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Impact of Infield Irrigation Management by Botswana Cabbage Farmers on Soil Salinity

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ABSTRACT

Some vegetable farmers in the semi- arid Botswana are struggling or closing down their enterprises citing the cost of irrigation and salty water as the problem. Irrigation with water from the salt-laden underground water is known to be the main sources of salts for arid and semi-arid agricultural land. Crops grown in saline environments show symptoms similar to those shown by drought-affected crops hence more irrigation is needed therefore increasing the irrigation cost. Research from other semi arid areas shows that water with high salinity levels can be used for irrigation without increasing soil salinity to values beyond critical levels. A lot of studies have been done which show that the impacts of saline irrigation water depend on the irrigation management. This study therefore aims at recommending infield irrigation management practices to be used by cabbage farmers in Botswana without increase in soil salinity to levels that will affect crop yield.

A survey was conducted to identify the infield irrigation management practices presently used by cabbage farmers in Botswana. Rootzone salinity trend due to the identified infield irrigation management was simulated for 20 years using WaSim simulation model. Recommendations on irrigation management practices were made for those soil salinity trends that reached critical levels.

It was realised that there are no common infield irrigation management used by farmers. The way farmers manage infield irrigation could not be identified with the factors involved in irrigation scheduling. Infield irrigation management by the farmers contribute to the soil salinity increase in their fields and some of the farmers are already using saline soils. Most farmers are not aware of the saline conditions they are farming on and those who know do not know about the soil salinity control measures. The study recommends a need to educate farmers on irrigation under saline environments and also a need for farmers to include soil salinity control in their irrigation planning.

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A - Area of bed (m^2)
A_c - surface area of the catch can (m^2)
A_d - area per dripper (m^2)
AE - Application Efficiency (%)
A_s - Area irrigated by a single sprinkler (m^2)
CU - Christiansen’s coefficient of uniformity (%)
d - Root depth for cabbage (m)
D - Slope vapour pressure curve [kPa $°C^{-1}$]
D_i - Average irrigation depth per day (mm/day)
DU - Distribution uniformity (%)
EC_e - Electrical conductivity of soil saturation extract [dS/m]
EC_{iw} - Electrical conductivity of irrigation water [dS/m]
$e°(T)$ - saturation vapour pressure at the air temperature T [kPa],
e_a - Actual vapour pressure [kPa]
e_s - saturation vapour pressure [kPa]
$e_s - e_a$ - saturation vapour pressure deficit [kPa]
ET_c - Crop evapotranspiration (mm/day)
ET_o - reference evapotranspiration [mm day^{-1}]
g - psychrometric constant [kPa $°C^{-1}$]
G - soil heat flux density [MJ m^{-2} day^{-1}]
G_{sc} - Solar constant (118.08 MJ m^{-2} d^{-1})
I - Irrigation depth (mm)
I_c - Collected depth in a catch can (mm)
k_c - Crop coefficient (Dimensionless)
LF - Leaching fraction (Dimensionless)
M - Mean application depth (mm)
M_{all} - Mean of all collection from catch cans (Dimensionless)
M_{lq} - Mean of last quarter collection from catch cans (Dimensionless)
n - Number of catch cans (Dimensionless)

p - Allowable depletion water content of the soil before the plant start reducing (Dimensionless)

q - Application rate (mm/ hour)

R_n - net radiation at the crop surface [MJ m^{-2} day^{-1}]

S_a - Available water capacity for the loam soil (mm/m)

T - Mean daily air temperature at 2 m height [°C]

T_a - Air temperature [°C],

T_i - Irrigation interval (days)

t - Set time for irrigation (hours)

T_{max} - maximum temperature [^oC]

T_{min} - minimum temperature [^oC]

u_2 - wind speed at 2 m height [m s^{-1}]

V - Volume of water applied (l)

V_c - average volume in catch cans (l)

Vs - Volume exiting sprinkler when measuring flow rate (l).

X_i - Individual application depth from the catch cans (mm)

Chapter 1

Introduction

1.1 INTRODUCTION

The need to increase agricultural production to cater for the demands of the growing population of the world has resulted in the use of some areas to produce crops which will naturally not grow there. This has resulted in upsetting the natural balanced state in the environment. In irrigated agricultural land of the arid and semi arid areas, the result of the disturbance has been among others formation of saline soils (Chhabra, 1996; Rhoades *et al*, 1992). This is due to the fact that in the most arid and semi regions, water available for irrigation is underground water (which in most cases is saline). High evapotranspiration results in most cases excess water being used for irrigation therefore raising watertable that later introduce salts into the rootzone.

1.2 BOTSWANA SITUATION

1.2.1 Botswana location and climate

Botswana is a landlocked country located between longitude 20^o and 30^o east of Greenwich and latitude 18^o and 27^o south of equator. Botswana is situated in Southern Africa nestled between South Africa, Namibia, Zambia and Zimbabwe (Figure 1. 1). Its climate is a semi arid. The land is mainly flat with occasional gentle undulations and rock outcrop. The country has an average elevation of 1000 m above sea level. About 85 % of the land is covered by the Kalahari sands and shrub savannah with the driest region towards the south characterised by active sand dunes and very sparse vegetation.

Figure 1. 1: Position of Botswana

The hottest time of the year is also the wettest and this comes between October and April. The coldest part of the year is also the driest and comes between May and September. The average wind speed in the country is 112 km per day. Variation between the maximum and the minimum temperature is very high (Figure 1. 2). The country has an average precipitation of 450 mm, which is unreliable and unpredictable, while the average reference evapotranspiration is 1400 mm (FAO, 1984). Reference evapotranspiration far exceeding precipitation is evident all the year round. The high reference evapotranspiration relative to precipitation has resulted in all the water from the pans (collected during the wet season) evaporating leaving behind salts, brought in by capillary action and other sources, therefore resulting in natural salt pans during the dry season in most parts of the country (Figure 1. 3).

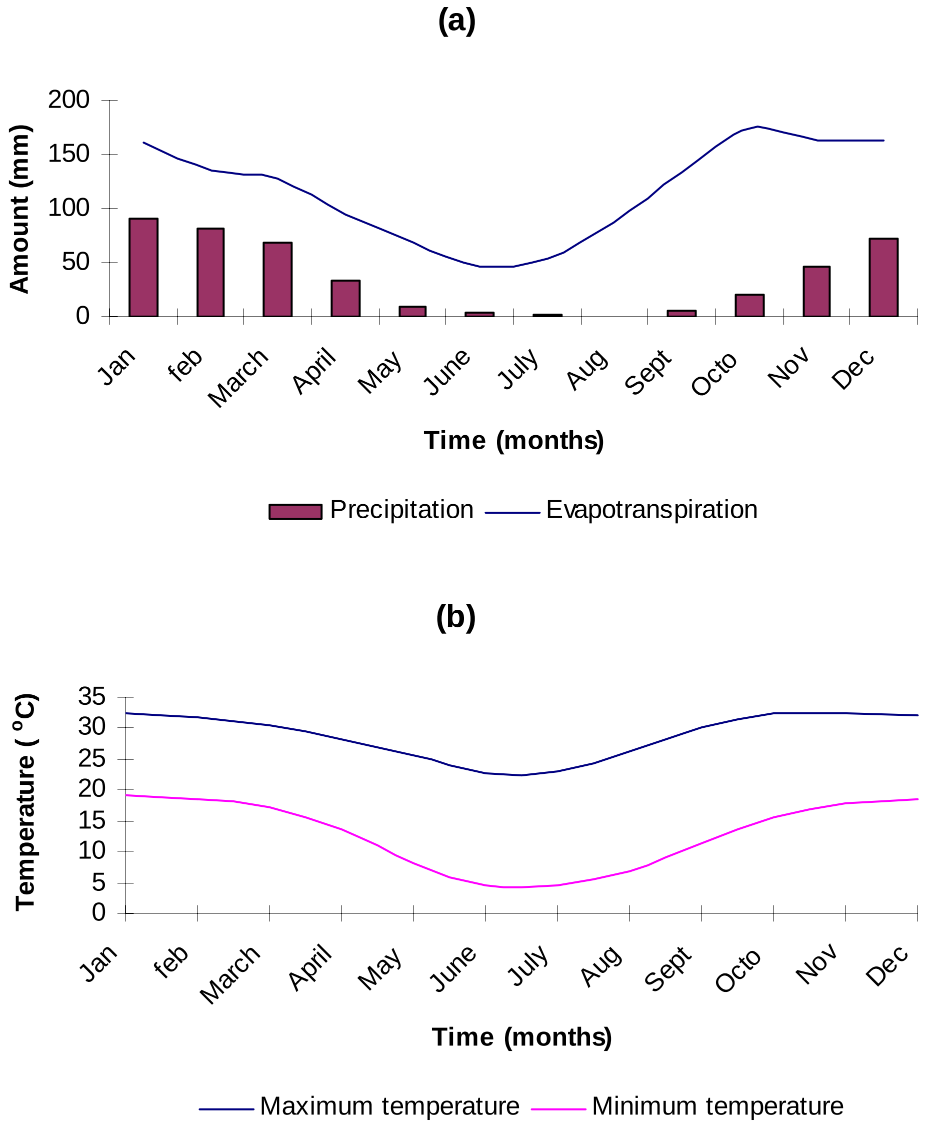


Figure 1. 2: Botswana climate in terms of precipitation and reference evapotranspiration (a) and temperature (b) (FAO, 1984)

Figure 1. 3: Salt pan in Makgadikgadi area, Botswana (Burgess, 2003)

1.2.2 Water resources and irrigation water

Water resources are extremely scarce in many parts of the country. Although ground water occurs in some places, it is often saline (Gould and Nissen-Petersen, 1999). The potential of using surface water for irrigation development in Botswana is limited as all the rivers (all with seasonal flow) within the country are either dammed or planned for damming for domestic water use. This has led to use of ground water which is from poor aquifers (in terms of recharge and water quality) for irrigation by most of the existing horticultural farms (Tahal Consulting Engineers, 2000). Water with an electrical conductivity of 2.36 dS/m is reportedly being used for irrigation in Botswana (Ayers and Westcot, 1985). This figure falls in the range of moderately saline irrigation water according to Rhoades *et al.* (1992).

1.2.3 Vegetable production and irrigated agriculture

Irrigated agriculture in Botswana mainly refers to horticulture production as a significant part of crop production is being produced under irrigation. The horticulture farmers in the country are divided into five regions, which are part of the six agricultural regions, throughout the country for management purposes by the agriculture extension services. In Botswana, irrigation is an absolute necessity for all vegetable crops (Bok *et al*., 2003). Cabbage, kale and rape, tomatoes and onion are at present the most produced vegetables. The country has a potential of producing 75% of its national demand of horticultural produce but at the moment it can only produce only 20%. The current status can be increased by adopting modern cultivation, farm management methods and efficient irrigation (Tahal Consulting Engineers, 2000).

The present practices for irrigation schemes are not well defined. Every region has its own working relations as there are no guidelines. But the common thing with the regions is that there is inadequate investigation and/ or poor design of irrigation schemes resulting in inefficiently operating schemes, high cost of pumping and the use of saline water in some schemes (FAO and Ministry of Agriculture, 1998). Many farmers have limited ability when it comes to managing and operating irrigation projects and they are not made aware of the pros and the cons of irrigated agriculture.

Though commercial vegetable production is a new industry (around 5 years as an average age), some farmers in the country have been complaining about high cost of irrigation and some citing salts as a problem in the fields (Figure 1. 4) which initially did not have the problem. Irrigation with water from the salt-laden underground water is cited as the main sources of salts for arid and semi-arid agricultural land Chhabra (1996). According to Abrol (1988) crops affected by salts in the soil show signs similar to those of crops affected by drought. This kind of plant response usually leads to farmers irrigating more therefore using too much water and increasing the cost of irrigation.

Figure 1. 4: Salt deposits on the soil surface of an irrigated field in the Central region, Botswana

Several research works have been done around the world on the production of crops under salt affected environments (Qadir and Oster, 2004) and it has been shown that with proper management of the farm situation, salt affected land and saline water can be used for crop production without increasing soil salinity to levels obove critical values. This research is done with the aim to recommend infield irrigation management practices to be used by cabbage farmers in Botswana without increase in soil salinity to levels that will affect crop yield.

This aim will be achieved through the following objectives.

- To identify the infield irrigation management practices presently used by cabbage farmers in Botswana.

- To model impacts brought about by the current irrigation management practices on soil salinity using WaSim model.

- To recommend irrigation management practices that would keep soil salinity within the levels which will not result in yield loss whilist conserving water.

1.3 EXPERIMENT DESIGN AND THESIS OUTLINE

1.3.1 Survey

A survey was done with the farms in the five agricultural regions of Botswana that grow horticultural crops. The aim is to identify the infield irrigation management for the regions. During this time, climate data was collected to check if there is any significant difference in climate of the different regions. Factors contributing to infield irrigation management were also collected. All this information was important in identifying what to consider as infield irrigation practices by the farmers in the country when modelling the impact of the irrigation management on soil salinity. It was also important in identify which climate data to use in modelling the soil salinity as some regions might be sharing the same climate.

1.3.2 Field testing of soil salinity and simulation model verification

Cabbage was grown in a research station under three irrigation depth treatments and rootzone salinity observations were made over time. The aim of this on station testing of soil salinity is to produce results under controlled situation which can be used in validating a simulation model which was used in simulating the long term soil salinity trends due to infield irrigation management by cabbage farmers in Botswana. Irrigation treatments and climate during the field-testing of soil salinity were used to simulate rootzone salinity using the model. Results from the model and the field trial were compared.

1.3.3 Soil salinity simulations

Management practices and the climate identified during the survey were used to simulate rootzone salinity over 20 years using the simulation model tested during the model verification. The aim is to identify rootzone salinity trends over a long time due to the different infield irrigation management by the cabbage farmers in Botswana.

1.3.4 Recommendations

To recommend the infield irrigation management practices to be used by the farmers without increasing soil salinity to levels affecting crop yields, amendments were made on the current infield irrigation management practices resulting in soil salinity problems. Simulations of rootzone salinity were made using the amended irrigation management practices to observe the soil salinity.

Chapter 2

Soil Salinity and Irrigated Crop production

2.1 INTRODUCTON

For an irrigation system to be sustainable in the long term, salinity problems should not be allowed to develop. If soil salinity is adequate in the first instance, management must be directed towards maintaining the situation from year to year (Withers and Vipond, 1974). In this chapter soil salinity and irrigation management for salinity control are discussed.

2.2 SOIL SALINITY

Soil is defined as the top most layer of the earth's surface, consisting of rocks and mineral particles mixed with organic matter. Interest in evaluating the quality of the soil resource is stimulated by awareness that soil is a critically important component of the earth's biosphere, functioning in the production of food and fibre (Doran and Parkin, 1994). For the soil to provide this function well it has to provide suitable conditions for plant growth and thus soil quality is assessed by the crop need. Rhoades *et al*. (1992) wrote that the suitability of soil for cropping depends heavily on the readiness with which they conduct water and air and on the aggregate properties that control the friability of the soil. According to Davis *et al*. (1993), good soil should be suitably aerated, drained and not accumulating chemicals poisonous to the roots.

Generally soils contain some soluble amount of salts, which in most cases act as a source of essential nutrients for the healthy growth of plants. But when the soil contains excess salts to impair its productivity, it is called salt affected soil. From an agricultural standpoint, productivity is measured by the effect the soil has on the growth of most crop plants. For definition, saline soils are those that have electrical conductivity of the saturation soil extract of more than 4 dS/m at 25 ^{o}C (Abrol *et al*, 1988). Salt distribution in the soil is highly dynamic, varying greatly in time and space due to the fact that it moves in soil water (Smedema and Rycroft, 1983).

Saline soils can be identified in the field by the presence of white deposits of salts on the soil surface. The deposits can be wet, fluffy or solid and light to dark colour depending on the main constituent of the salt. Saline soils have good physical conditions and high permeability (Chhabra, 1996). Saline soils can also be recognised by patchy and stunted growth of crops. The extent and frequency of bare patches is often an indication of the concentration of salts in the soil (Abrol *et al*, 1988).

Excess salinity in the soil makes less water available to plants although some is still present in the rootzone hence poor and patchy growth stands, uneven and stunted growth and poor yields of crops. This is because high total salt concentration of the soil solution raises osmotic potential exerted by the soil therefore making it difficult for the plant to uptake water from the soil (Abrol *et al*, 1988). Soil may also be toxic to plants due to high concentration in the soil solution of some particular ion or by imbalance between two or more ions (Smedema *et al*, 2004).

Impact of saline soils on the plants depends on the salt concentration at any particular time. But it is difficult to measure soil salt concentration at the usual field moisture contents due to sampling problems. A simplified procedure is used where soil is brought to a saturation state before extracting the water (soil saturation extract) for measuring the amount of total dissolved salts (TDS) in it (Abrol *et al*, 1988). TDS, which is a measure of the concentration of soluble salts in a water sample, is expressed in terms of electrical conductivity (EC). The standard unit of electrical conductivity is deci-Siemens per meter (dS/m) (Scherer *et al*, 1996).

2.3 DEVELOPMENT OF SALINE SOILS

Salt affected soils develop from several processes that in most cases are interrelated. These are divided into two main groups called primary and secondary salinisation.

Primary salinisation involves accumulation of salts through natural processes due to high salt content in the parent material or ground water (FAO, AGL, 2000). During weathering, salts are formed in the soil of both the humid and the arid areas of the world. Whereas in the humid regions salts formed are leached in to streams and rivers then transported to the sea, in the arid and semi-arid regions, due to dry conditions, the salts remain and accumulate where they are formed (Chhabra, 1996). Capillary rise of ground water often transports salts into the higher profiles.

Secondary salinisation is caused by human intervention such as inappropriate irrigation practice with salt-rich irrigation water or insufficient drainage (FAO, AGL, 2000). When there is inadequate drainage, salts that were originally evenly distributed throughout the soil profile will be transported to the top layers by irrigation water and left behind as the water evaporates (Owens, 2001). The common practice in the arid and semi arid regions of the world is to irrigate land on regular basis as a way of coping with the high evapotranspiration. But as the water evaporates, it leaves behind the salts that were dissolved in the water during irrigation, thus increasing the salinity in the soil (FAO, 1973). Most of the salinisation in most of the irrigated land has resulted from an excessive use of irrigation water as a result of (among others) poor on farm management practices. This problem occurs even when waters of low salinity have been used (Rhoades *et al*, 1992). Secondary salinisation is more widespread since changing use and management in connection with industrialised agriculture has affected the balanced salt cycle of the earth.

In all the salinisation processes, the basis of salinisation is that it occurs where potential evapotranspiration greatly exceeds precipitation which is usually in the arid and semi arid environments (FAO-AGL, 2000). Type of soil in an area influences the accumulation of salts in the soil mainly because of the texture. Heavy soil (e.g. clay) will favour accumulation of salts more than the light soils (e.g. sand). This is because light textured soils are highly drained therefore allow easy leaching and they have low cation exchange capacity therefore retain less salts than the heavy textured soils. Light textured soils also have poor capillary rise making them less likely to be affected by salts from below (Chhabra, 1996).

2.4 IRRIGATION MANAGEMENT FOR SOIL SALINITY CONTROL

Irrigated agriculture is a major contributor to many surface and ground water salinities (Rhoades *et al*, 1992) and as mentioned above, the use of salt laden irrigation water facilitates salinisation. Therefore managing infield irrigation well can maintain soil salinity within the tolerable levels. Key aspects in irrigation for salinity control are leaching and drainage (Chhabra, 1996).

It is important to observe the water table as leaching water can bring the water table too high to reintroduce the leached salts into the rootzone (FAO/ UNESCO, 1973). High water table can be due to other sources. But if it is a problem, there might be a need to install drainage system. Drainage systems will also be important to help leaching where heavy soils are involved.

Crops rotation should be done with crops tolerant to salts by absorbing the salts from the soil. These crops can either absorb the salts and restrict them to the lower parts of the plant or absorb and excrete them. Although it is argued that the use of halophytes to lower salt concentrations in most saline soils would be slow (at best), halophytes can transpire sufficient water to lower watertables therefore allowing chance for leaching (Barrett-Lennard, 2002).

Where there is an alternative less saline water source, using both sources can be an option. This can be done by alternating the use of saline (for tolerant crops) and non-saline water (for sensitive crops) in crop rotation. The two waters might be blended to lower the salinity of the saline water (Qadir and Oster, 2003) so that salinity build-up during the irrigation season can be enough to be washed out during the rainy season (Sharma and Rao, 1998).

2.5 RECLAIMING SALT AFFECTED SOILS

If the irrigated land has already reached a point where it is unproductive, reclaiming the land is needed. This means removing the soluble salts from the rootzone. Salt deposits accumulating on the surface of the soil can be scraped out mechanically or flushed away with water (Chhabra, 1996). Leaching with water is another way salts can be removed from the rootzone but as mentioned above, drainage of the soil has to be good. Drainage of the soil can be improved by ripping the soil to depths more than the rootzone. Adding organic matter to the soil will also improve its drainage (FAO/ UNESCO, 1973)

After reclaiming the land it is important to cut out the sources of salts to avoid resalinisation. This can be done by following proper infield irrigation management as discussed above.

