower areas in the scheme due to salt transport by groundwater flow was supported since the lower transect had soil salinities up to 8.6 dS/m.

Objective 5

To estimate the soil salinity threshold for action or water table level at which growers need to actively reduce applied water.

- ✓ Irrigation water and groundwater salinity are all at low levels and not likely to be affecting sugar cane yield at the present time.
- ✓ However, soil salinity in the scheme is very high which could negatively be affecting yields because salts accumulated after years of irrigation which puts at risk the groundwater resource.

- ✓ The effect of water table depth on crop water requirement was used to investigate if irrigation frequencies could be increased from the current 7 days. It was estimated from literature data that 50, 15 and 8-days irrigation frequency could be applied if the water table depth is at < 0.5 m, 0.5 – 1.2 m and 1.2 m to 1.5 m respectively.

7.2 Recommendations for future research

- ✓ A floating flag has been proposed as a monitoring tool for shallow groundwater table fluctuations which will work on the principle of colour changes that will be displayed as the float rises due to shallow groundwater rise or fall using the demarcations developed. This was done after considering soil types to determine thresholds for action which growers need to manage irrigation. This method will be compatible to work together with chameleon sensors and wetting front detectors for soil salinity management. The use of these flags in combination with wetting front detectors and chameleon sensors needs to be researched.
- ✓ The conclusions derived in this research are mostly preliminary, as research is highly recommended so that water table fluctuation monitoring can be undertaken at a greater frequency and with more monitoring points to better understand water table responses to irrigation and rainfall events and the groundwater system at Kasinthula.
- ✓ The floating flags need to be tested and monitored in order for that technology to be fully understood.
- ✓ Soil salinity levels were found to be very high and could affect sugarcane growth, but the effect of water tables on yields was not directly linked. Therefore, more research is needed to understand the link between the water tables, poor aeration and soil salinity on lower yields being experienced at Kasinthula and the reasons for the spatial variation. The small amount of data from chameleon sensors and wetting front detectors appeared to show that where there was over-irrigation leaving the soil wet and leaching out nitrates, yields were low. Therefore, irrigation and fertiliser management need to be investigated more.

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