Chapter 3

Infield Irrigation Management Practices used by Cabbage Farmers in Botswana

3.1 INTRODUCTION

Irrigation scheduling depends on several factors namely climate, plant, soil type and irrigation water. Various methods can be used depending on the situation at hand. This section aims at identifying infield irrigation management practices presently used by cabbage farmers in Botswana. This was achieved through the following objectives:

1 To identify and compare climate in the different agricultural regions of Botswana.

2 To identify water salinity for irrigation water used by Botswana cabbage farmers.

3 To identify rootzone salinity in the Botswana cabbage farmers' fields.

3 To identify soil type used by the farmers for growing cabbage.

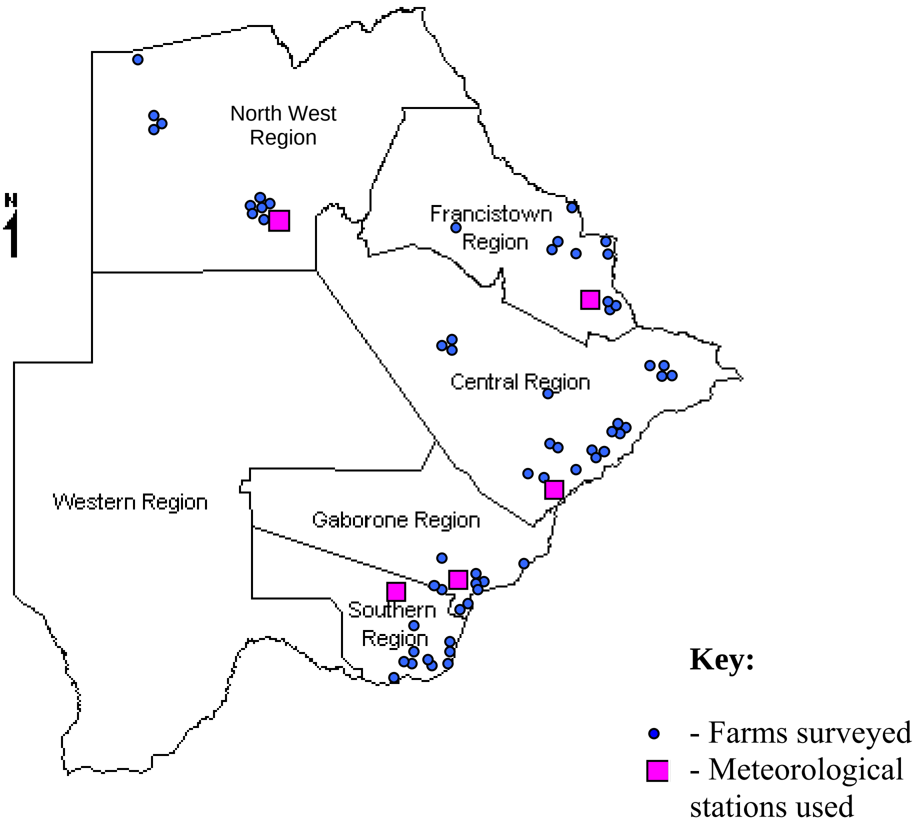
4 To identify the irrigation depth used by cabbage farmers in Botswana.

A survey was carried out and was composed of a questionnaire, irrigation water electrical conductivity test, farm soil (rootzone) electrical conductivity test and irrigation depth estimation. The actual application rate of the irrigation system used by each farmer was measured in the field.

3.2 METHODOLOGY

3.2.1 Survey Location

The Survey was carried out in the farmers' fields in five of the six agricultural regions of the country (Figure 3. 1). Western region was left out as it is not a vegetable producing area.



Adapted from FAO (2004)

Figure 3. 1: Map of Botswana showing agricultural regions, location of farms surveyed and meteorological stations

3.2.2 Choosing farms for survey

Quota sampling method as described by Hoinville *et al.* (1978) was followed when conducting the survey. Twenty farmers were chosen from the central region while 10 were chosen from each of the other regions. More farmers were chosen in the Central region after an advice from a personal communication with a senior staff member of Horticultural section in the Extension Services of the Ministry of Agriculture Mr Pilara. Central region has more farmers than the other regions (The number of all horticulture farmers in the region is 47). The farmers had to be growing cabbage and irrigating with water from boreholes. Farms were identified through the help of the Irrigation and Horticultural sections in the Extension Services of the Ministry of Agriculture, as they are in the forefront in the irrigation farmers support services.

3.2.3 Time of visit to the farms

The survey was conducted between June and September 2004. Each region was allocated two weeks to finish so that at least one farmer could be interviewed every day during the two weeks depending on the distance of the farm from the camping station. At all times, an Irrigation Officer for the region visited was available in order to help locate the farms and introduce the researcher to the farmers. Dates of visits are shown in Table 3. 1.

Table 3. 1: Number of farmers and the dates during which each agricultural region was visited for interview

Agricultural Region	Dates of Visit (2004)	Number of Farmers interviewed
Gaborone	14 – 26 June	10
Southern	5 – 10 July	10
Central	2 – 14 August	20
Francistown	16 – 21 August	10
North West	6 – 11 September	10

3.2.4 Questionnaire

A questionnaire was administered at the time the farms were visited. It contained questions on: 1) farm identity such as name of the farm, size, location of the farm, depth of cultivation used in the farm and the time during which the farm has been in operation. 2) Crop data such as crops grown, time grown and area allocated to cabbage and its ground cover at maturity. 3) Irrigation such as duration and interval.

The farmer was asked to talk about his/ her infield irrigation management. While the farmer was talking, important points raised by the farmer, which answer questions on the paper, were noted and marked on the question paper by the researcher. Any question that was not covered when the farmer was narrating were then asked and filled in. See appendix A.1 for the questionnaire.

3.2.5 Cultivation

Farmers were asked about the type of cultivation they use which is divided into deep and light cultivation. A standard cultivation method, that is where mouldboard ploughs, disc plough and hand tools such as digging forks and spades were considered as light cultivation. Any situation where the implements rip the soil deeper than the above mentioned was considered as deep cultivation.

3.2.6 Ground cover

Ground cover refers to the crop ground cover at maturity but during the time of visit for interviews, farmers' crops were at different stages. Therefore ground cover at maturity was estimated as follows: In the question paper, diagrams were drawn to represent different percentage cover. The diagrams represented the maximum percentage within the following ranges: 0 - 20 %, 21- 40 %. 41 – 60 %, 61 – 80 % and 81 – 100 %. A farmer was then asked to choose the one which most likely to represent the stand of his crop in the field at maturity. Diagrams are shown in the questionnaire in appendix A.1.

3.2.7 Irrigation

Average irrigation depth per day was estimated as the amount of irrigation water applied per day using the following formula:

$$D_i = I \div T_i \text{ --- } (3.1)$$

Where:

D_i - Average irrigation depth per day (mm / day)
I - Irrigation depth (mm)
T_i - Irrigation interval (days)

Methods followed to arrive at the irrigation depth were different depending on the irrigation system used. The methods are described below.

3.2.7.1 Hand irrigation

Hand irrigation is used to refer to irrigation where farmers apply irrigation water using portable containers with which they fetch water from the source (reservoir or stand pipe). To find the irrigation depth for this type of irrigation, the amount of water applied was first estimated by estimating the volume of the container used for irrigation and the area of the bed irrigated. The volume was then multiplied by the number of containers applied during irrigation. The area of irrigated bed was found by measuring the necessary dimensions of the bed. Irrigation depth was then estimated as:

$$I = V \div A \quad \text{------------------------------------} \quad (3.2)$$

Where:

I - Irrigation depth (mm)
V - Volume of water applied (l)
A - Area of bed (m^2)

3.2.7.2 Sprinkler and Drip

For sprinkler and drip irrigation systems, the application rate of the system was first estimated in the field (see section on sprinkler and drip application rate below). Then with the use of irrigation duration obtained from the questionnaire, Irrigation depth was estimated as:

$$I = q \times t \quad \text{------------------------------------} \quad (3.3)$$

Where:

I - Irrigation depth (mm)

q - Application rate (mm / hour)
t - Set time for irrigation (hours)

Sprinkler application rate

Five catch cans were placed at spacing intervals of at most 3 m (depending on the sprinkler spacing) between the sprinklers (Figure 3. 2) to collect water. The 500 ml catch cans were left until each one of them had collected water of at least up to the minimum mark which was 50 ml. Volume of water collected in each can was recorded. Time taken to collect the water was also recorded. Where the farmer was using one sprinkler and just moving it around (Figure 3. 3), the radius of the wetted circle was measured from the sprinkler position up to the end of the wetted soil in the direction of the move. From the end of the wetted soil to the sprinkler, five catch cans were then placed at equal intervals in the direction of the sprinkler move. The cans were left until the sprinkler throw on the opposite side of the direction of the move had gone past all of them and no more water being collected in any one of them. Volume of water collected in each can was recorded. Time taken to collect the water was also recorded. Then application rate was estimated using the following formula.

$$q = I_c \div t \text{ -- } (3.4)$$

Where:

q - Application rate (mm / hour)
I_c - Collected depth in a catch can (mm)
t - Set time for irrigation (hours)

NOTE: $I_c = V_c \div A_c$

Where: V_c - average volume in catch cans (l)
A_c - surface area of the catch can (m^2)

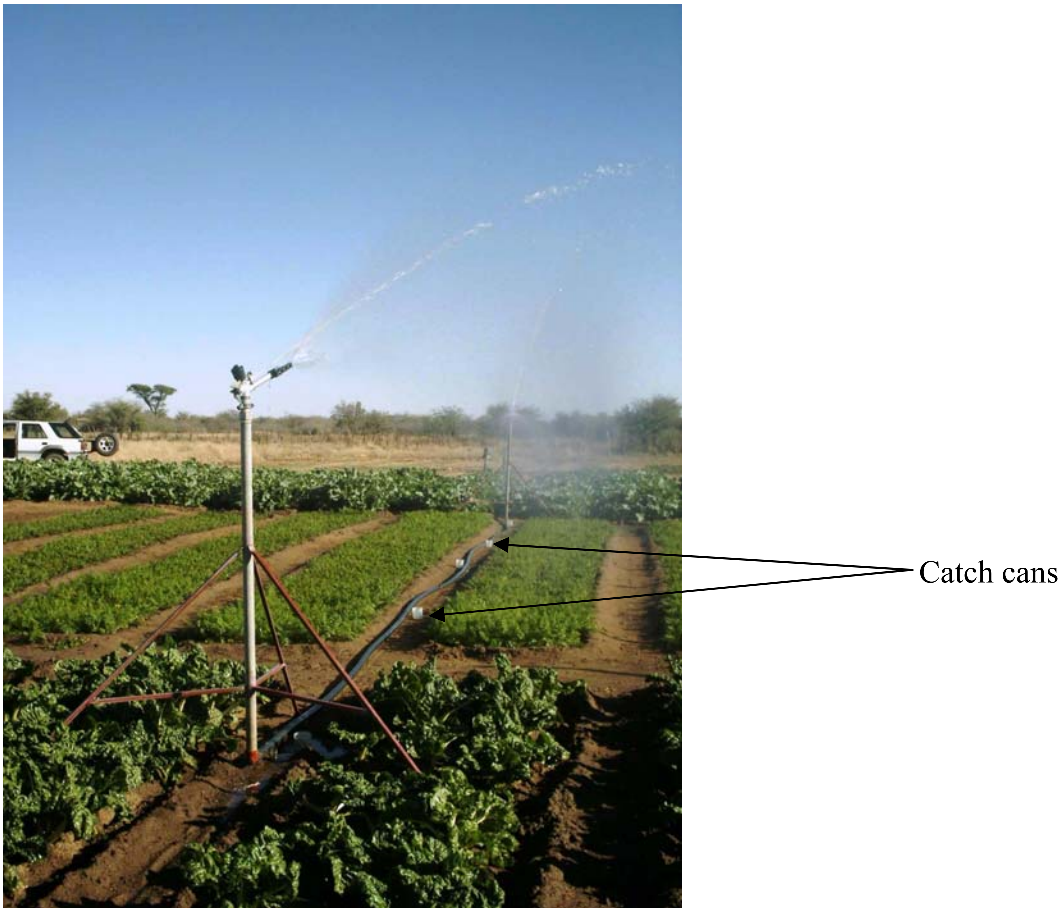


Figure 3. 2: Water being collected for application rate estimation

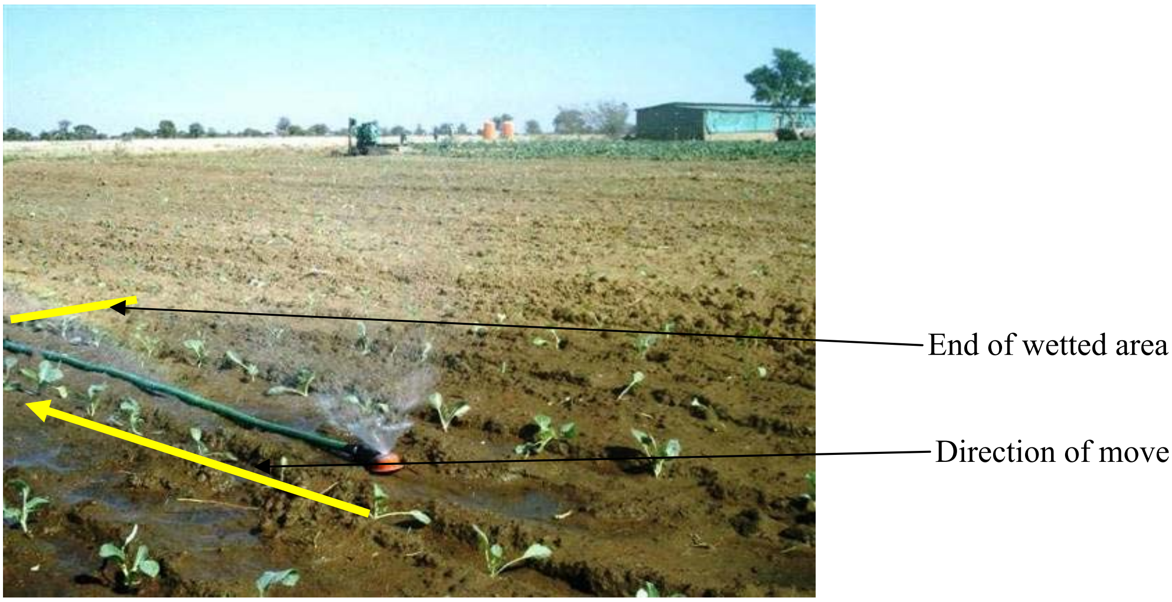


Figure 3. 3: Single sprinkler in use

Drip application rate

A 500 ml catch can was placed under the first emitter and a second under the last emitter of the first lateral. This was also done at the middle and the last lateral. Cans were left to stand until the amount of water collected was at least 50 ml (which was the minimum mark). Time taken to collect the water was noted. Application rate was estimated using the same formula as above for sprinkler application rate. But in this case collected depth was found as follows:

$$I_c = V_c \div A_d$$

Where: I_c - Collected depth in a catch can (mm)
V_c - average volume in catch cans (l)
A_d - area per dripper (m^2)

3.2.8 Irrigation water salinity

Water collected during application rate determination was mixed and used for testing irrigation water salinity in the field. For hand irrigation, water was collected from the reservoir storing irrigation water or from the standpipe where they were used. The test was done using a portable model 4070 conductivity meter (model specifications in appendix A.2). This instrument has an electrical conductivity (EC) and temperature probe/electrode. Electrical conductivity probe measures the actual EC whereas the temperature adjusts the EC reading to the equivalent measured at 25°C temperature. Both probes of the meter were dipped inside the water, and allowed to stand until the meter reading stabilised before a reading could be taken. See the Figure 3. 4 below.

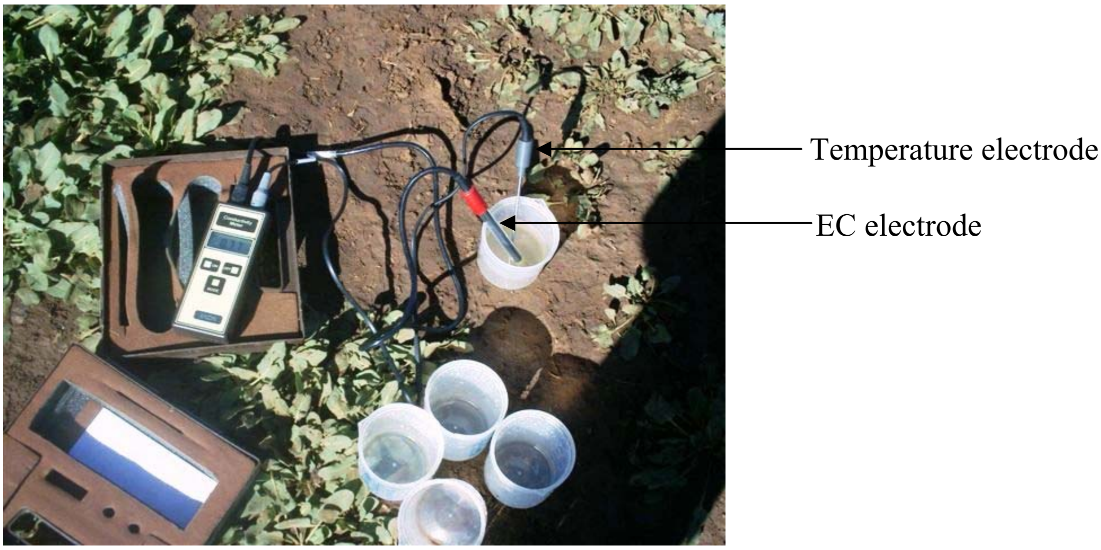


Figure 3. 4: Water salinity testing and equipment

3.2.9 Root zone salinity

3.2.9.1 Soil Sampling

Three different positions in the field were chosen for soil sampling. The first position was within the plant row, the second one between the rows and the last one at the edge of the cropped area (Figure 3. 5). At each position, a vertical hole down to 0.5 m (cabbage effective rooting depth) was dug using a spade. Then using a measuring tape to get the depth at which to sample, soil samples were taken at the soil surface, 0.12, 0.25, 0.37, and 0.5 m below the soil surface. These depths were arrived at by assuming 40-30-20-10 crop water use pattern (Ayers & Westcot, 1985). This method is based on the plant root development under uniform soil where moisture is not limited (Withers & Vipond, 1974). About 300 g of soil from each depth was collected in a sampling bag.

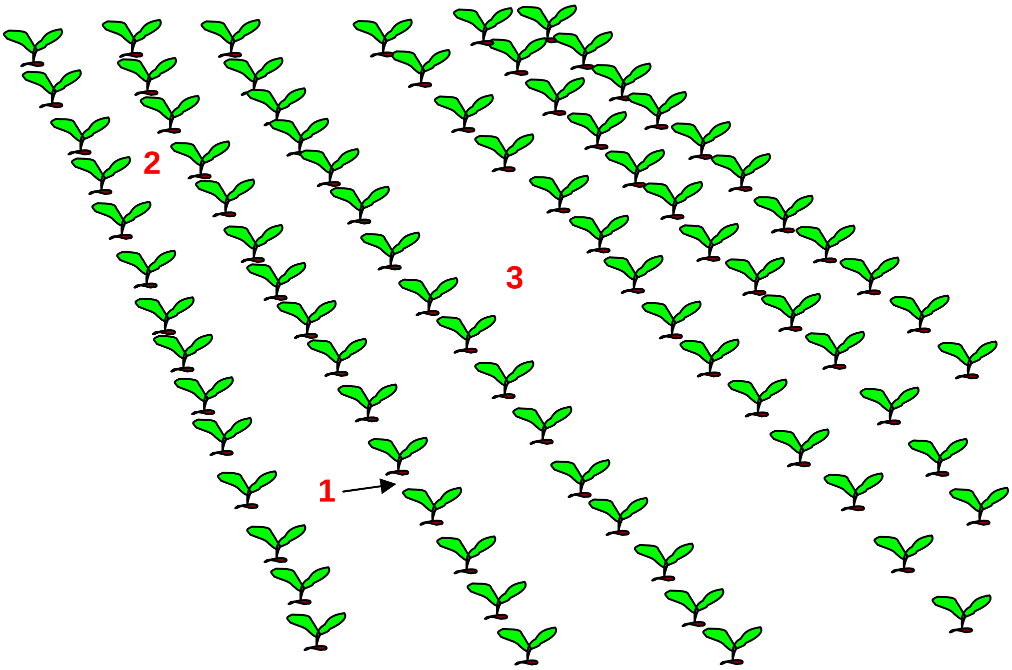


Figure 3. 5: Positions of soil sampling in the field

3.2.9.2 Electrical conductivity analysis

The soil samples were then taken to the laboratory for electrical conductivity analysis test. Each soil sample was air-dried after which it was ground to break some lumps. The soil was then passed through a 2 mm sieve and then used for preparing saturation extracts (Cetin & Kirda, 2003). Electrical conductivity of saturation extract was determined by first saturating the soil samples and then using a Buchner funnel and vacuum pump to remove the saturation paste extract (Gartley, 1995). Electrical conductivity of the extract was then measured using a conductivity meter as shown in Figure 3. 4.

3.2.10 Soil identification

Soil collected when sampling for salinity test was also used for textural class identification. The feel method was used for the identification. Soil was wetted and kneaded thoroughly between the finger and the thumb until the soil crumbs were broken. The soil was wetted until it showed maximum stickiness. Pebbles, grit, roots and other bodies were removed from the soil during the kneading process. Guidelines for identifying soil textural class outlined by James and Lovelace (2004) were then followed to identify the soil. Guidelines for textural class identification are shown in appendix A.3.

3.2.11 Climate and water table

There are few meteorological stations in Botswana with long-term data. Data from certain meteorological stations with long-term data were used to represent the climate of the whole region. The stations used for each region are shown on Table 3. 2.

Table 3. 2: Meteorological stations used to represent climate of different regions

Region	Meteorological station	Location
North West region	Maun	19^{o} 59’ S, 23^{o} 25’ E, altitude 994 m
Francistown	Francistown	21^{o} 13’ S, 27^{o} 30’ E, altitude 1000 m
Central	Mahalapye	23^{o} 05’ S, 28^{o} 48’ E, altitude 1006 m
Gaborone	SSKA, Gaborone	24^{o} 40’ S, 25^{o} 55’ E, altitude 994 m
Southern	Jwaneng	24° 60' S, 24° 66' E, altitude1189 m

Long term monthly averages of rainfall and reference evapotranspiration from these stations (FAO, 1984) were compared amongst each other to identify difference in climate data between the regions. Jwaneng meteorological station does not have data provided in the FAO (1984). Therefore monthly averages from the Department of Meteorological Services, Botswana made from data of the years 1989 to 2000 were used.

Botswana is divided into 24 locations according to average watertable depth. The location borders are not related to regional borders. Depths to watertables and their location in the whole country were collected from the Department of Water Affairs headquarters. The depths are shown on Table 3. 3 below.

Table 3. 3: Depths to watertables in Botswana

Area Identity	**2**	**3**	**4**	**5**	**6**	**7**
Depth to Ground water (m)	10	30	10	50	70	90
Area Identity	**8**	**9**	**10**	**11**	**12**	**13**
Depth to Ground water (m)	50	10	70	70	50	90
Area Identity	**14**	**15**	**16**	**17**	**18**	**19**
Depth to Ground water (m)	10	70	10	50	90	70
Area Identity	**20**	**21**	**22**	**23**	**24**	**25**
Depth to Ground water (m)	110	110	130	-	70	50

3.2.12 Statistical analysis

All attribute data analysed in the project was tested using the chi-square test. Unless otherwise stated, all the measurement data was analysed using the Duncan multiple range test (DMRT), and all the error bars in the figures represent the range of 95 % confidence interval. All tests were done at the alpha level of 0.05.

3.3 PRESENTATION OF RESULTS

3.3.1 General information

All the farmers interviewed produced crops under open fields. They were also doing light cultivation and of all the farmers surveyed, 17 % of them do mulch, and the mulching was restricted to seedbeds only. There were no farmers mulching out in the field after the crops are transplanted. No farmer had drainage system installed. All the farmers were found to be growing different types of vegetables with cabbage.

3.3.1.1 Farm size

With an average farm size of 2.8 hectares (ranging from 0.1 ha to 30 ha), the area of farm land grown with cabbage varied from 0.006 ha to 5 ha with an average of 0.66 ha. Some of the farmers who give 100 % of their land to cabbage are only doing that for one season, growing other crops during the other season.

3.3.1.2 Farm age

Results from the survey showed that farms had been producing cabbage from a minimum of 1 year to a maximum of 30 years. With an average year of production at 6 years and only 15 % of the farms having been on production for over five years, it is clear that the farmers are really new.

3.3.1.3 Soil

Soils used in the farms were from a wide range of textural classes from clay soils to sandy soils. Therefore the soils were classified as light, medium and heavy depending on the available water holding capacity. All soils with available water holding capacity below 100 mm/m were considered light while those between 100 mm/m and 140 mm/m were considered medium. Above 140 mm/m soils were considered heavy (Doneen and Westcot, 1984). The proportion of each soil used in different regions is shown on Figure 3. 6. There was no significant difference between the type of soil used in different regions.

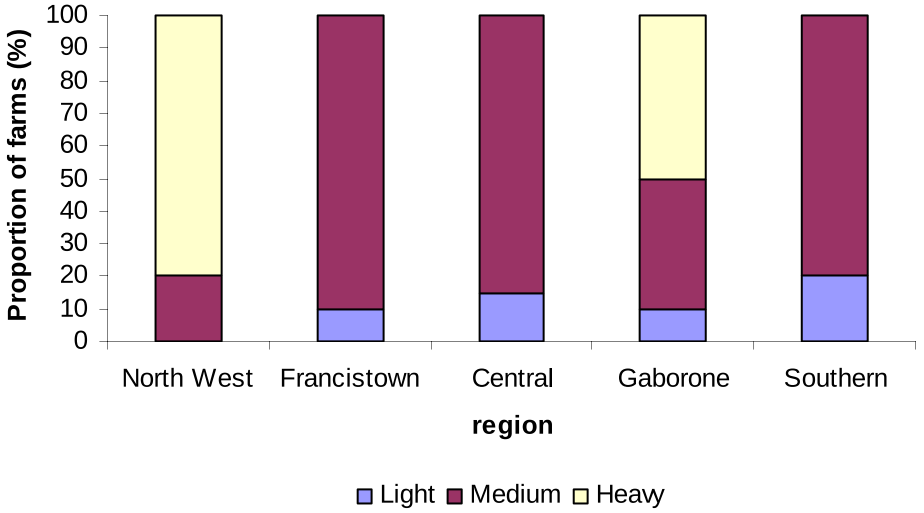


Figure 3. 6: Proportion of farms using different soil types in different regions

3.3.1.4 Cropping season

The survey established that there are two cropping seasons for cabbage in Botswana. In one season (referred to as a winter season) the crop is planted between March and May so that it grows through the winter months (May to August). In the other season (referred to as the summer season) the crops are planted between October and November and they grow through the summer months (November to February). It was established that 82 % of the farmers produce cabbage in winter, and only 18 % of the farmers produce throughout the year. For all the farmers who are producing throughout the year, it was found that the production is not continuous but divided into two seasons described above. Farmers who produce cabbage during winter only, produce other vegetables during the summer season whereas those producing throughout the year produce it alongside other vegetables. Statistical analysis shows that there is no significant difference in the time of planting between regions.

3.3.1.5 Irrigation system

Irrigation systems used by the farms vary significantly between the regions. From Figure 3. 7, it is evident that the most popular irrigation system used in Gaborone, North West and Southern region is the sprinklers whereas in Francistown region hand irrigation is most popular. In the Central region, the most popular system is drip system. There were no farms using drip irrigation in the North West as compared to the Gaborone and Southern where there were no farmers using the hand irrigation.

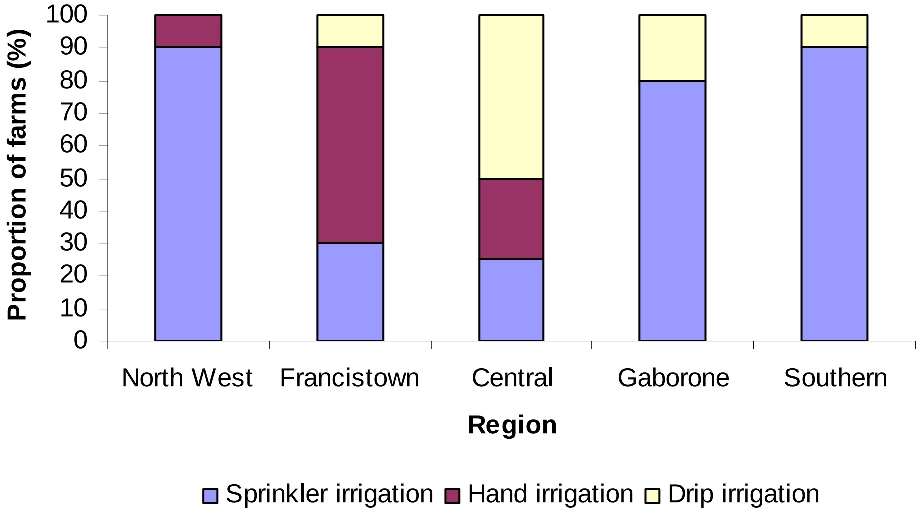


Figure 3. 7: Prorpotion of farms using different irrigation system in different regions.

3.3.1.6 Climate

Average long term monthly data of the different stations (Figure 3. 8) show that in all the regions, precipitation is high during the summer months (November to March) and lowest during the winter months. Reference evapotranspiration is also low in winter months and highest in summer months with the peak around October.

In all the stations, precipitation is lower than reference evapotranspiration throughout the year. It was found that there is no significant difference in both precipitation and reference evapotranspiration between Maun and Francistown, and Gaborone and Jwaneng (more details on appendix 4).

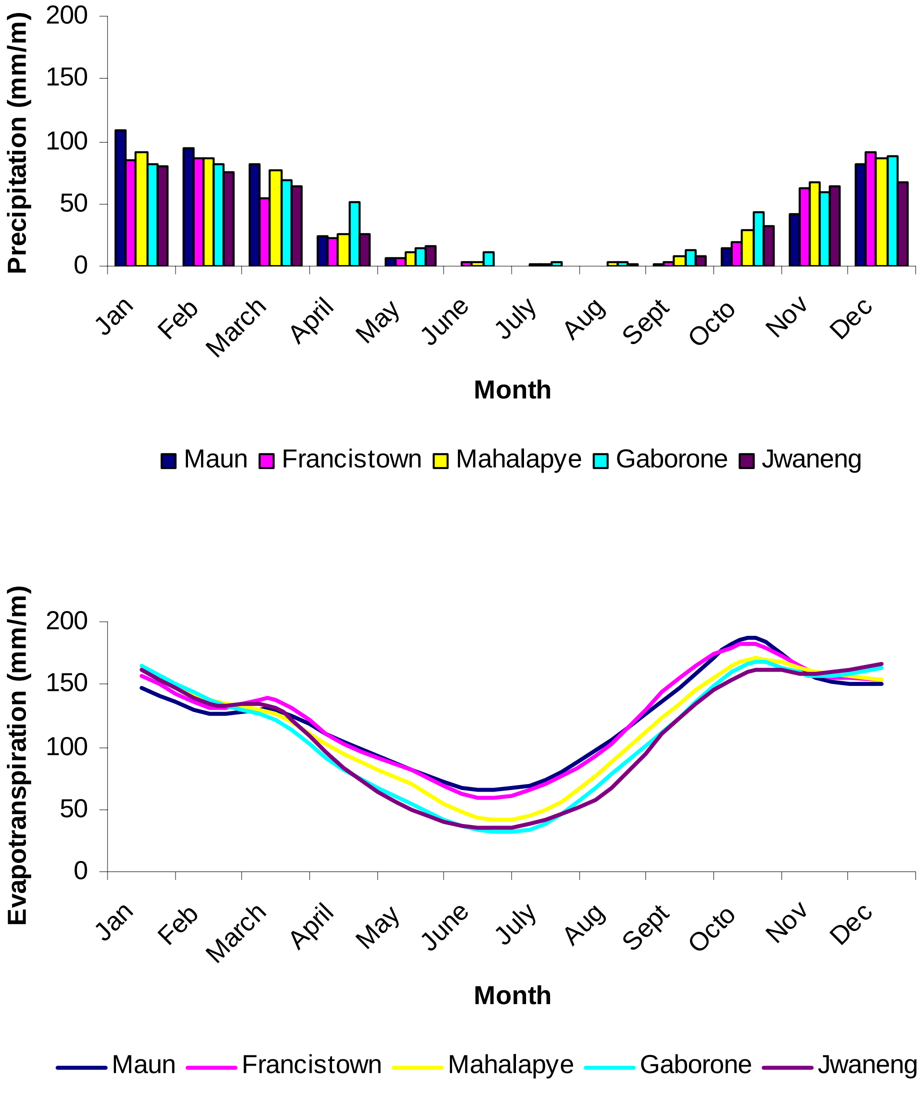


Figure 3. 8: Average monthly precipitation and reference evapotranspiration for the different regions (FAO, 1984)

3.3.2 Irrigation Depth

Most of the farmers have settled for the irrigation scheduling they use through observing how dry the soil is or looking at how water stressed the crops are before irrigating. Farmers interviewed do not schedule irrigation independently for the different crops they grow. They irrigate different crops at the same irrigation depth and at the same time. It was found that 78 % of the farmers do not change their irrigation schedule between growing seasons. This is irrespective of whether the farmers grow cabbage throughout the year or in one season or whether they grow different crops. It was established that there is no significant difference in the amount of irrigation water applied by the farmers on different types of soils. It was also found that there is no significant difference in irrigation depth between irrigation systems in all the regions. No significant relationship is observed in irrigation depth among the different cultural practices e.g. ground cover and tillage depth which was light for all the farmers. Irrigation depth does not vary significantly with the type of soil.

Figure 3. 9 shows that on average, for all the regions, in winter farmers irrigate more than the transpiration requirement whereas in summer farmers do not irrigate enough to cover for the evapotranspiration requirement except in North West and Gaborone region. There is a lot of variability in the irrigation depth within each region as shown by the 95% confidence interval error bars. Irrigation depth used by the farmers in different agricultural regions does not vary significantly.

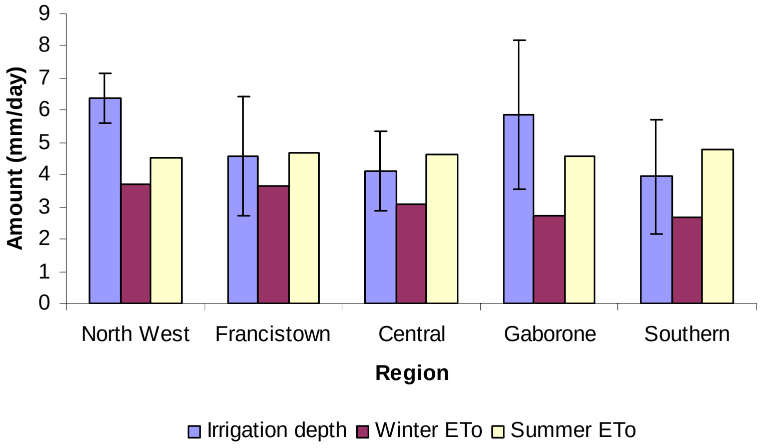


Figure 3. 9: Irrigation depth applied by farmers and average reference evapotranspiration (ET_o) in different agricultural regions. The error bars represent the 95% confidence intervals for the irrigation depth means.

Figure 3. 10 shows that most farmers are irrigating at around 4 mm/day which is the daily average evapotranspiration for all the regions. Around half of all the farmers interviewed are irrigating at levels below average daily average evapotranspiration throughout the whole year.

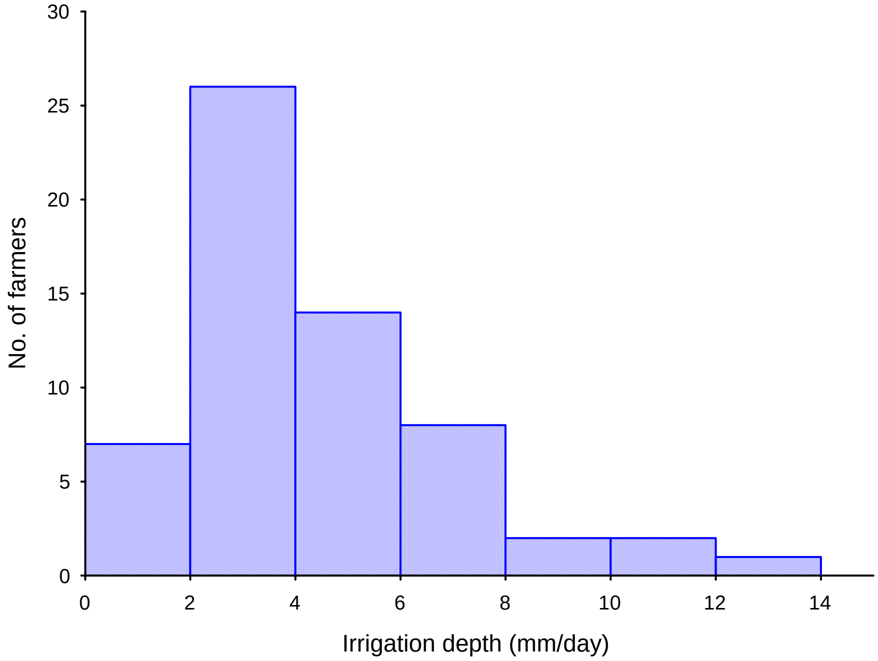


Figure 3. 10: Distribution of irrigation depth used by farmers

3.3.3 Irrigation Water salinity

3.3.3.1 Farmers' perception

Farmers from different regions view the status of their irrigation water significantly different. Most of the farmers in the Central region believe that the water they use for irrigation is salty whereas in the Southern and in the North West most farmers believe that the water they use is not salty. In the Gaborone region, most farmers say that they do not know the salt status of their irrigation water (Figure 3. 11). Although some of the farmers say they know the salt status of their water, none of them has done any test to determine the amount of salts in the water. Farmers estimate the salt status of their water by either tasting the water or the observing the presence of white depositing on top of the soil on their irrigated land. None of the farmers who believe that their water is salty are doing anything about it.

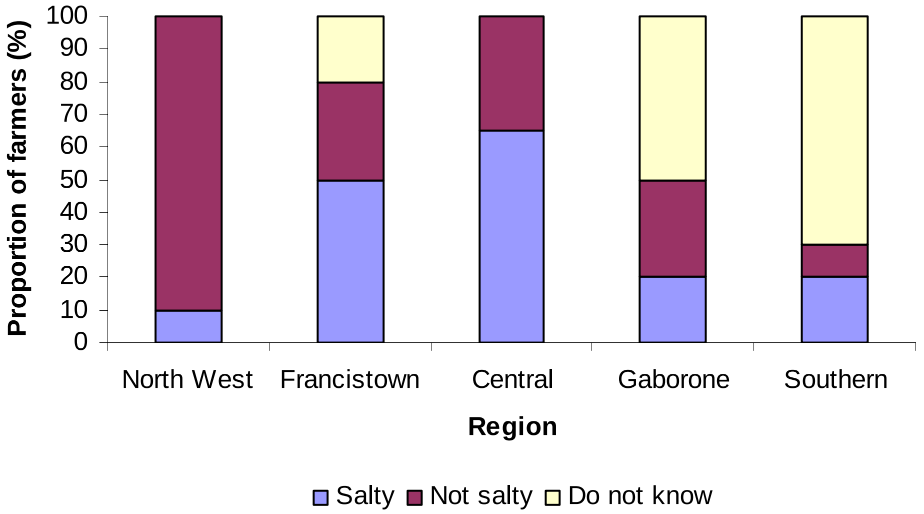


Figure 3. 11: Farmers' perception about the salt status of their irrigation water.

3.3.3.2 Actual irrigation water electrical conductivity

In all the regions, on average farmers were using water that has slight to moderate restriction to use for irrigation (Ayers and Westcot, 1985) which is above the horizontal line on Figure 3.12. There is a lot of variability in the electrical conductivity of the irrigation water used by farmers within each region as shown by the 95% confidence ranges for the mean in each region. There is also no significant difference in irrigation water salinity between the regions (Figure 3. 12). Water of different salinities was also found to be used on any type of soil.

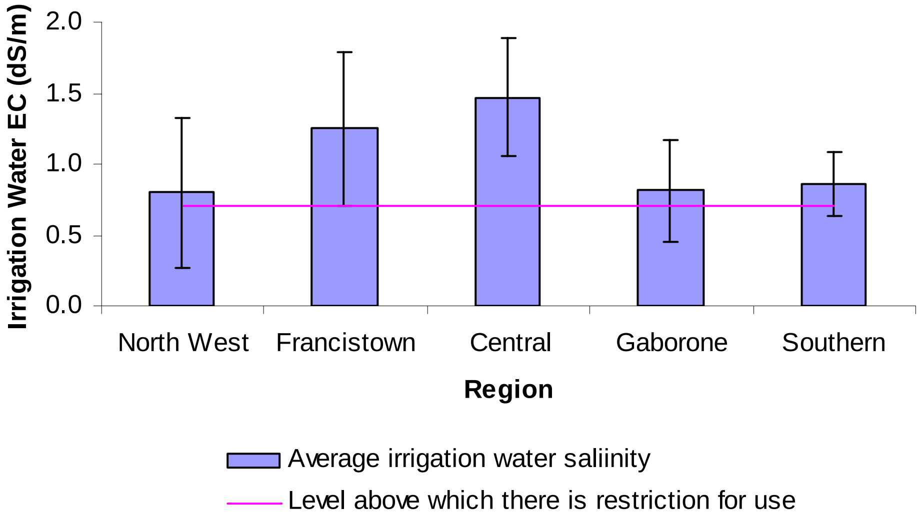


Figure 3. 12: Average irrigation water salinity for different regions. Error bars represent the 95% confidence interval of the mean.

There are some farmers who were using non saline water for irrigation but believing that they use saline water and those who use saline water and believing that their water is non saline (Figure 3. 13). The averages show that the 23 farmers who believed that they have saline water are using water that is moderately saline and 29 farmers who believe that their water is not saline have an average irrigation water salinity that is not saline. The average water salinity of the 8 farmers who do not know the status of their water is slightly saline.

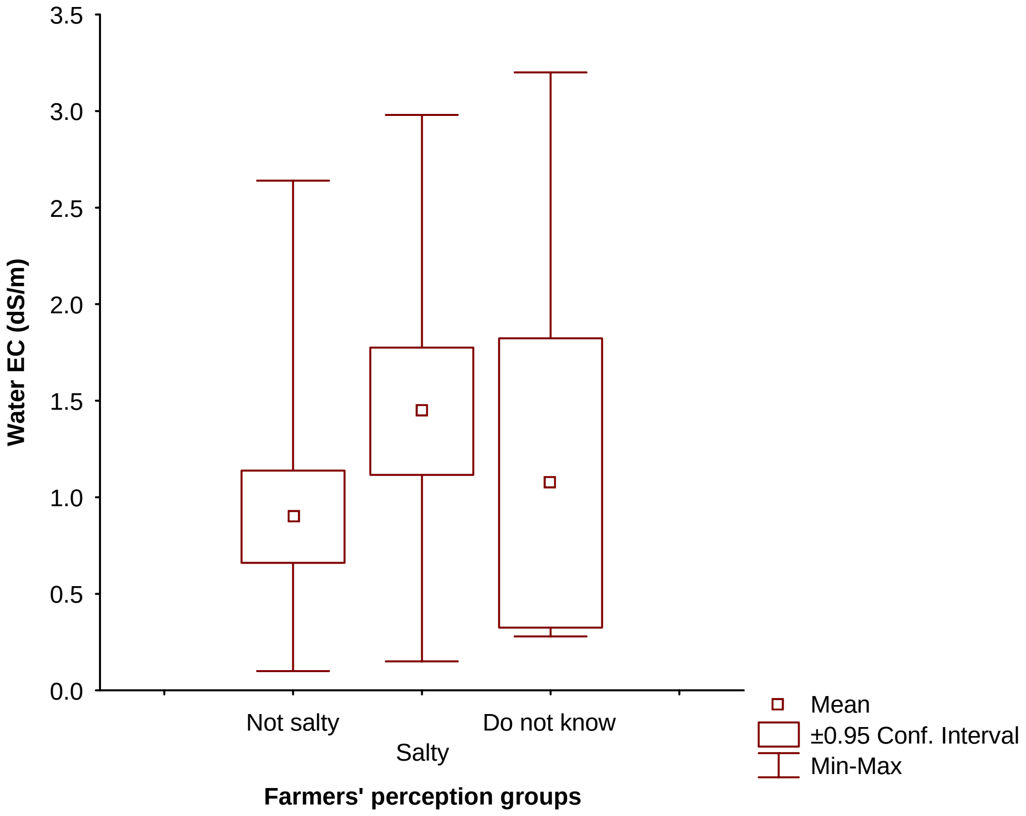


Figure 3. 13: Actual average irrigation water salinity for the farmers' perception groups

3.3.4 Soil EC_e

3.3.4.1 Farmers' perception

From Figure 3. 14, it is significant that most of the farmers do not know about the salt status of the soil they use for production. It is in the Gaborone and Southern regions that most farmers believe that they are using non-saline soils. The farmers who believe that their soil is salty as with irrigation water say they are doing nothing about it.

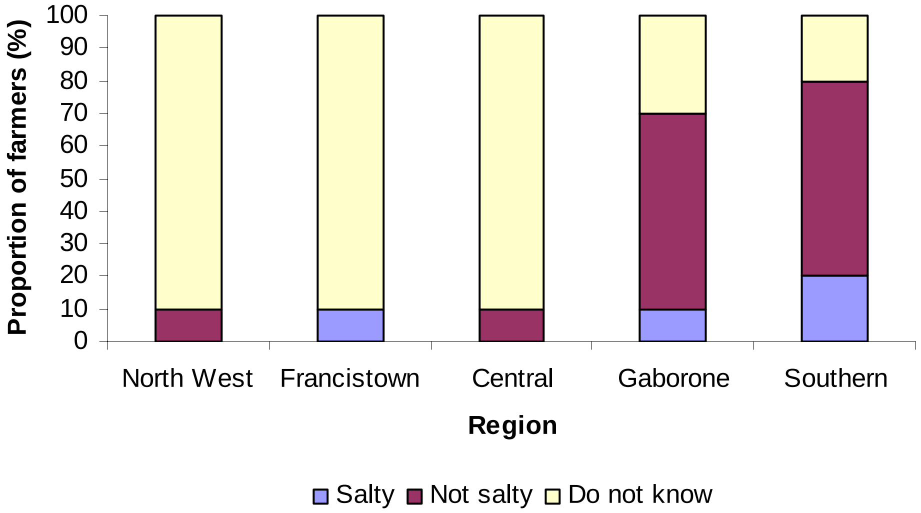


Figure 3. 14: Response of farmers about the salt status of the soil in their farms

3.3.4.2 Actual rootzone EC_e

The measured average rootzone electrical conductivity for the three sampling positions show that in the Central Region the level of salt in the soil is significantly ($p = 0.0009$) higher than in all the other regions. There are farmers in all the regions who are growing cabbage in soils that are too salty to maintain yield at 100 % (Figure 3. 15). It also was established that there is no significant difference in rootzone salinity between the soil types.

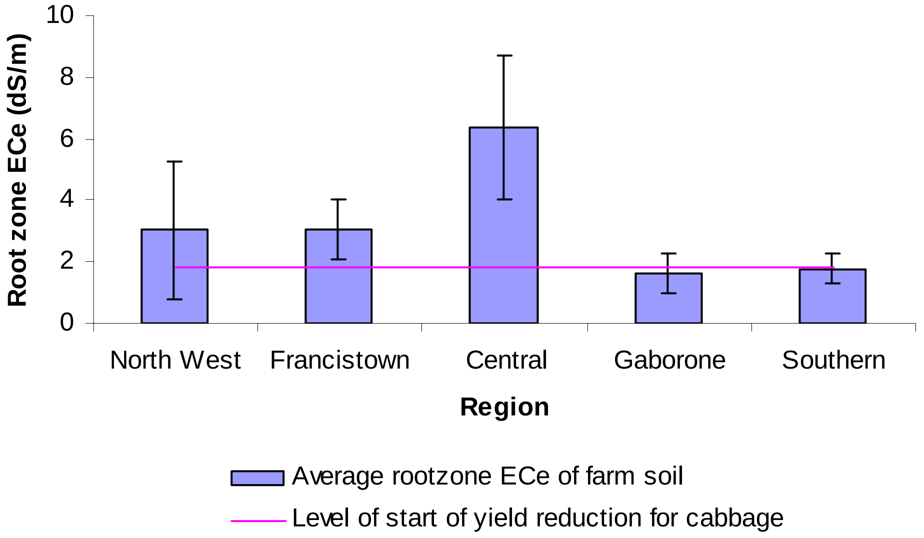


Figure 3. 15: Rootzone salinity of farm soils in different regions. Error bars represent 95 % confidence interval range EC_e within the region.

When grouped into their belief about the salinity level of the soil they are using, it was found that on average all the groups (even those who believe they do not have saline soil) use soil that is too saline for cabbage (Figure 3. 16). Within the group (42 farmers) that do not know about the salinity of their soil, the salinity had a very wide range from around 2 dS/m to 22 dS/m. Only 4 farmers believe that their soil is salty and they all have low saline soils compared to the other groups. It was found that here is no significant difference in average soil salinity between the groups.

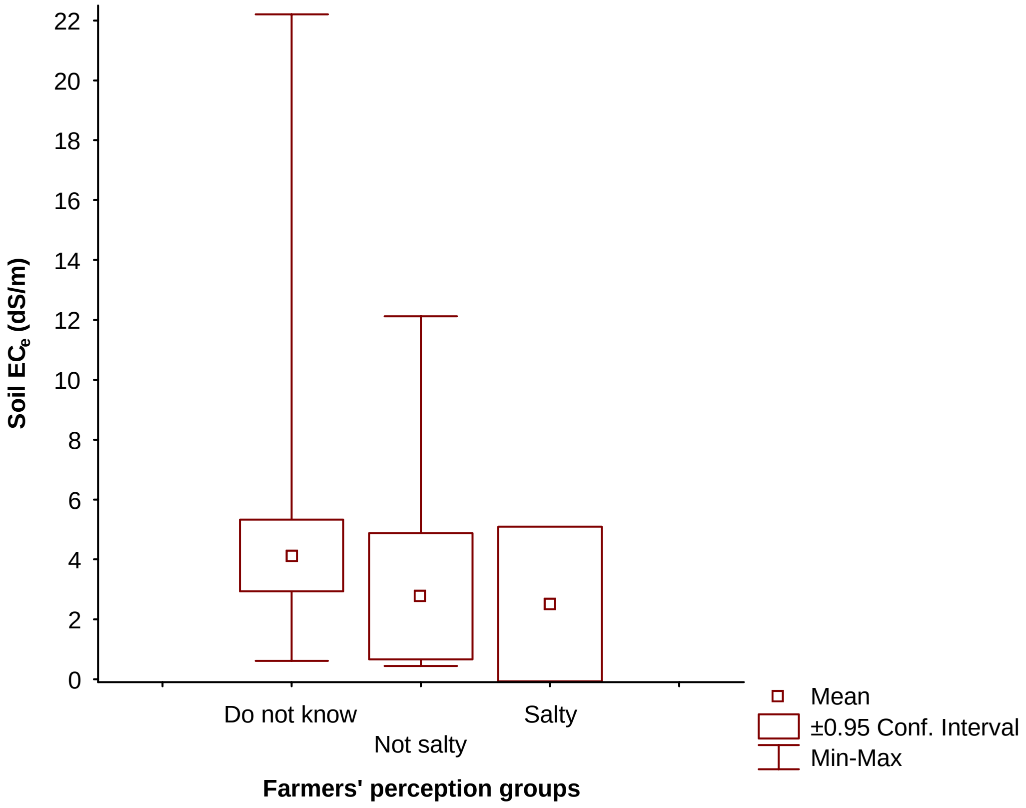


Figure 3. 16: Actual average rootzone salinity for the farmers' perception groups

3.3.5 Irrigation Water EC Vs Rootzone EC_e

Figure 3.17 below shows that irrigation water salinity is significantly related to the rootzone salinity in the Gaborone region, Central region with $p = 0.001028$ and $p = 0.037789$ respectively. In overall farmers using high salinity irrigation water have higher soil salinity. When farmers from all the regions are combined, the regression shows significant relationship between irrigation water salinity and soil salinity (Figure 3. 17). For the rest of other regions, there is no significant relationship between irrigation water salinity and soil salinity.

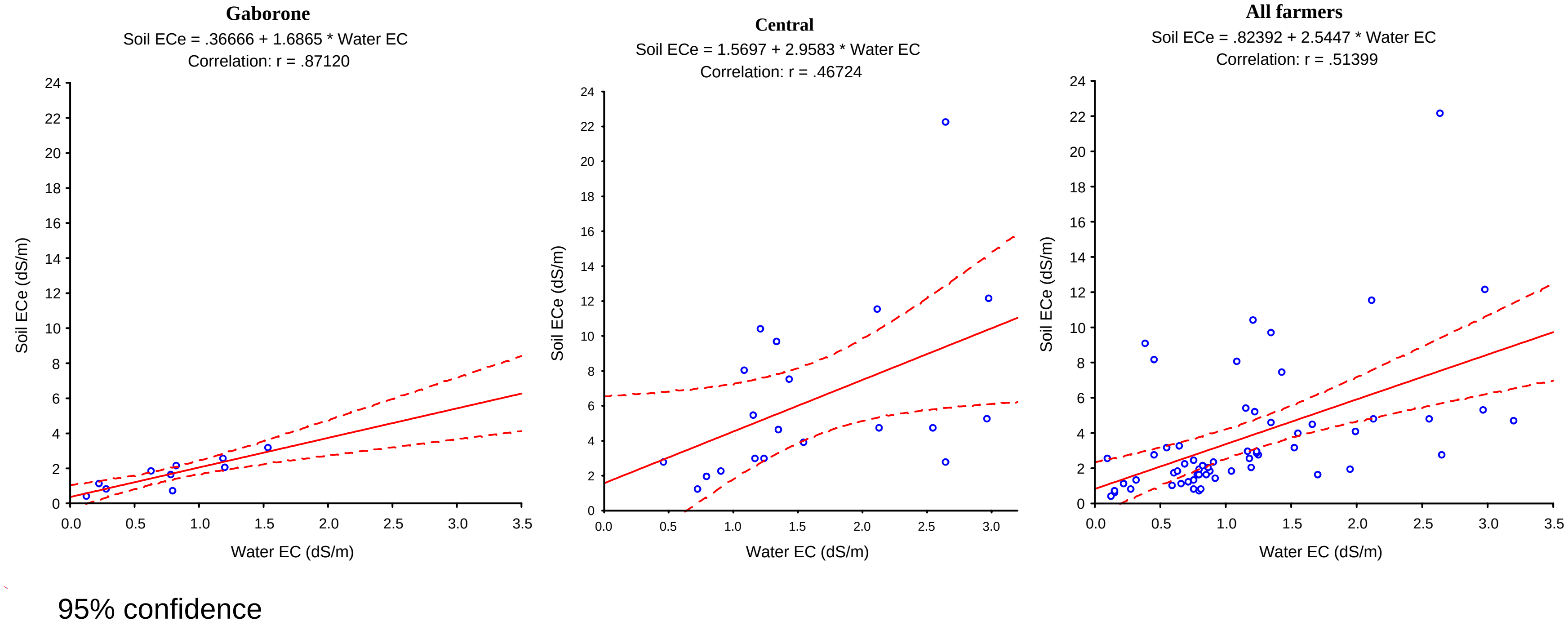


Figure 3. 17: Relationship between irrigation water EC and soil EC$_e$ for Gaborone region, Central region and all the farmers

3.3.6 Irrigation depth Vs Irrigation Water EC

Quality of irrigation water with respect to restriction for use due to irrigation water salinity is represented by the regions demarcated on the graph as none (<0.7 dS/m), slight to moderate (0.7 - 3 dS/m) and severe (>3 dS/m) as per Ayers and Westcot (1985). It can be seen that farmers are using water from all the water use restriction regions. In the no restriction and the slight to moderate restrictions, there are some farmers who are irrigating below average evapotranspiration while some are irrigating high above average reference evapotranspiration. There is no significant relationship between irrigation water salinity and irrigation depth within each region (Figure 3. 18).

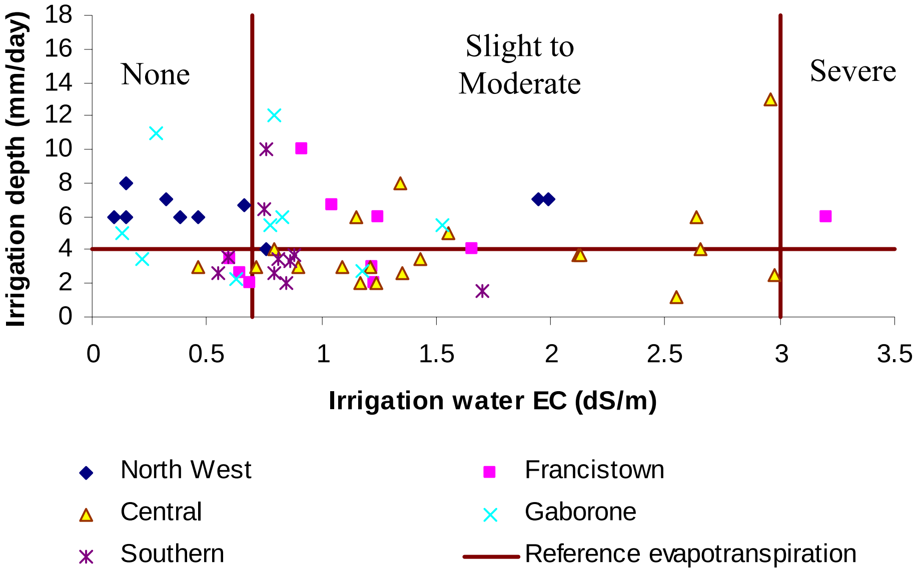


Figure 3. 18: Irrigation depth applied for different irrigation water salinity in different regions.

3.3.7 Soil EC_e Vs Irrigation depth

From Figure 3. 19 it can be seen that the actual amount of irrigation water applied varies in each region. There is no significant relationship between the amount of irrigation water applied per day and the electrical conductivity of the soil.

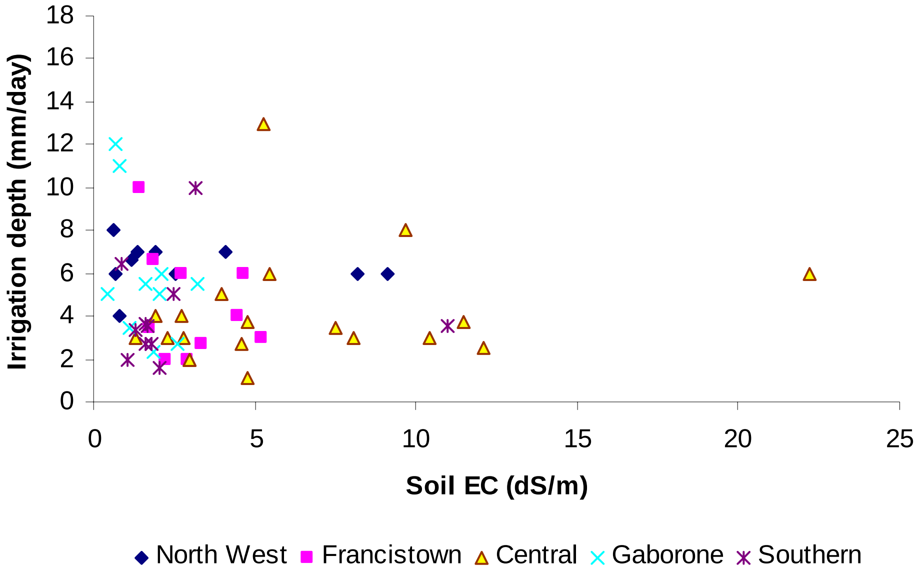


Figure 3. 19: Relationship between irrigation depth and soil ECe for the different regions

It was found that there is no significant relationship between the soil salinity and the number of years the farms have been cropped.

3.4 DISCUSSION OF RESULTS

3.4.1 Irrigation Depth

Most farmers say they have settled for the schedule they are using through observing how dry is the soil or observing plants. Therefore in this case, it is expected that irrigation depth should show some relationship when compared to the type of soil, climate (region and season), type of irrigation system or the type of crop grown as these affect evapotranspiration (Doorenbos & Kassam, 1984). In this case, the soil used by the farmers is different, climate from different regions except between Francistown and North West is significantly different, irrigation systems used are also different and the types of crop grown by the farmers differ. But from the results it shows that irrigation depth does not vary significantly with any of the above.

3.4.2 Irrigation water and soil salt content

Most of the farmers believe they know the salt status of their water though they have not done lab tests. It was shown that some of the farmers' beliefs were the opposite of the reality about the salt status of the water. Most of the farmers do not know the salt status of the soil they use and what some of those who believe they know the status say of their soils is the opposite of the reality of the salt status of the soil. A relationship between irrigation water EC and soil ECe for all the farmers show that some of the soil salts is contributed by irrigation water. The contribution of irrigation water to soil salts is also shown in Gaborone region. The fact that soil salts do not differ significantly with soil type and water table is too deep to contribute to the rootzone salts leaves irrigation water as the only likely factor that determines the differences in root zone salts. Tedeschi and Menenti (2001) did work on relationship between irrigation water salinity and soil salinity and found that there is a relationship. In the regions where this kind of relationship is not significant might be due to the fact that results were not obtained from a controlled experiment. Therefore there were a lot of other factors influencing the soil salt content such the amount of water that the soil had already received as it determines the amount of salts that have already been put into the soil.

Although irrigation water contributes to salts in the soil, there is no relationship between irrigation water electrical conductivity and irrigation depth in all the regions. This was not expected as when farmers come up with the irrigation depth by observing the plants and soil moisture content, irrigation depth should be determined by the salt content in the irrigation water as plants affected by salts show the same signs as those affected by water shortages (Rhoades *et al.*, 1992). In all the regions, there are farmers applying low irrigation and those applying high irrespective of the salt content of the water. Farms apply different amounts of water per day and irrigation water salinity differs between different farms therefore the amount of irrigation salts added to the soil per volume of irrigation water differ from farm to farm, hence no relationship between soil salinity and the number of years the farms have been cropped.

The fact that the farmers irrigation scheduling does not vary significantly with the type of soil, climate, irrigation water salt content, soil salt content and crops raises a question of how really are they meeting the crop water demands. The probable reason might be that farmers lack knowledge (Tahal Consulting Engineers, 2000) of identification of a water starved crop or the intention to irrigate before the crop suffer water stress by looking at the soil leads them into irrigating even before there is a need to do so. Farmers who believe that they are producing cabbage under saline conditions say they are doing nothing about it. The reasons being that there is nothing they can do or they have reported to agriculture officials for help as they themselves do not know what to do.

It is important to note that soil sampling for electrical conductivity tests was done at the time of survey. Crops were found to be at different growth stages meaning that the soil had received different amount of water for the season.

3.4.3 Survey limitations

When an experiment is done outside research stations, in a big area where several people are involved, it is always difficult to control some situations that affect the accuracy of the results. Discussed below are such factors that could not be avoided during the collection of data.

Most of the enterprises surveyed are not managed by the owners. Farm managers, who were answering the technical questions in most cases, are changed quite often and each new manager might bring new ideas of management. So the information in this paper is based on the irrigation management practices at the time of survey (that is between April and October 2004).

Estimation of irrigation depth is based on measuring the application rate and then doing some calculations on data from the interview. The time taken irrigating might not be always exact as the manager says it. This might result in either underestimation or overestimation of irrigation depth. Irrigation depth was measured only once at the time of visit to the farms. The day might have not been a representative day for all the time when irrigation is done due to daily variations in wind speed or pressure (especially due to dirtiness of the filter) or the filling of the container used for irrigation.

Farms do not record any meteorological data, so any information involving the meteorological data is based on the data from the nearest meteorological station which in some cases is far from the farms and might be slightly different from the condition on the farm depending on the distance of the farm from the station. This use of data from these stations might either overestimate or underestimate the evapotranspiration and rainfall at the farms.

3.5 CONCLUSIONS

Cabbage farmers in Botswana are operating in a situation where weather varies through the year. Rainfall varies from around 0 mm/month during the dry season to around 100 mm/month during the wet season. Evapotranspiration follows the same pattern for all the regions throughout the year with the lowest values in the dry winter season and the highest in the wet summer season but the amount differs between the regions. Potential evapotranspiration is always higher than precipitation. The climate can be classified into three groups. These groups are the

North West/ Francistown regions, Central region and the Gaborone/ Southern regions.

On average farmers in all the regions use irrigation water that requires attention when scheduling for irrigation as the water is within the moderate restriction band (0.7 – 3.0 dS/m) in use due to salt content. Farmers use water with electrical conductivity that ranges from 0.1 dS/m to 3.2 dS/m.

Salt content of the soil used by the farmers differ between the regions. Central region has the highest average soil electrical conductivity of over 6 dS/m. Irrigation by the farmers is found to be contributing to current levels of salts in the soils. Watertables are too deep to contribute to the salts into the rootzone.

Farmers use a wide range of soil (from clay to sand) for cabbage production. But sandy loam is the most commonly used soil.

Irrigation depth used by the farmers does not differ between the regions. It is established that irrigation depth applied by the farmers does not significantly follow or respond to the factors that determine crop evapotranspiration. Irrigation depth does not vary with the type of soil and does not have any relationship with soil ECe.

Chapter 4

Field Testing of Soil Salinity and WaSim Simulation Model Verification

4.1 INTRODUCTION

The aim of this section is to verify the WaSim simulation model which will be later in the project to simulate soil salinity situations in the farmers' fields. This section is divided into two parts. The first part is the field experiment on irrigation and soil salinity and the second one is on the testing of the model using data from the field experiment.

There are some changes, especially in the environment, which take a very long time to study. In response, several simulation models have been developed to shorten the time taken in understanding what happen over a long time. Several simulation models have been used effectively and extensively in irrigation research for predicting infield irrigation management strategies and their impacts on the environment. When using a simulation model it is very important to choose the right model for the situation at hand. The following factors have to be considered in choosing the model to use: The original purpose of the model, conditions in which the model performs correctly, accuracy that can be expected from a model and the limitations associated with the model (Parsons *et al*., 2004)

In this project, WaSim simulation model was chosen to be used to simulate soil salinity in the farmers' fields in the long run. WaSim simulation model is a computer-based model developed by HR Wallingford and Cranfield University (with support from UK Department for International Development) for teaching and demonstration of issues involved in irrigation, drainage and salinity management (Abbott *et al*., 2001). This model is relatively easy to use, has reasonable level of accuracy, minimal data requirements and provides good visualisation of model calculations. It can also be used to simulate a range of water management situations (Hess and Counsell, 2000).

WaSim simulation model has been tested before by Abbott *et al*. (2001) in a KAR Project 7133 carried out by Water Management Department of HR Wallingford in collaboration with the Drainage Research Institute of the National Water Research Centre, Egypt over two growing seasons. In the experiment, the model was tested against the field data from conventional irrigation, drainage management, and controlled drainage management projects where key parameters were compared on daily and seasonal basis. The parameters tested were predicted crop water use, mid-drain watertable depth throughout the crop season, watertable depth at end of season, seasonal total and throughout the season drainflow, soil salinity at end of season, crop effects and reduction in crop yield. Though the model gave adequate agreement with the field data and was concluded that WaSim model is an acceptable tool, the testing was limited only to two crop seasons. This then raises the need to test the model again before using it.

4.2 FIELD EXPERIMENT

4.2.1 Introduction

The aim of this section was to evaluate the impacts of irrigation depth for cabbage (*Brassica oleracia var. capitata*) on soil salinity. This was to be achieved with the following objectives.

- To compare soil salinity levels through the growing season due to different irrigation depth.

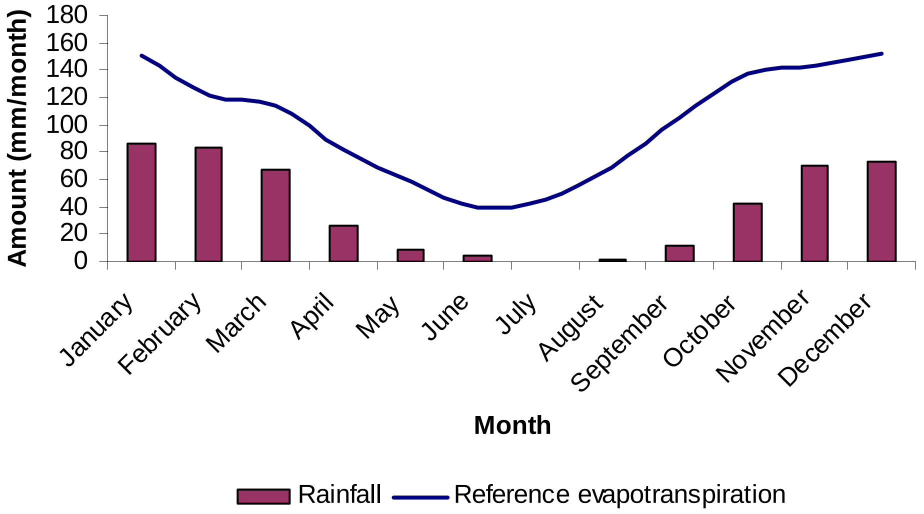
- To compare the weather during the time of the experiment to the long term weather of the area.

Cabbage, moderately sensitive to soil salinity (Doorenbos *et al*, 1986; Allen *et al*, 1998), was grown and exposed to different irrigation depths treatments throughout the whole growing season. Cabbage is used in this section because it is used in the study of soil salinity later in the experiment.

4.2.2 Methodology

4.2.2.1 Experimental site

The experiment was conducted in the horticulture field of the Department of Agricultural Research farm in Sebele Agricultural Research Station Gaborone, Botswana (24° 34’ S, 25° 57’ E, altitude 994 m). The field is made up of loam soil and is located in an area where the average depth to watertable is 10 m. The area has an annual average rainfall of 520 mm and an annual average reference evapotranspiration of 1318 mm (FAO, 1984). The area is characterised by three distinct seasons. The cool and dry season comes between May and August. This season is followed by the hot and dry season from September to October and finally the hot and wet season from November to April. Figure 4.1 shows the monthly average rainfall, average reference evapotranspiration and average temperature throughout the year.



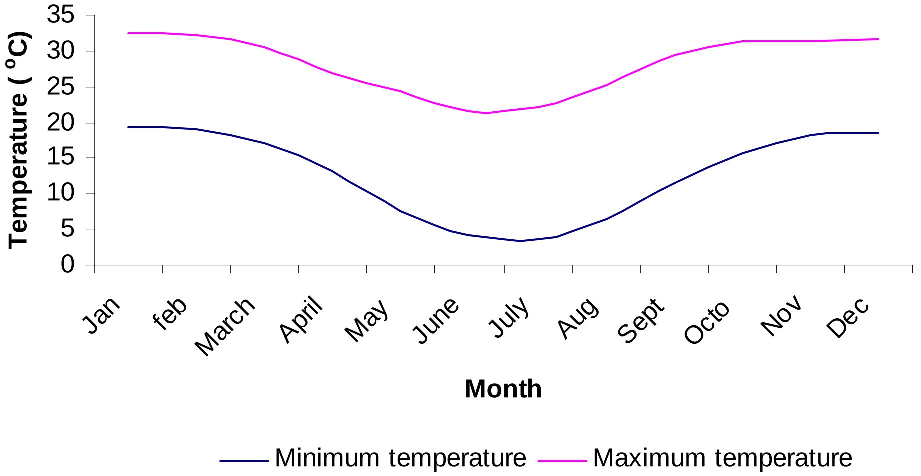


Figure 4.1: Relationship between average rainfall and reference evapotranspiration and average maximum and minimum temperature of each of the season in Sebele.

This farm is used for producing vegetables, both for research and commercial purpose, throughout the year. Because of differences in climatic conditions through the year and pest problems, different crops are produced at different seasons of the year every year. Cool season crops such as the Brassicas are produced during the cool and dry season into the hot and dry season while crops such as the Solanacae group are produced from the hot and dry to the hot and wet season. Regardless of the season all the crops grown in this area are irrigated. Irrigation water comes from a borehole in the farm and has electrical conductivity of 1.2 dS/m (DAR, 2002). The water is first pumped into a reservoir before being pumped out to the field for irrigation. The farm uses either drip and/ or sprinkler irrigation systems.

4.2.2.2 Soil type

For cross checking the type of soil, the hand feel method was used to determine the soil textural class. This method is described in section 3.2.10. The test was carried out before the experiment so that the result could be used for irrigation scheduling.

4.2.2.3 Irrigation water electrical conductivity

Prior to transplanting the seedlings to the field, irrigation water electrical conductivity (EC_w) test was done. The test was carried out using a 4070 model portable conductivity meter as described in section 3.2.8. Five readings were taken on five different days in order to establish the variation of electrical conductivity of the water with time. The EC_w was monitored throughout the growing season by measuring the EC_w ten more times at the time of irrigations.

4.2.2.4 Irrigation Treatments

The experiment was divided in to three treatments represented by **I.1**, **I.2** and **I.3**. The treatments, described below involved water application at different amounts.

I.2 – Water was applied in such a way that at all times, the actual rootzone receives enough water to cover for evapotranspiration and leaching requirement. So the amount of water applied changed with root depth as the roots were growing deep through the season. This treatment is expected to leave the crop under no water or salinity stress. The treatment was chosen to asses how the overall rootzone (0.5 m depth) salinity reacts to the water application.

I.1 – Water was applied to cover 60 % of the water applied in treatment **I.2**. This treatment is expected to allow some water and/ or salinity stress on the crop. The treatment was chosen to asses how the overall rootzone salinity reacts when the crop is stressed.

I.3 – Water applied to meet 140 % of water applied in treatment **I.2**. The treatment was chosen to asses how the overall rootzone salinity reacts to excessive water application

4.2.2.5 Irrigation water application

Establishment irrigation

The whole experimental block received a pre-transplant irrigation a day before transplanting (that is on the 27th of July 2004). Irrigation was applied at 7 mm / day every two days for a week after transplanting. This was to allow for establishment before the different irrigation treatments were applied.

Treatment irrigation

The amount of water applied for each treatment was controlled by varying the amount of water applied at each irrigation but keeping frequency of water application the same for all the treatments. Controlling the amount of time taken irrigating controlled irrigation depth. Irrigation depth, interval and set time were calculated for treatment **I.2**. Then for treatment **I.1** and **I.3**, the amount of water applied was monitored by setting time taken irrigation at 60 % and 140 % respectively of set time for **I.2**. This allowed irrigation depth for **I.1** and **I.3** to be 60 % and 140 % respectively of that for **I.2** at all times irrigation was done. Irrigation depth, interval and set time for **I.2** was calculated as shown below.

$I = p \times d \times S_a \div (1 - LF)$ -- (4.1)

Where:

I - Irrigation depth (mm)

p - Allowable depletion water content of the soil before the plant start reducing water uptake which is 0.35 for cabbage (Smith, 1992)

d - Root depth for cabbage (Table 4. 1)

S_a - Available water capacity for the loam soil (150 mm/m)

LF - Leaching fraction described by the formula below

$LF = EC_w \div (5 (EC_e) - EC_w)$ -- (4.2)

Where: EC_w – Electrical conductivity of irrigation water as measured below (dS/m).

EC_e – average soil salinity tolerated by cabbage (1.8 dS/m (Ayers & Westcot, 1985))

Root depth was estimated basing on the theory that root increases in depth and reaches at the same time as when the shoots reach the maximum growth (Withers & Vipond, 1974). Root depth used for each month is shown on Table 4. 1. The cabbage grown was started from transplants with root depth of 0.15 m.

Table 4. 1: Root depth used for each month through the growing season

Month	Root depth (m)
July	0.15
August	0.35
September	0.50
October	0.50

Using irrigation depth estimated above, irrigation interval was calculated as follows.

$T_i = I \div ET_c$ -- (4.3)

Where:

T_i - Irrigation interval (days)
I - Irrigation depth (mm)
ET_c - Crop evapotranspiration (mm / day) estimated by the equation below.

$ET_c = ET_o \times k_c$ -- (4.4)

Where: ET_o – Monthly average evapotranspiration (mm / day) (FAO, 1984)
k_c - Crop coefficient (0.95 for cabbage (Allen *et al*, 1998))

Equation 4.5 below was used to estimate the time taken irrigating any time irrigation was applied.

$t = I \div q$ -- (4.5)

Where:

t - Set time for irrigation (hours)
I - Irrigation depth (mm)
q - Sprinkler application rate (mm / hour)

Irrigation scheduling for each treatment for each month during the time of experiment is summarised in Table 4. 2.

Table 4. 2: Summary of irrigation schedules for each treatment during each month and total irrigation depth per treatment.

Month	**Interval (days)**	**Irrigation depth (mm)**		
		I. 1	**I. 2**	**I. 3**
July	2	4	7	9
August	2	4	7	9
September	3	11	18	25
October	4	16	26	35

4.2.2.6 Experiment Layout

The experimental block was divided into two. One block (which will be called the pressure release block in this discussion) was there just to keep the pressure in the system balanced when water supply to some treatments was stopped. While the other one (which will be called the treatment block in this discussion) was the one where all the treatments were laid and all the measurements were taken. Micro sprinklers were used in the experiment. For all the treatment plots, the sprinklers were spaced at 0.5 by 1.5 m (as they had a rectangular wetting area of 0.5 by 1.5 m), whereas for the pressure release blocks, the sprinklers spacing were adjusted accordingly so as to satisfy crop water need during the time at which they will be operating.

In the treatment block, the treatments were laid out in a randomised complete block design with each one replicated three times resulting in a block of 3 by 3 plots. The plots were separated by 1.5 m spacing and each one measured 1.5 by 5 m. Pipes were laid such that all pipes supplying water to sprinklers in replicates of the same treatment had a valve connected to them such that when the valve is closed, water supply to all the replicates is cut off. On the side of the pressure release block, the number of sprinklers was twice as much as that of each treatment and divided in to two by a valve.

Before the start of irrigation, all the valves to the treatment plots were opened and all those to the pressure release block closed. The valve to the whole block was then opened so that all the treatment plots received irrigation but not pressure release block. After the time for **I. 1** had received the enough water (see Table 4. 2), the valve to the treatment was closed and one valve on the pressure release block opened so that the first half of the sprinklers on the pressure release block sprinklers was operating. After **I. 2** had finished irrigating, the valve supplying it was also closed and the last valve one on the pressure release block opened. After **I. 3** had finished irrigating, the main valve supplying the whole block was closed so irrigation stops. This resulted in the same number of sprinklers operating at all time throughout irrigation time.

4.2.2.7 Irrigation System Evaluation

Christiansen’s coefficient of uniformity was used to asses the application uniformity of the water application pattern and application efficiency was used to asses the amount of water lost between the sprinkler nozzle and the ground. A pressure gauge was used to check the operating pressure for the sprinklers tested. Nine catch cans were laid out in a grid between four sprinklers. Irrigation was allowed to run until enough water to give a reading was collected in the cans. The time taken to collect the water was noted. Then the amount collected inside each can was recorded. Flow rate from a single sprinkler was measured by letting it run into a bucket for the same amount of time which was allowed for collecting water into the catch cans (Merriam, 1968).

Christiansen's coefficient of uniformity was then calculated using the following formula.

$CU = 100 \times (1 - D \div M)$ -- (4.6)
$D = (1 \div n) \times \sum \left| X_i - M \right|$
$M = (1 \div n) \times \sum X_i$

Where:

CU	- Christiansen's coefficient of uniformity (%)
M	- Mean application depth (mm)
X_i	- Individual application depth as measured from the catch cans (mm)
n	- Number of catch cans

(Zoldoske *et al.*, 1994)

Using the data collected for calculating the application uniformity, the distribution uniformity was calculated as:

$DU = M_{lq} \div M_{all} \times 100$ -- (4.7)

Where:

DU	- Distribution uniformity in percentage (%)
M_{lq}	- Mean of last quarter collection from catch cans
M_{all}	- Mean of all collection from catch cans

(Keller and Bliesner, 1990)

Application efficiency was calculated as follows.

$AE = 100\ (M \times A_s) \div Vs$-- (4.8)

Where:

AE - Application Efficiency (%)

M - Mean application depth (mm)

A_s - Area irrigated by a single sprinkler i.e. sprinkler spacing × lateral spacing (m^2)

Vs - Volume exiting sprinkler when measuring flow rate (l).

(Merriam, 1968)

4.2.2.8 Crop Husbandry

Seedling stage

Cabbage seedlings were sown in seedling trays at three seeds per pot to a depth of 1 cm on the 28th May 2004. The trays were then put in a net shade where the seedlings were raised. Light watering was done every morning before emergence then every other day after two weeks to keep the soil moisture at field capacity. Thinning was done after the seedlings have produced one true leaf leaving one seedling per pot. Seedlings were transplanted to the field after eight weeks when they were about 15 cm high.

Field stage

The land was first ploughed using a disc plough two days before transplanting. Then basal dress of 62 kg nitrogen, 94 kg phosphorus and 62 kg potassium in the form of NPK (2:3:2) was broadcasted before harrowing was done to create a fine tilth and level up the farrows left by the plough. Cabbage seedlings were then transplanted to the field on the 28th of July. Seedlings were spaced at 0.5 m between and within rows (giving population of 40 000 plants per hectare). Two top dressings with nitrogen (urea) were later banded at 65 kg each at three and six weeks after transplanting. The trial was kept free from weeds by hand weeding. Cypermethrin was used for the control of bagrada bug and diamond back moth.

4.2.2.9 Soil salinity

Soil samples were taken for baseline salinity test on the rootzone saturation extract electrical conductivity (EC_e) test before transplanting. Three sets of samples were taken from each experimental unit (plot). Each set contained five samples collected down the soil as described in section 3.2.9.1. Samples were taken to the laboratory for salinity test as described section 3.2.9.2. Soil sampling was repeated two more times, at 49 and 75 days after transplanting.

4.2.2.10 Climate data

Meteorological data for the period of study (April 2004 – October 2004) was obtained from the meteorological section of the Department of Agriculture Research. The data was recorded on daily basis from a weather station ($24^o33'$ S., $25^o57'$ E., 994 m elevation) located within 100 m from the experimental site. The data includes rainfall amount, relative humidity, sunshine hours, minimum temperature, maximum temperature and wind speed. Apart from rainfall the other data was used to calculating the reference evapotranspiration (ET_o) using the FAO Penman-Monteith equation (equation 4.9).

Maximum temperature (T_{max}, ^oC) and minimum temperatures (T_{min}, ^oC) were recorded from thermometers sheltered in a Stevenson screen. Wind speed (recorded at the height of 2 m above the ground) and sunshine hours were also collected. Only information on relative humidity recorded at 08:00 and 14:00 hours was available so relative humidity recorded at 08:00 was used as the average relative humidity. See appendix C.1.

Reference evapotranspiration (ET_o)

Several methods of calculating ET_o have been described but FAO Penman Monteith is the most recommended method. This is because the method provides values more consistent with actual crop water use data worldwide. The method is accepted internationally and is recommended by FAO, World Meteorological Organisation (WMO) and the International Commission on Drainage (ICID). When using the FAO Penman-Monteith, the reference surface is defined as a crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered (Allen *et al.*, 1998). Reference evapotranspiration is referred to as a climate factor as the only factors affecting it are climatic parameters (Allen *et al.*, 1998). Parameters needed for determining ET_o include air temperature, solar radiation, wind speed and air humidity. ET_o was estimated using the FAO Penman-Monteith method described by the equation below.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \text{ -- } (4.9)$$

Where:

ET_o - reference evapotranspiration [mm day^{-1}],
R_n - net radiation at the crop surface [MJ m^{-2} day^{-1}],
G - soil heat flux density [MJ m^{-2} day^{-1}],
T - mean daily air temperature at 2 m height [°C],
u_2 - wind speed at 2 m height [m s^{-1}],
e_s - saturation vapour pressure [kPa],
e_a - actual vapour pressure [kPa],
$e_s - e_a$ - vapour pressure deficit [kPa],

D - slope vapour pressure curve [kPa °C^{-1}],

g - psychrometric constant [kPa °C^{-1}].

(Allen *et al.*, 1998)

The monthly mean T_{max} , T_{min} , rainfall, sunshine hours and wind speed collected were compared with the long term averages from Gaborone meteorological station (24°40’ S., 25°55’ E., 980 m elevation) which is about 20 km from the experimental station. Reference evapotranspiration calculated was also compared with the long-term figures.

4.2.3 Presentation of results

4.2.3.1 Climate

Monthly averages of the climate data during the time of the research are shown on Table 4. 3 below. It is important to note that the rain that fell in April was before the experiment and rain in October came on the 19th and 20th which was after the soil sampling for EC_e was done.

Table 4. 3: Weather data for Sebele during the period April 2004 – October 2004. Vapour pressure deficit was calculated with the 08:00 relative humidity as the mean relative humidity. Calculation method for vapour pressure deficit is shown in appendix B.2.

Month	Monthly Rainfall (mm)	Monthly ET_o (mm)	T_{min} (^oC)	T_{max} (^oC)	Sunshine hours	Wind speed (km/day)	Relative humidity (08:00)	Vapour pressure deficit (kPa)
April	38.6	84	12.3	27.1	7.7	85	88	0.48
May	0	68	5.9	26.2	8.4	76	88	0.43
June	0	50	2.1	22.3	7.4	100	81	0.57
July	0	60	0.8	22.4	8.8	100	78	0.66
August	0	89	5.2	27.2	8.3	108	65	1.29
September	0	134	8.2	28.4	9.5	174	55	1.79
October	21.5	180	14.7	32.3	9.7	191	52	2.36

Although the April 2004 – October 2004 factors affecting reference evapotranspiration except minimum temperature were established as not being significantly different (Table 4.4) from the long term averages, it was realised that averages for April 2004 – October 2004 were higher that the long term averages. Evapotranspiration for the period April 2004 – October 2004 was significantly higher than the long term average by 0.5 mm/day (Figure 4. 2).

Table 4. 4: Differences in climate parameters between the April 2004 – October 2004 and long term average for the same months

Parameter	Difference (2004 data minus FAO data)	Significance
Rainfall (mm)	6.8	NS
T_{min} (^oC)	-2.7	*
T_{max} (^oC)	2.6	NS
Wind speed (km/day)	4.5	NS

Sunshine hours

NS – Not significant difference
* - Significant difference

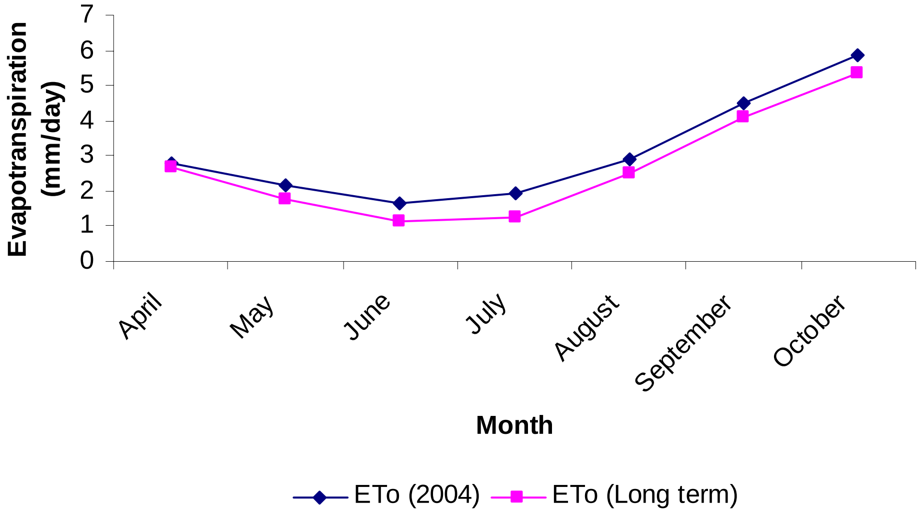


Figure 4. 2: Comparison between reference evapotranspiration for 2004 and the long term averages.

4.2.3.2 Irrigation system evaluation

The water application for the whole experimental block had good application uniformity with Christiansen's coefficient of uniformity of 84 % and distribution uniformity of 79 %. Application efficiency of 81 % was recorded with the minimum of 76 % and the maximum of 85 %.

Irrigation water salinity

Average salt content of the irrigation water measured before the experiment was found to be the same as that measured after transplanting and was 1.25 dS/m. The variation in the irrigation water EC value measured was small with a maximum and minimum of 1.20 dS/m and 1.35 dS/m respectively.

4.2.3.3 Soil salinity

Soil EC_e with depth

Figure 4.3 shows soil salinity (EC_e) at different depths down the roozone for the three treatments I.1, I.2 and I.3. Each graph in the figure represents the three different times at which sampling was done. Each of the points in the graphs is an an average of electrical conductivity of nine samples. At the beginning of the experiment, soil salinity for the plot area in all the demarcated plots had a similar pattern down the soil profile (0.5 m depth). Soil salinity was found to be significantly higher at the surface. Starting from 0.12 m down to 0.5 m below the soil surface, soil EC_e was the same at around 1.9 dS/m (Figure 4. 3, Initial).

At 49 days after transplanting (Figure 4. 3, At 49 days), the surface soil for treatments **I.1** and **I.2** are showing significantly higher salt content than for **I.3**. For all the treatments though, surface soil is still showing higher salt levels than the bottom soil. It is important to note that the graphs take different shapes. Treatment **I.1** is showing highest salinity at the top, low in the middle but higher at the bottom. In general it can be seen that the soil salinity of the whole profile has increased. From 0.12 m to 0.5 m below the surface, there are no significant differences in soil salinity between the different treatments.

At 75 days after transplanting, significantly higher salinity is evident on the surface soil salinity on treatment I.2 (Figure 4. 3, At 75 days). It is important to note that at this date also, soil salinity for the three treatments follows the same pattern down the soil depth with the lowest salinity at around 0.12 m below the surface.

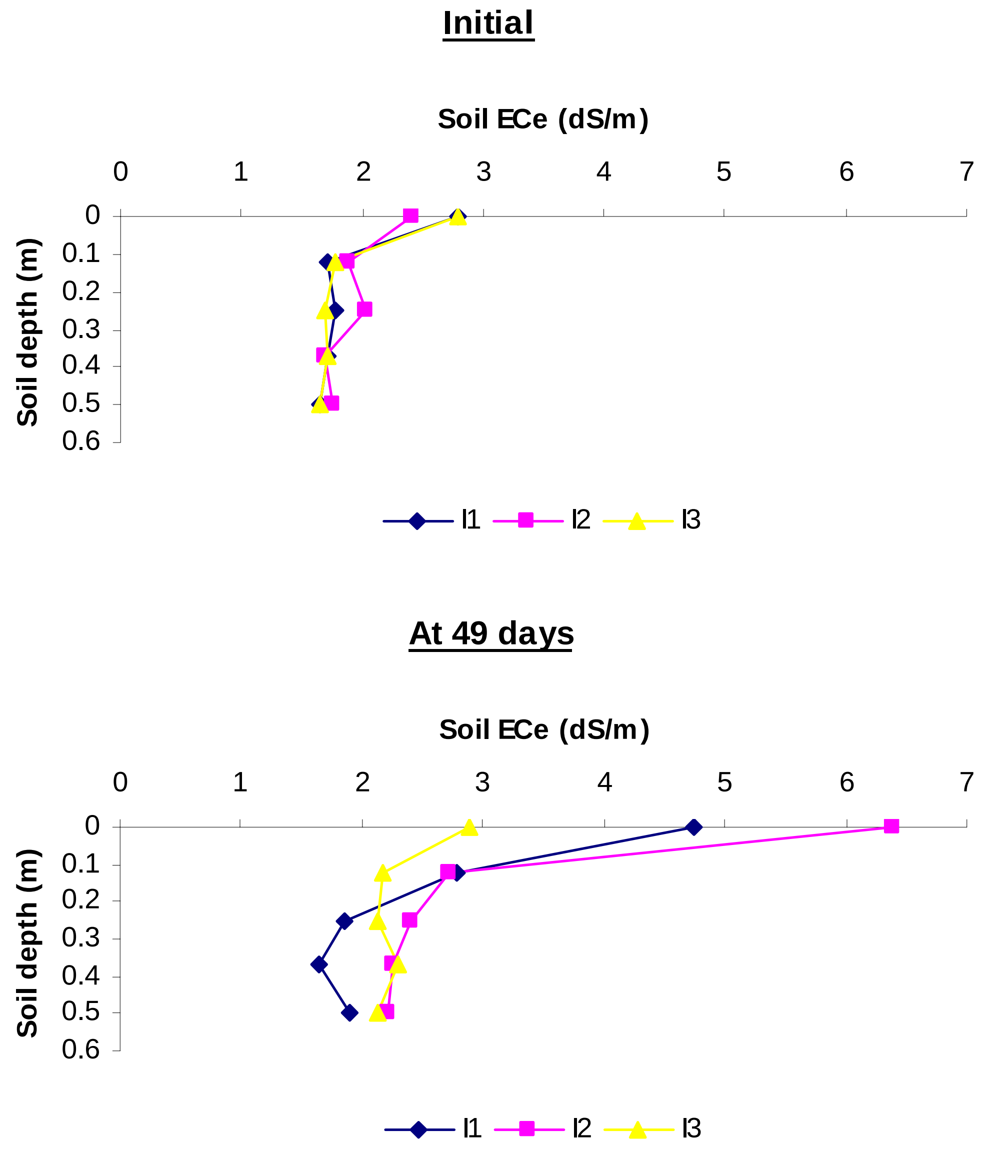
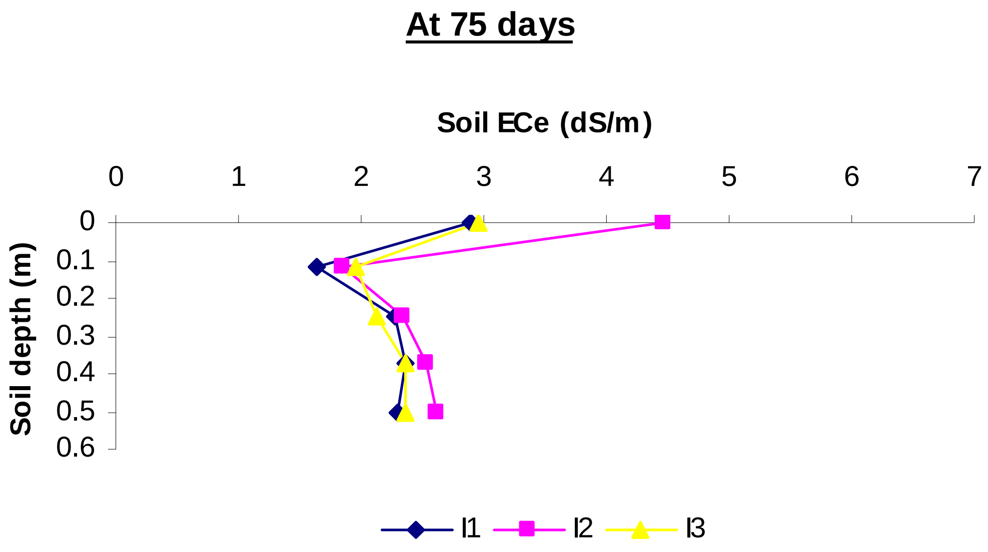


Figure 4. 3: Soil salinity changes down the soil profile for the three treatments before transplanting (initial), 49 days after transplanting and 75 days after transplanting.



At 75 days

Figure 4. 3 continued: Soil salinity changes down the soil profile for the three treatments before transplanting (initial), 49 days after transplanting and 75 days after transplanting.

Rootzone electrical conductivity (ECe)

Rootzone in this case is used to refer to the depth of 0.5 m. Results from soil electrical conductivity tests for the different treatments at different times after transplanting are shown on Figure 4. 4. There is a lot of variability in soil salinity for all treatment as shown by the error 95 % confidence interval error bars. The results show that at the beginning of the experiment, there is no significant difference in soil salinity between the treatment plots which is represented in the graph by samples taken two days before transplanting. Averages for all the treatments show an increase in rootzone salinity from the beginning of the experiment to 79 days after transplanting.

At averages of 2.45 dS/m and 2.71 dS/m general rootzone salinity for 49 and 75 days after transplanting respectively are not significantly different from each other, but both significantly higher than at the beginning of the experiment (1.88 dS/m). Accumulated salts in **I.2** are significantly higher than in **I.3**.

Treatment **I.1** shows that at 49 days after transplanting, rootzone salinity was not significantly different from the initial one but at 75 days after transplanting the rootzone salinity was significantly higher. For treatment **I.2**, rootzone salinity increased significantly from the initial time to 49 days after transplanting where it reached an average of 2.75 dS/m. But between 49 days and 75 days after transplanting rootzone salinity showed no significant increase. Rootzone salinity for treatment **I.3** shows no significant change from the beginning of the experiment until 75 days after transplanting.

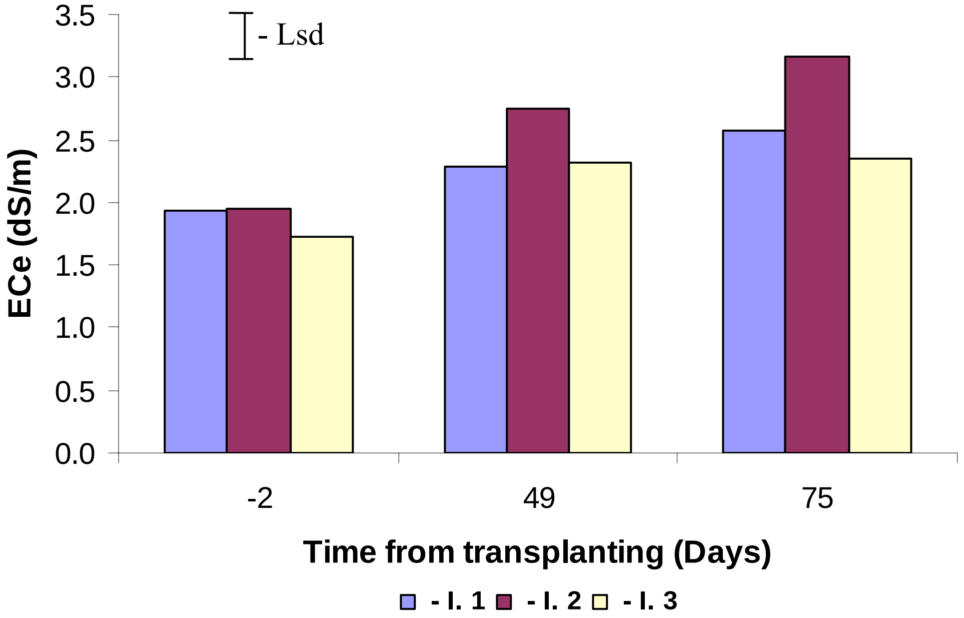


Figure 4. 4: Root zone salinity change over growing period due to different water application amounts

4.2.4 Discussions of results

4.2.4.1 Climate

Evapotranspiration at the time of the experiment show higher values than the long term values. Although the parameters affecting evapotranspiration show no significant difference between the two times, maximum temperature and wind speed, show higher averages at the time of the experiment. Collectively they might have contributed to the significantly different reference evapotranspiration.

4.2.4.2 Soil salinity

Soil ECe down the soil

Movement of salts in the soil is controlled largely by the soil water movement (Smedema *et al*, 2004). So the distribution of salts in the soil can be used to predict the movement of water in the soil over time.

Before the experiment, the soil salinity was not significantly different between the treatment plots and is showing the same trend because the whole plot has been under the same treatment before the measurements were taken. Higher salinity at the surface might be due salts dissolved in soil water moving up with the water as hydraulic potential is created by evaporation at the soil surface. The salts are then left behind when the water evaporates.

At 49 days after transplanting, the shape of the graph for treatment **I.1** might be due to the fact that the water provided was not reaching the 0.5 m depth. This might mean that water applied is reaching a depth of around 0.37 m depth and because of the hydraulic potential as it is dry at the lower layers, some water is moved down below with some of the salts while the rest is moving up the soil by capillary action due to evaporation at the soil surface. For the other two treatments, the shape of the graph shows that the water applied was going beyond the 0.5 m below the surface. This time salinity at the surface is higher than at the beginning of the experiment and at 75 days after transplanting as more salts have been added to the soil than at the start of the experiment but there is still less ground cover than at 75 days after transplanting. At this point, more water was lost to the atmosphere through evaporation than transpiration as compared to the situation at 75 days after transplanting due to less crop cover. This resulted in salts moving up the soil profile with water. The status of the salts at any of these three times when salinity was measured time was responding to expected movement of water considering the amount and the way water was applied to each treatment.

General Rootzone ECe

Rootzone salinity is showing the expected response when considering the way the scheduling was done. In all the treatments, rootzone ECe started going up because salts were still accumulating within the rootzone (0.5 m depth). This was because irrigation scheduling was done monthly basing on the expected root depth on the month. At 49 days from transplanting, which was already the time when water was applied basing on the whole 0.5 m root depth, treatment **I.2** and **I.3** showed no further significant increase in ECe because by then the some of the salts which were accumulating in the rootzone were being washed down. For treatment **I.1**, the rate of accumulation of salts was still increasing because there was no leaching taking place. Treatment **I.2** ECe was higher than that of other treatments at 49 days and 75 days after transplanting as more salts were being added to the soil with irrigation water than in **I.1** but less were being washed out of the rootzone as compared to the situation in **I.3**.

4.2.5 Conclusions

When irrigation is applied to cater for leaching salts out of the actual rootzone, soil salinity increases at the beginning and then stops increasing later. Under-irrigation (by 40 %) results in soil salinity increasing continuously from the start of the experiment to 75 days after transplanting. The increase is slow at the beginning and faster towards the end. Over irrigation (by 40 %), results in slight increase in soil salinity at the beginning and then slight decrease.

4.3 TESTING THE WaSim SIMULATION MODEL USING FIELD EXPERIMENT DATA

4.3.1 Aim

The aim of this section is to validate the WaSim simulation model. The one dimensional daily water balance model deals with the soil water and salts balance between the upper boundary (soil surface) and the bottom boundary (impermeable layer). Within the boundaries, there are five layers within which there are water inputs and outputs determining the water and salt status of the layer. Water added to the boundaries is from net rainfall and net irrigation (i.e. amount left after removing interception losses and surface runoff from gross rainfall/ irrigation). Water is lost from the boundaries through drain flow, capillary rise, plant transpiration, soil evaporation and open water evaporation (Abbott *et al*, 2001; Hess *et al*, 2000).

WaSim allows the user to enter information on irrigation management, the crop being grown and climate data in the form of rainfall and evapotranspiration. The model provides, as an output, the status of water and salt quantities in each of the layers. Also as an output, the model provides total yield loss as well as separate yield losses due to water and salinity stress. WaSim simulation model uses the water balance and salt balance models to carry out the commands. Details on the equations used by the model are described by Hess *et al.* (2000). See appendix B. 3.

4.3.2 Methodology

Rootzone electrical conductivity and yield for the cabbage grown (Field experiment section) were simulated using the WaSim simulation model. So the input data for the model was representative of the field experiment. Results obtained using the model were then compared with those obtained from the field experiment.

4.3.2.1 Setting up the model

There was no drainage system installed during the field experiment and it was assumed that the watertable of the area is at 10 m below the surface. Therefore drainage was not implemented.

Soil

The default soil water characteristics values of loam soil in the WaSim model were used and are as shown on Table 4. 5.

Table 4. 5: WaSim soil input data. All moisture contents are volumetric.

Soil Parameter	Value
Soil moisture content at saturation (%)	46.3
Soil moisture content at field capacity (%)	27.9
Soil moisture content at permanent wilting point (%)	11.7
Soil moisture content of saturated paste (%)	46.3
Drainage coefficient, Tau	0.23
Hydraulic conductivity (m/d)	1.0
Curve number	81
Leaching efficiency	90

Climate data

WaSim requires rainfall and reference evapotranspiration data (Hess and Counsell, 2000). So the climate data collected during the experimental field trial was used to calculate the reference evapotranspiration. Reference evapotranspiration was calculated using FAO Penman-Monteith equation (section 4.2.2.10) provided by the WaSim ET (part of the WaSim simulation model).

Crop data

Crop factors used are shown in Table 4. 6 below.

Table 4. 6: Summary of crop data used on running the model

Crop Parameter	**Value used**	**Comments**
Crop Cover Development		
Planting date	28 July	From field observation
Emergence date	28 July	
20% cover	28 July	
Full cover	01 October	
Maturity		
Harvest	26 October	
Maximum root date	01 October	
Cover		
Mulch cover (%)	0	From field observation
Crop coefficient at full cover (%)	95	Mid value of the range. (Doorenbos *et al.*, 1986)
Roots		
Planting depth (m)	0.1	Transplanting depth (Field observation)
Maximum root depth (m)	0.5	Effective root depth. (Doorenbos *et al.*, 1986)
Transpiration factors		
p-factor	0.35	Doorenbos *et al.* (1986)
Yield response	0.95	For total growing period (Doorenbos *et al.*, 1986)
Salinity threshold (dS/m)	1.0 to 1.8	(Allen *et al.*, 1998)
Slope (%/dS/m)	12	(Allen *et al.*, 1998)

Irrigation

Irrigation data (interval and amounts) used is from field observation as shown in Table 4. 2 (Section 4.2.2.5).

Model run settings

Initial settings before running the model is summarised in Table 4. 7.

Table 4. 7: Summary of the run settings

Parameter	Setting	Comments
Initial water content	Field capacity	
Initial salinity (ECe)of soil rootzone (dS/m)	1.9	Baseline salinity from the field
Water table depth below the surface (m)	10	From department of Water Affairs
Run duration	26/07/2004-11/10/2004	

After running the model, comparisons were made on rootzone salinity with the field data at day 49 and 75 after transplanting. The values from the model simulation at the dates were compared to the 95% confidence range as suggested by Snedecor and Cochran (1989) for rootzone salinity as measured from the field.

4.3.3 Presentation of the results

Rootzone salinity

From Figure 4.5, each point of field measured EC_e is an average of nine values of electrical conductivity measured from the field. The value shown by WaSim simulation at two days before transplanting was set as an input data that correspond to baseline salinity value. There was no installed drainage system therefore drain flow in this case refers to the amount of water going beyond the rootzone (0.5 m depth). For treatment **I. 1** (Figure 4.5 a) root zone salinity increases continuously with time while the drain flow below the rootzone (0.5 m) remains constant at zero. For treatment **I. 2** (Figure 4.5 b), the root zone salinity increases while drain flow remains at zero. As the water start draining below the root zone, root zone salinity becomes generally constant. The same trend as in **I.2** is seen with treatment **I. 3.** But in **I.3** the rate of drain flow increase is higher than with **I. 2** and the root zone salinity decreases as the drain flow increases.

The means with error bars in the graphs represent results from the field. It can be seen that in all the treatments, at all the two times, the rootzone salinity from the model simulations is not significantly different from that one found from the field. This is evident by the simulated rootzone salinity falling within the 95 % confidence range of the means from the field experiment.

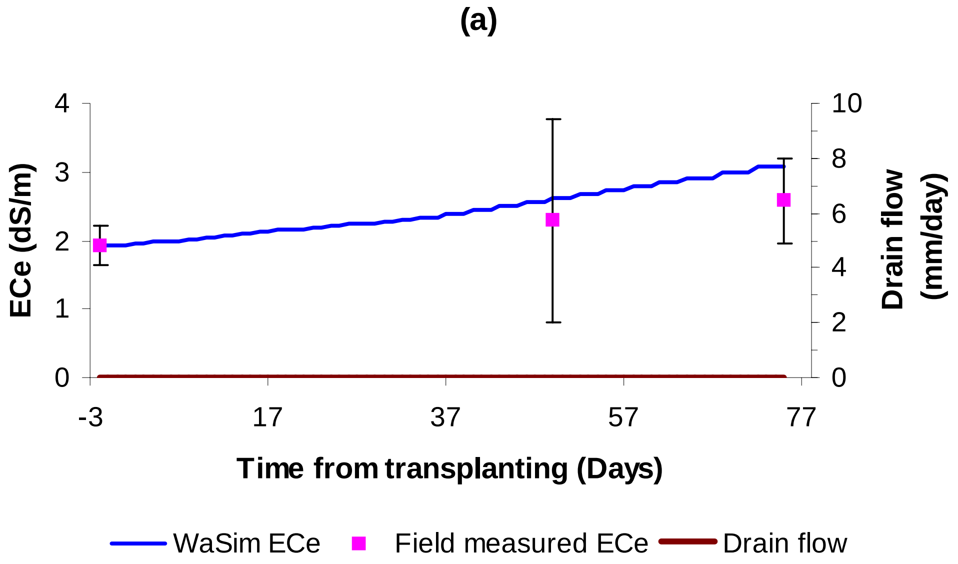
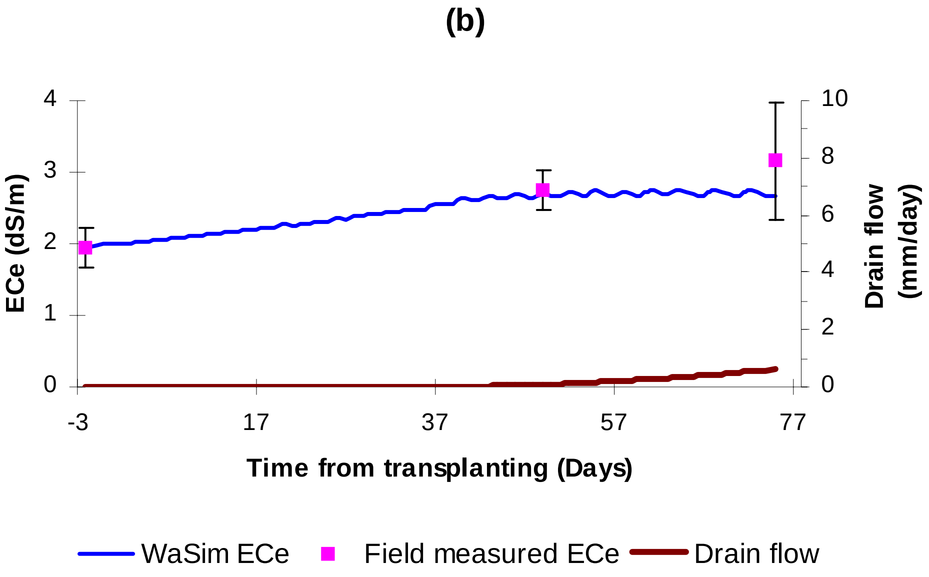


Figure 4. 5: Simulated root zone salinity trend and drain water flow for treatments a) I. 1, b) I. 2 and c) I. 3 compared against the measured values. Error bars represent the 95% confidence interval for the mean



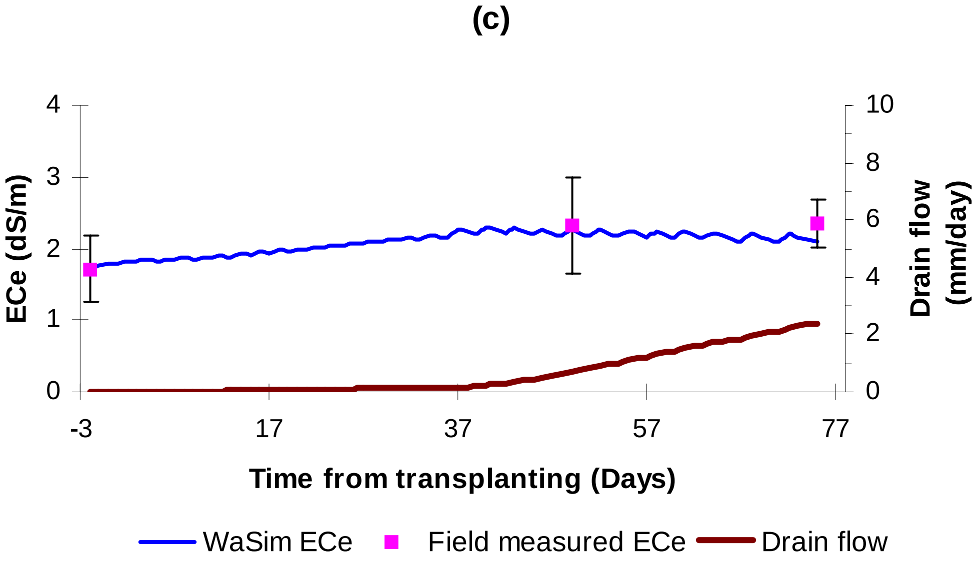


Figure 4. 5 continued: Simulated root zone salinity trend and drain water flow for treatments a) I. 1, b) I. 2 and c) I. 3 compared against the measured values. Error bars represent the 95% confidence interval for the mean

4.3.4 Discussion of results

When there is no drainflow, the soil salinity increases continuously. This is because all the salts accumulate within the rootzone. Effect of drainflow likely reducing the amount of salts accumulating in the rootzone is shown by the situations in I.2 and I.3 where the increase in the amount of salts in the soil stops increasing when the drainflow begins. Root zone salinity values obtained from simulation using the model fall within the 95% confidence interval of the means for all the treatments. The ability of the model to predict the field results correctly agrees with what was found by Abbort (2001).

4.3.5 Overall conclusions

From the study it can be concluded that WaSim model predicts salt level in the soil accurately. Though the comparison is for one growing season only, based on the fact that the model has been tested before and predicting the results accurately, it can be concluded that the model can be used in the experiment.

Chapter 5

Rootzone Salinity Response to Infield Irrigation Management by Cabbage Farmers in Botswana

5.1 INTRODUCTION

It was identified in chapter 1 that salinisation depends on the climate, soil and irrigation management. Lower rainfall as compared to evapotranspiration favours salinisation while heavier soils favour salinisation more than lighter soils. Salt accumulation in the rootzone increases with increasing irrigation water salinity and time.

In an experiment over seven years, Tedeschi and Dell'Aquila (2004) showed that water application below 100% evapotranspiration, will increase ECe of a soil profile linearly over time (7 years) if the water EC is between 1 dS/m and 15 dS/m. They also found that rate of increase in soil ECe was increasing with irrigation depth and irrigation water EC, and the highest being at irrigation depth equals evapotranspiration. This is so because when irrigation is applied below evapotranspiration, fewer salts are added by irrigation water whereas above evapotranspiration, extra water leaches some of the salts out of the rootzone. Increased salinity of soil due to irrigation water in the dry season may be washed out of the soil if there is enough rainfall during the rainy season (Sharma and Rao, 1998).

From chapter 3 it was identified that in Botswana about half of the farmers irrigate at or below average reference evapotranspiration using irrigation water salinity that goes up to 3.2 dS/m. It was established that cabbage farmers in Botswana operate under different climates. The climate can be classified into three groups due to differences in evapotranspiration. These groups are the North West/ Francistown regions, Central region and the Gaborone/ Southern regions. In all the regions, reference evapotranspiration is always higher than precipitation. Farmers use a wide range of soil (from clay to sand) for cabbage production and they produce the crop twice a year. It was also realised that the farmers irrigation scheduling does not vary with the factors that influence plant water use and salt accumulation in the rootzone. These factors are climate soil type and irrigation water salinity. No farmer has drainage system installed in the field.

This chapter therefore aims at identifying the impacts brought about by the current infield irrigation management practices by Botswana cabbage farmers on soil salinity over time. This is achieved through the following objectives:

- To identify different infield irrigation management practices used by Botswana cabbage farmers that might influence the accumulation of salts in the rootzone.
- To identify and compare the meteorological data to be used in the rootzone salinity simulations with the long time averages.
- To use the identified irrigation management practices and meteorological data to simulate the effect they have on the soil salinity levels over twenty years using WaSim simulation model (Chapter 4).

5.2 METHODOLOGY

5.2.1 Identifying infield irrigation management practices

As common infield irrigation management practices could not be identified, two farms were identified and used as case studies (Figure 5.1) basing on the findings discussed above (section 5.1). The two were chosen because the scheduling applied in the cases are the most likely to cause maximum accumulation of salts at their level of irrigation water EC.

It was also important to assess whether the rainfall available could control salinisation. Case A provides the maximum possible salt build-up on the lower side of irrigation water EC whereas Case B does the same on the higher side of irrigation water EC. The two cases provide the maximum possible salinity build-up at their level of salinity because the water application provided is at the same rate as evapotranspiration and all the salts added to the to the rootzone by irrigation water accumulate in there. Below this level of water application, salts added to the soil with irrigation water is lower whereas above this level, excess water drains below the rootzone carrying some of the salts out of the rootzone with it. Characteristics of the individual cases chosen are summarised in table 5.1.

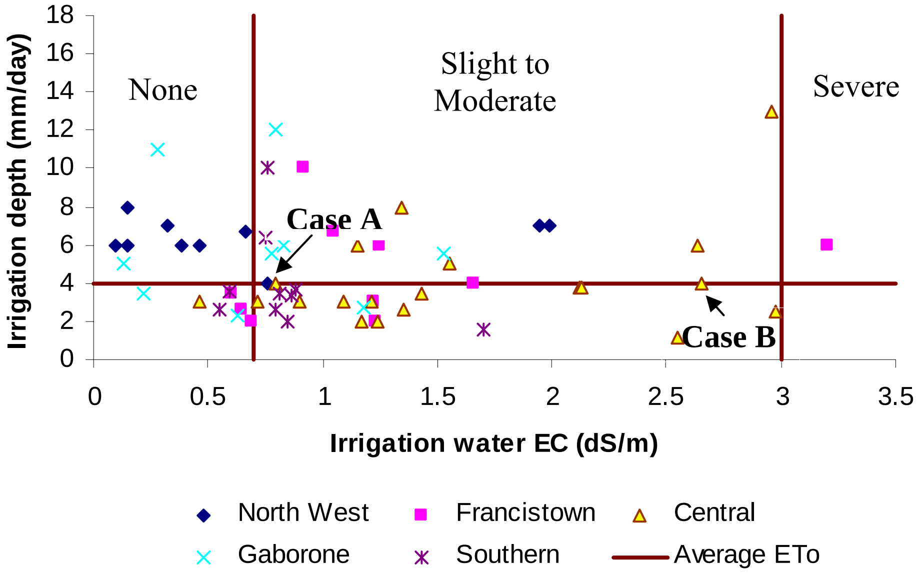


Figure 5. 1: Irrigation depth applied for different irrigation water salinity in different regions. None, slight to moderate and severe in the graph refer to the ranges in which irrigation water is classified according to restriction of use due to salinity (Ayers and Westcot, 1985)

Table 5. 1: Characteristics of the two farms chosen for study as Case A and B.

Character	Case A	Case B
Irrigation water EC (dS/m)	2.65	0.76
Irrigation depth (mm)	4	8
Irrigation interval (days)	1	2
Soil type	Sandy loam	Silt loam
Region	Central	North West

5.2.2 Simulations

Simulations were made for twenty years using the climate data from January 1980 to December 1998 using the WaSim simulation model. First, simulations were run for the case study farms. This was meant to find what happens to soil salinity in the existing current situation.

According to conclusions drawn from the survey in chapter 3, infield irrigation management used by any of the farmers can be applied in any of the regions on any of the soils available for the farmers in the country. Therefore irrigation schedule and soil salinity for each of the two cases were then used to do simulations using the different regions (climate) for the lightest textured soil (sand) and the heaviest textured soil (clay). All the three regions were used because any of the case could be in any of the regions as irrigation depth and water EC do not differ between the regions. Irrigation depth and water EC also do not differ between different soils but the two soils were chosen as clay will favour salt accumulation most whereas sand will favour it least among all the soil types used by the farmers.

5.2.3 Setting up the Model

Setting up the model was, unless otherwise stated, based on the characteristics of the case studies as outlined in section 5.2.1. These are described below.

5.2.3.1 Soil

Characteristics of soil of the same textural class would vary slightly depending on the area and time. In the experiment each of the soils involved are used in different area and/ or different time therefore only general characteristics of the textural classes were used to run the model. The default soil water characteristics provided in the WaSim simulation model were adopted for the soil types used. The characteristics for the individual soils are provided in table 5.2.

Table 5. 2: Soil water characteristics of the soil types used in the experiment

Soil Parameter	Clay	Sandy loam	Silt loam	Sand
Soil moisture content (by volume) at saturation (%)	47.5	45.3	50.1	43.7
Soil moisture content (by volume) at field capacity (%)	36.8	24.5	32.4	11.5
Soil moisture content (by volume) at permanent wilting point (%)	27.2	9.5	13.3	3.3
Soil moisture content (by volume) of saturated paste (%)	47.5	45.3	50.1	43.7
Drainage coefficient, Tau	0.06	0.37	0.17	0.69
Hydraulic conductivity (m/d)	0.1	2.0	0.5	15
Curve number	89	67	81	67
Leaching efficiency (%)	90	90	90	90

5.2.3.2 Drainage

In this section, the aim was to fond the impacts on soil salinity by the current infield irrigation management and there was no farm with drainage system installed. Therefore, the drainage system option in the model was not activated.

5.2.3.3 Climate data

Climate data for the five meteorological stations was collected from the Meteorological Services Headquarters. The five stations include Maun (19^o 59’ S, 23^o 25’ E, altitude 994 m), Francistown (21^o 13’ S, 27^o 30’ E, altitude 1000 m), Mahalapye (23^o 05’ S, 28^o 48’ E, altitude 1006 m), Gaborone (24^o 40’ S, 25^o 55’ E, altitude 994 m) and Jwaneng (24^{o} 60' S, 24^{o} 66' E, altitude 1189 m). Climate data for Francistown was used for the Francistown/ North West regions, Mahalapye climate for the Central region and SSKA, Gaborone for the Gaborone/ Southern regions. Data from Jwaneng and Maun data were used for filling up missing data from other stations (see section on evapotranspiration below).

WaSim requires rainfall and reference evapotranspiration on daily basis. The information collected was daily data for the period from 1980 to 1999. The data includes information on rainfall amount, relative humidity, sunshine hours, minimum temperature, maximum temperature and wind speed. Apart from rainfall the other data was needed for calculating the reference evapotranspiration (ET_o) using the FAO Penman-Monteith equation (section 4.2.2.2) and the Hargreaves equation (equation 5.1). Monthly averages for the data collected were then compared with the long term data for the same areas as available in FAO (1984).

Reference evapotranspiration

There are many days with missing data especially sunshine duration (over 2000 days, in each of the station) so that FAO Penman-Monteith equation could not be used to calculate the reference ET_o. Hargreaves equation (equation 5.3) was then used to calculate reference evapotranspiration.

Hargreaves equation is one of the methods used for calculating the reference evapotranspiration when some climate data is not enough for the Penman Monteith equation. The equation is based on minimum and maximum temperature. Days with missing minimum and maximum temperatures were filled with data from other meteorological stations after testing the data for homogeneity. Missing data for Gaborone station was filled with data from Jwaneng and Mahalapye where Jwaneng data was also missing, Mahalapye filled with data from Gaborone and Francistown where Gaborone data was missing. Missing Francistown data was filled by Maun and Mahalapye data was used where Maun data was also missing.

$ET_{oH} = 0.0023\ (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}R_a$ -------------------------------------- (5.3)

Where:

ET_{oH} - Hargreaves reference evapotranspiration
T_{max} - Maximum temperature
T_{min} - Minimum temperature
T_{mean} - Mean temperature
$R_a = G_{sc}\, d_r \div \pi\ [\omega \sin(L)\sin(\delta) + \cos(L)\cos(\delta)\sin(\omega)]$

Where:

δ - 0.409 Sin ($2\ \pi J \div 365 - 1.39$)
ω - arcos [-Tan (L) Tan (δ)]
d_r - $1 + 0.033(2\ \pi J \div 365)$
L - Latitude (rad)
J - Julian day
G_{sc} - Solar constant (118.08 MJ m^{-2} d^{-1})

(Allen *et al*, 1998)

The use of an alternative ETo calculation procedure, requiring only limited parameters, should generally be avoided. Hargreaves ETo equation tends to overpredict and underpredict under conditions of high relative humidity and under high wind conditions (> 3m/s) respectively (Allen *et-al*, 1998). The ET_{oH} values found were adjusted towards the FAO Penman-Monteith evapotranspiration values for each station. This was done by comparing the FAO Penman-Monteith and the Hargreaves reference evapotranspiration, based on the days with complete data, in order to get a formula linking the two. An appropriate adjustment for each region was then made using the formula linking the FAO Penman-Monteith and the Hargreaves reference evapotranspiration for the region.

5.2.3.4 Crop data

Two growing seasons in a year were assumed based on the fact that farmers produce crops on their land twice a year. Those farmers who produce one crop of cabbage in a year produce many different vegetables during the other season. The first crop is planted so that it grows through the winter months while the second one grows through summer. So basing on the general observation for the time of planting for both winter and summer production and the average growth period, it was assumed that all the crops for winter season are planted in the 01st of May whereas those for summer production are grown on the 01st of November.

Cabbage varieties grown in Botswana take on average 60 to 140 days to reach maturity from transplanting (Bok *et al*, 2003), so an average length of 95 days from transplanting was used for running the model. The length of the development stages was taken as of cruciferous crops with the same growth time as cited by Allen *et al* (1998). It was assumed that harvesting comes a week after crop maturity considering the fact that farmers do not harvest the all crop at once. Crop data used to run the model is shown in table 5.3 below.

Table 5. 3: WaSim crop data input used for the treatments

Crop Parameter	**Value used**		**Comments**
	Winter	**Summer**	
Crop Cover Development			
Planting date	01 May	01 November	Planting date, Emergence date and 20% cover were taken as one date as the seedlings are not raised in the field but transplanted to the field
Emergence date	01 May	01 November	
20% cover	01 May	01 November	
Full cover	29 June	30 December	
Maturity	2 September	5 March	
Harvest	9 September	12 March	
Maximum root date	29 June	30 December	
Cover			
Mulch cover (%)	0		From field observation
Crop coefficient at full cover (%)	95		Mid value of the range. (Doorenbos *et al*, 1986)
Roots			
Planting depth (m)	0.1		Transplanting depth (Field observation)
Maximum root depth (m)	0.5		Effective root depth. (Doorenbos *et al*, 1986)
Transpiration factors			
p-factor	0.35		Doorenbos *et al*, 1986
Yield response	0.95		For total growing period (Doorenbos *et al*, 1986)
Salinity threshold (dS/m)	1.0 - 1.8		(Ayers and Westcot, 1998: Allen *et al*, 1998)
Slope (%/dS/m)	12		(Allen *et al*, 1998)

NOTE

Salinity threshold is the level of electrical conductivity of saturation extract at which crop yield starts reducing. The value for cabbage ranges from 1-1.8 dS/m depending on the sensitivity to salinity levels of the variety used (Allen *et al*, 1998). The effect on the yield when using each one of them was used on the two cases to assess the response of yield.

5.2.3.5 Irrigation

Irrigation depth, intervals and salinities described under cases in table 5.1 were used as input data. Pre-irrigation for all the cases was done to bring the root depth (0.5 m) to field capacity. For each case study, irrigation was aborted when the amount of cumulative rainfall exceeds the irrigation depth at the irrigation interval of the case used in the simulation.

5.2.3.6 Model run settings

The initial soil salinity at the start of the growing season is not available as during data collection (Chapter 3) for all the cases, the crop was already growing in the field. It was assumed that the initial soil salinity for all the scenarios is 0 dS/m. This would help in identifying how long it takes different scenarios before the salinity goes beyond the tolerable levels for cabbage yield loss. Initial settings were defined for each of the cases as shown on table 5.4.

Table 5. 4: Initial settings before running the model

Setting		Comments
Initial water content	Field capacity	Field observation
Initial salinity (ECe) of soil rootzone	0 dS/m	See section on assumption for the way 0 dS/m was come up with
Run duration	01/05/1980 - 31/12/1999	Years with data for meteorological station with minimum amount of data

5.2.4 Observations

Rootzone saturation extract electrical conductivity (ECe) was adjusted to a fixed 0.5 m depth as shown in chapter 4. In this section, rootzone ECe was recorded on annual basis. This was found by taking an average electrical conductivity for all the days between 1st May and 30th April. Drainage depth, drainage water salinity, yield losses due to moisture shortage and salinity were also noted. Annual rainfall presented for each region is an annual rainfall for a year beginning in 1st May until 30th April.

5.2.5 Statistical analysis

Unless otherwise stated, all the measurements was analysed using regression analysis and the Duncan multiple range test (DMRT). All the tests were done at 5 % alpha level.

5.3 RESULTS

5.3.1 Climate data

5.3.1.1 Comparison between FAO Penman-Monteith and Hargreaves

Reference evapotranspiration calculated using the Hargreaves equation was 0.69 mm/day, 0.61 mm/day and 0.64 mm/day higher in Francistown, Gaborone and Mahalapye respectively than that found using the Penmen Monteith equation (Figure 5. 3). This relation was made using monthly averages of over 3000 and 4000 days for Francistown and Mahalapye respectively between 1980 and 2000 were used. Over 2000 days between 1985 and 1987 were used for Gaborone (SSKA).

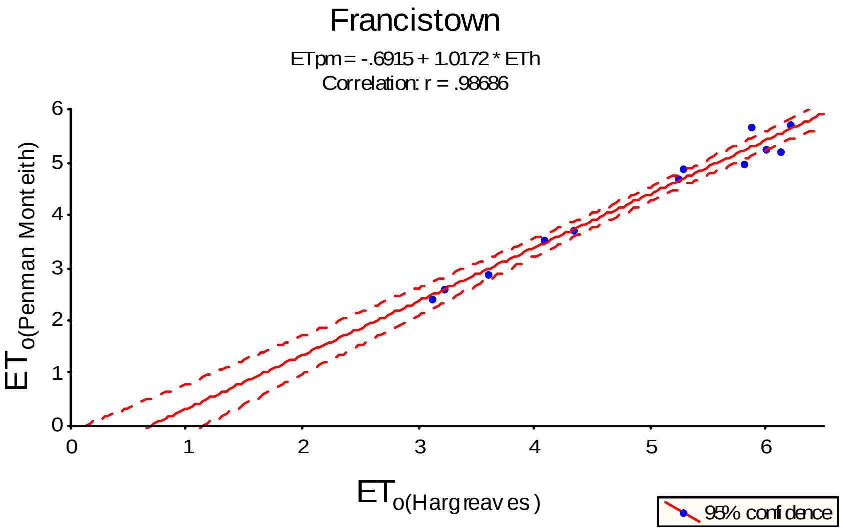


Figure 5. 2: Relationship between Penman Monteith and Hargreaves in mm per day for the different stations used for the regions

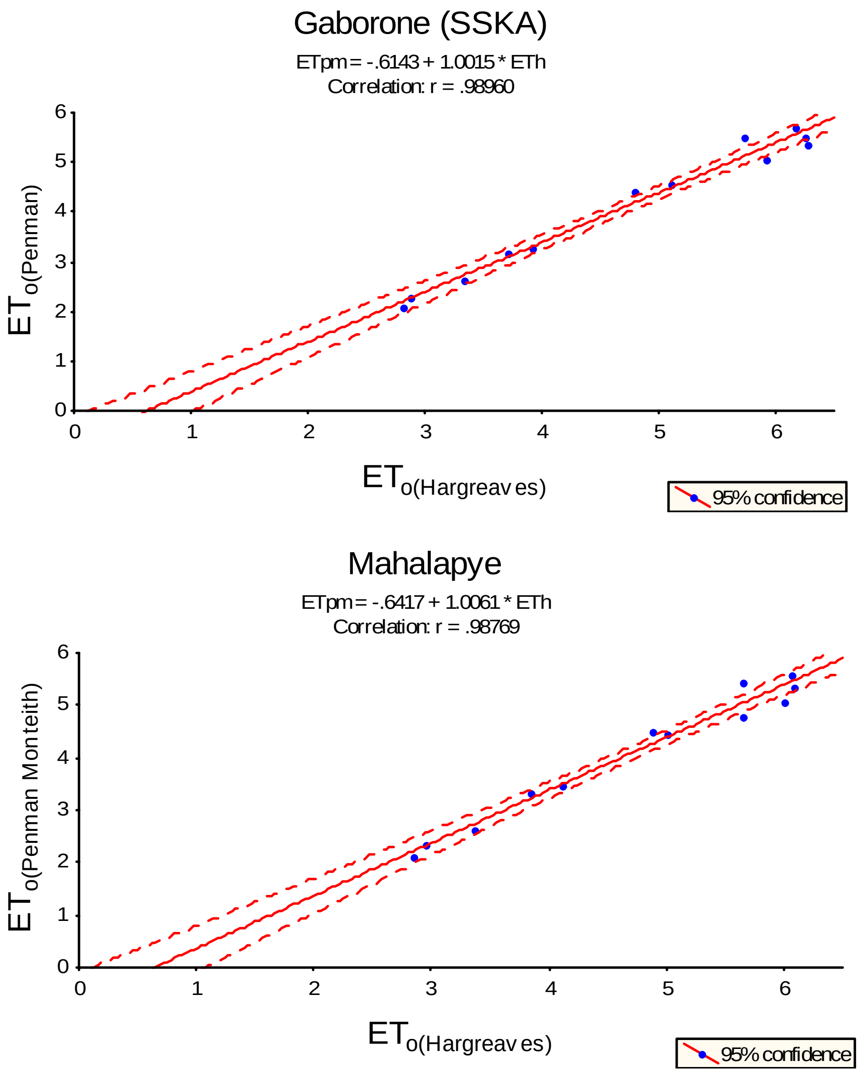


Figure 5. 3 Continued: Relationship between Penman Monteith and Hargreaves in mm per day for the different stations used for the regions

5.3.1.2 Summary of climate data

It can be seen from Figure 5. 4 that during the period of study, rainfall amount was varying a lot from year to year in all the stations. The variation does not show any distinguishable pattern in any of the regions. Reference evapotranspiration was more uniform from year to year. On comparison, average monthly rainfall and evapotranspiration for each of the three regions was found to be similar to the corresponding long term averages form FAO data (FAO, 1984).

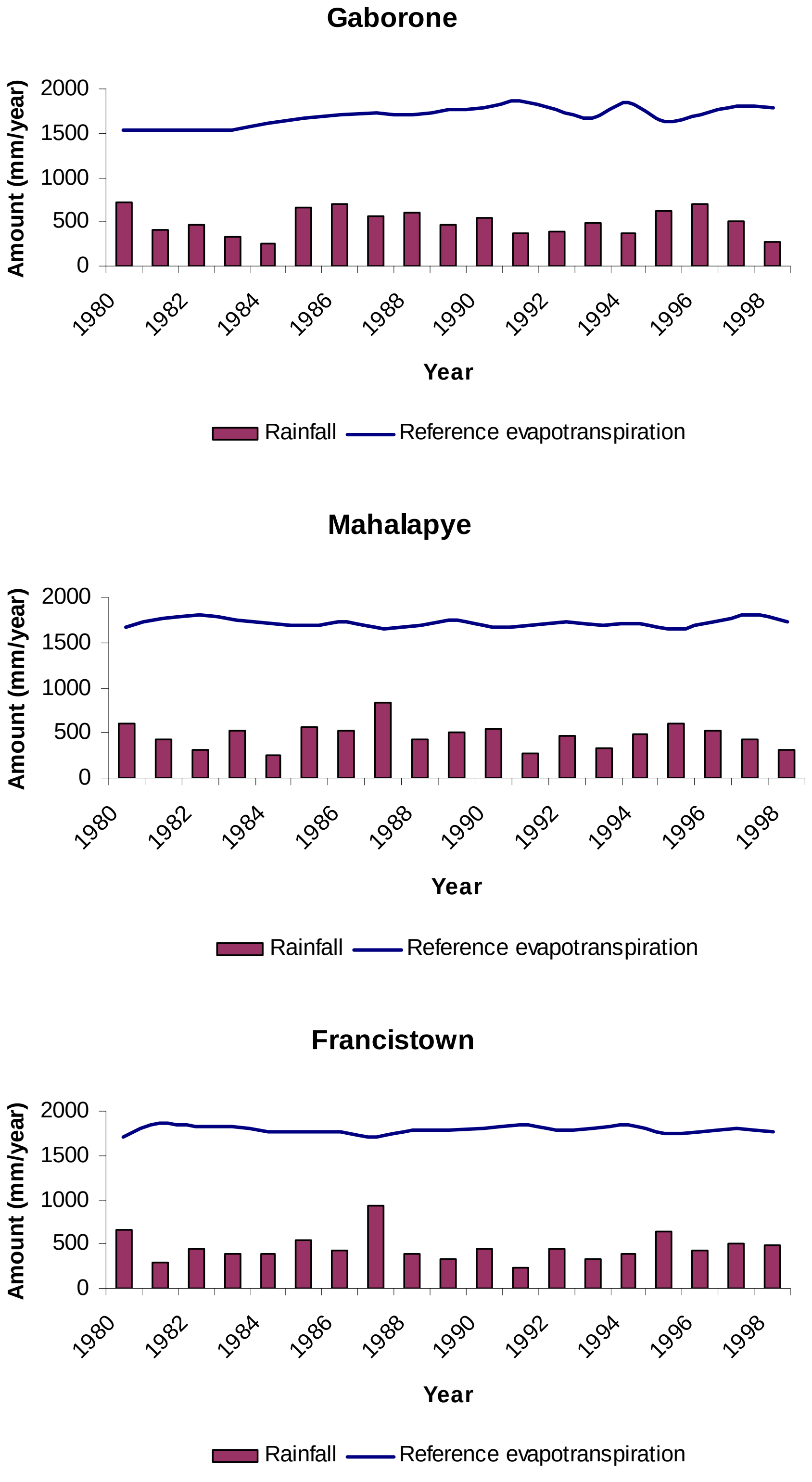


Figure 5. 4: Annual climate data for the three meteorological stations used in the simulations.

5.3.2 Simulations

Year zero in the graphs refers to the year when the simulation was started. Salinity during this year was zero for all the situations because it was set as the starting salinity. The test for significant relationships between the rootzone salinity and time was started at year one.

5.3.2.1 Cases

Soil salinity simulations were made for Case A and Case B (see Table 5. 1). Figure 5. 5 below shows the rootzone salinity trend due to Case A and Case B over a period of twenty years behaving differently. The range at which different varieties of cabbage start yield reduction due to salts in the rootzone is represented by the two horizontal lines in the graphs and is between 1.0 dS/m and 1.8 dS/m. The upper limit on the graph represents a level at which the most resistant varieties start reducing yield while the lower limit represent the level at which the most sensitive varieties start reducing yield. Average rootzone salinity for Case B is higher than that of Case A. Case B shows a rapid increase in soil salinity for the first year then the salinity starts increasing significantly ($p = 0.000552$) at 0.03 dS/m per year over the next 20 years. The increase is not a smooth one as in some years salinity reduces from one year to the next while in some it increases. After the first year of observation soil salinity trend due to Case A does not show a significant change with time. But it is important to observe that there are some years during which soil salinity for Case A is within the range of cabbage yield reduction while in some years it is below the range.

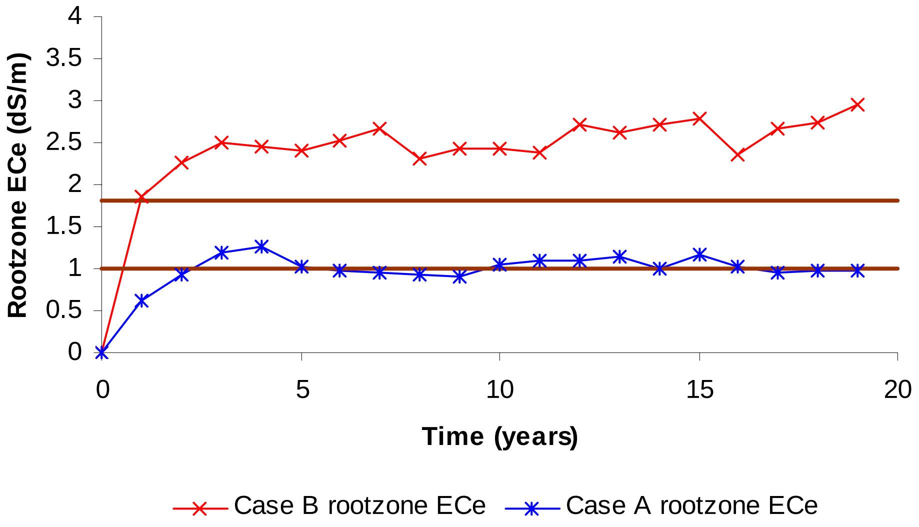
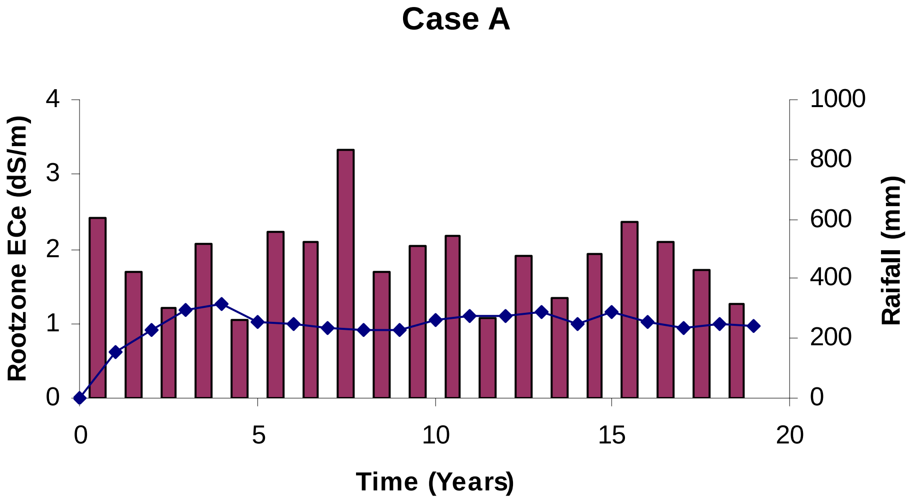


Figure 5. 5: Rootzone salinity trend for the two cases in their original situation. The two horizontal lines represent the lower and the upper limit of the salt tolerant range for cabbage varieties.

It can be seen that soil salinity build-up due to Case A will only affect yield for sensitive varieties in some years only. The salinity build-up due to Case B affects the yield of all the varieties at all times during the twenty years.

In Figure 5. 6 below, it can be seen that average annual soil salinity goes down during the year when rainfall is high and goes up when the rainfall is low. This is most pronounced in Case B where there is high variability in soil salinity from one year to the other.



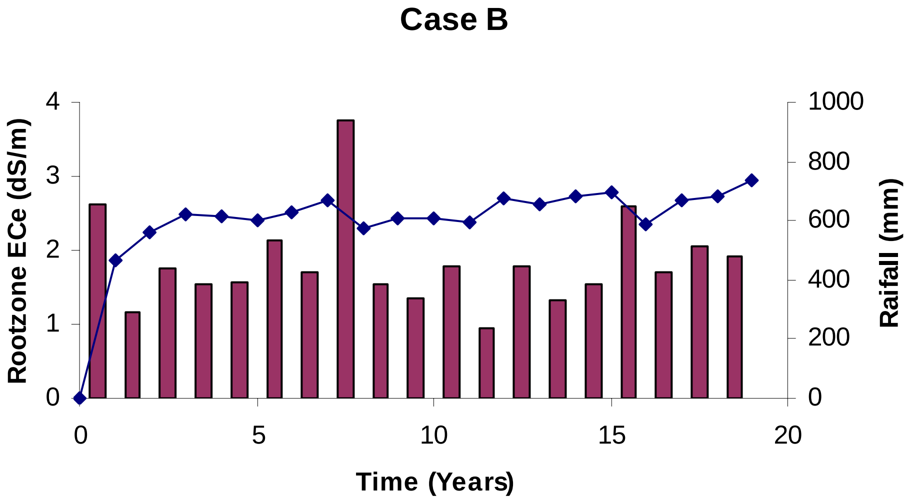


Figure 5. 6: Relationship between simulated rootzone salinity and rainfall for Case A and Case B

In both Case A and Case B, the farms have been used for four years. The observed average soil salinity during the time of survey for the two farms was 0.78 dS/m and

2.75 dS/m for Case A and Case B respectively. The simulated average soil salinity at the fourth year for the two cases was 1.27 dS/m and 2.45 dS/m for Case A and Case B respectively.

5.3.2.2 Simulation of cases under different conditions

Irrigation schedule and irrigation water salinity for each of the two cases above was used to simulate rootzone salinity under two different soils and the three different regions as discussed under section 5.2.2.

Average soil salinity

Table 5.5 shows average rootzone salinity levels due to use of irrigation water salinities of the Case A and Case B under different soils and different climate. For each of the irrigation water salinity levels, there is a lot of variation in soil salinity through the twenty years of simulations (Table 5. 5). The variation is higher for Case B irrigation water EC than that of Case A. In both cases, the mean soil salinity for clay soil is higher than that for sandy soil in all the regions. The mean annual soil salinity for clay soil in Case A irrigation water EC (Table 5. 5 a) in all the regions are within the range of cabbage yield loss whereas for sandy soil, all the averages are below the level of yield loss. But the maximum soil salinity in both clay and sand in all the regions over the range of cabbage yield loss. Mean annual soil salinity for Case A irrigation water (Table 5. 5 b) in all the regions is above the range likely to cause cabbage yield loss.

Table 5. 5: Mean and maximum rootzone salinity reached during the period of simulation for a) Case A and b) Case B irrigation water EC.

a) Case A irrigation water EC (0.76 dS/m)

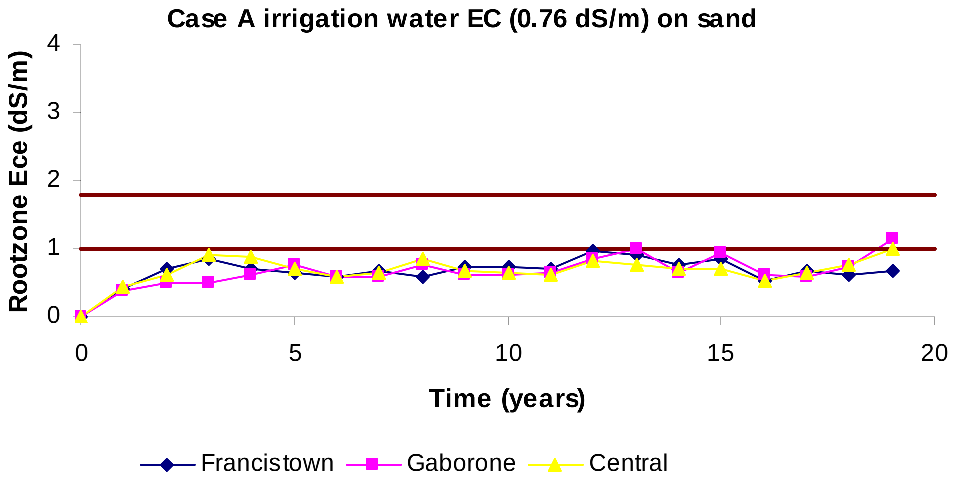
Region	Clay			Sand		
	Mean	Maximum	Std. Dev.	Mean	Maximum	Std. Dev.
Francistown/ North West	1.37	2.79	0.64	0.71	2.03	0.40
Gaborone/ Southern	1.33	2.55	0.61	0.72	2.17	0.43
Central	1.37	2.57	0.62	0.73	2.04	0.41

b) Case B irrigation water EC (2.65 dS/m)

Region	Clay			Sand		
	Mean	Maximum	Std. Dev.	Mean	Maximum	Std. Dev.
Francistown/ North West	3.07	6.39	1.28	2.08	5.95	1.03
Gaborone/ Southern	3.02	6.57	1.27	2.01	5.93	1.03
Central	3.08	6.44	1.27	2.06	5.82	0.95

Rootzone salinity accumulation rate

The pattern of accumulation of salt over the years in each region is shown to be unique (Figure 5.6) It was shown that there is a relationship between the rainfall pattern and rootzone salt accumulation pattern. From the figure, it can be seen that the amount and the rate of accumulation of salts differ depending on the combination of soil and case used. It is shown that on average some of the combinations will not affect the yield of cabbage (Case A water EC on sand) while some like Case B water EC on clay accumulate the salts too high for the cabbage yield right from the first year until the end of twenty years. Rootzone salinisation rate is highest for the clay and Case B water EC combination and lowest and not significant for the sand and Case A water EC combination. The rate of salt accumulation due to each of the soil and case combination do not differ between the different regions.



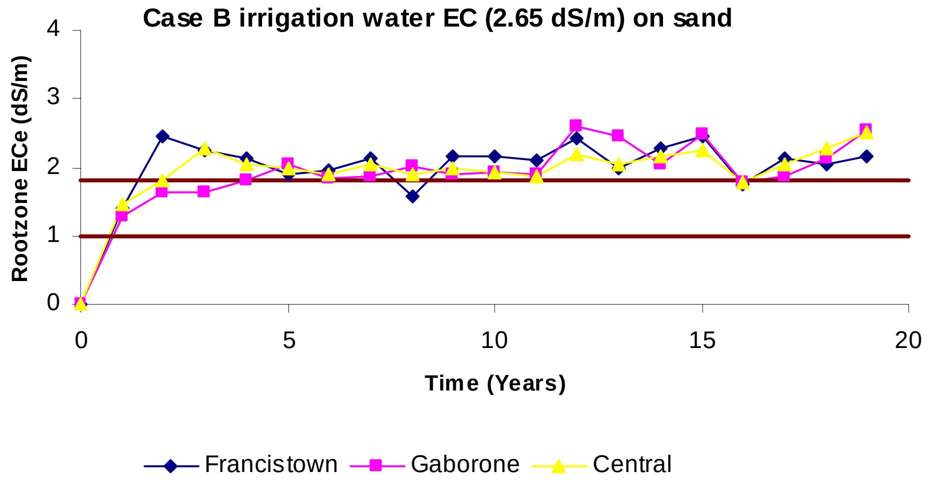
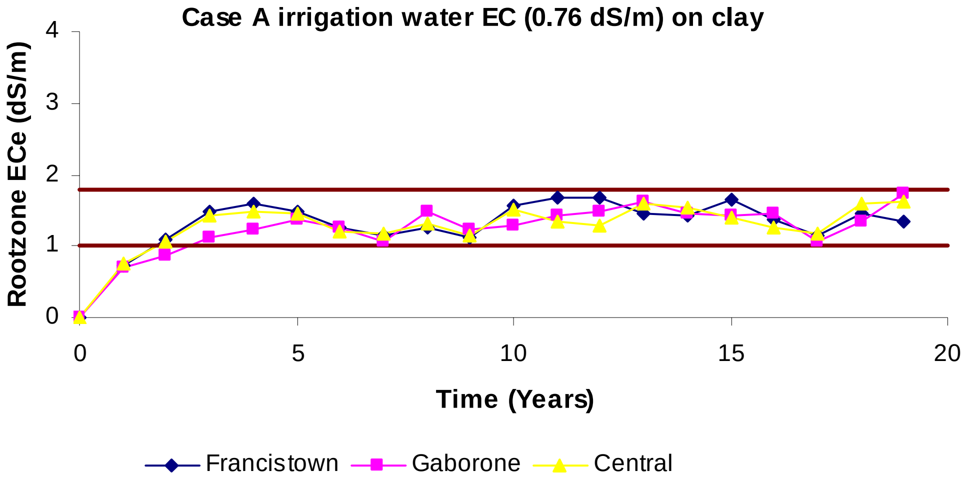


Figure 5. 7: Rootzone salinity for different regions simulated under different soil and cases. Two horizontal lines in the graphs represent the lower and the upper levels of rootzone salinity threshold for cabbage varieties



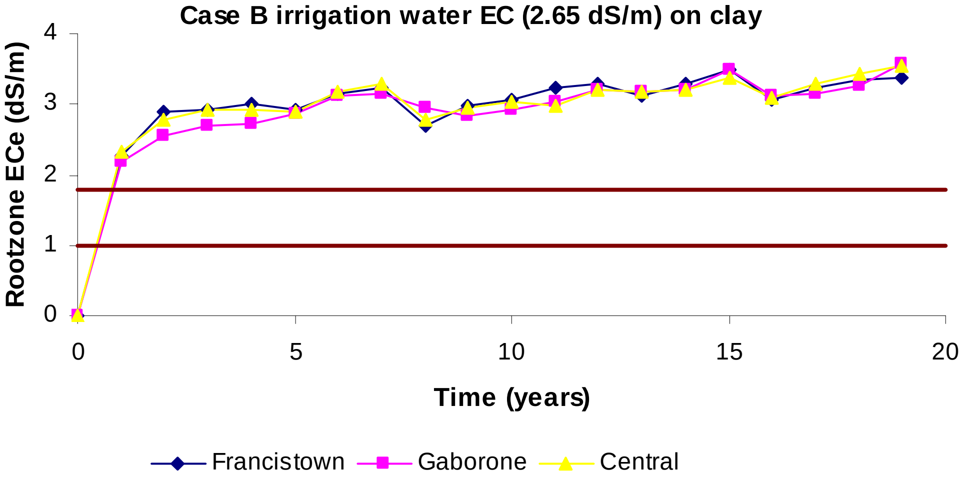


Figure 5. 6 continued: Rootzone salinity for different regions simulated under different soil and cases. Two horizontal lines in the graphs represent the lower and the upper levels of rootzone salinity threshold for cabbage varieties

5.4 DISCUSSION OF RESULTS

The results on meteorological data show that the data used in the experiment are representative of the general climate of the regions involved. So the results obtained during the simulations are representative of what would generally happen to soil salinity when the soil is exposed to the same irrigation treatments under the regions.

It is shown that there are management practices which when used on some soils accumulate only enough salts to be able to be leached out by rainfall. The situation of Case A shows that rainfall in the area (central region) rainfall might be enough to keep rootzone salinity from increasing (Sharma & Rao, 1998) and is the opposite for Case B where with a high irrigation water EC the amount of salts accumulated in a year needs more rain to leach than the rainfall of the region. There are some of the infield irrigation management currently practiced by the cabbage farmers in Botswana that need attention as they result in soil salinity build-up over time. While some irrigation management practices show rootzone salinity averages that do not seem to pose any problem for cabbage, depending on the combination of some management and soil type, there are some years within the time of simulations when the salinity levels keep going beyond the threshold levels. The varying amount of rainfall from year to year was found to be contributing to this varying salinity levels with higher rainfall years having low salinity levels.

5.5 CONCLUSIONS

Climate data identified and used in the simulations is found to the similar to the long term data for the meteorological stations.

Several distinct characteristics of soil salinity trends were identified as being due to the infield irrigation management practices used by Botswana cabbage farmers and are outlined below.

- Soil salinity trend that is maintained below the critical levels of cabbage throughout the years.
- Soil salinity trend that varies within the critical range. Depending on the variety used, this trend can have years with average salinity below or above the critical levels depending on rainfall in the year.
- Soil salinity trend that increases with time and reaching values beyond cabbage critical levels.
- Soil salinity that increases values above critical levels in the first year of production and continues increasing with time for years after.

Chapter 6

Soil Salinity Control for Cabbage Farmers in Botswana

6.1 INTRODUCTION

From the chapters above, it was realised that as a semi arid area, Botswana has all the conditions that can influence salinisation. It was also established that some of the land used for cabbage production has soils too saline for cabbage production. Irrigation water salinity and the infield irrigation management practices used by the farmers were found to be contributing to the soil salinity and farmers are not aware of it. This chapter therefore aims at recommending irrigation management practices that would keep soil salinity within the levels that will not result in yield loss but conserving water.

6.2 RECOMMENDATIONS

After assessing the climate, soil and infield irrigation management in Botswana, the following recommendations were made which will help keep soil salinity below the critical levels.

6.2.1 Farmers Education

The methods the farmers use for coming up with their irrigation scheduling (i.e. observing soil and plant) should not be posing any risk of rootzone salinity increase beyond the tolerable levels if used properly. High soil salinities show that the methods might not be properly used. There is a need to educate those who are already using the method on how to effectively use the method. This should involve education on identifying a crop or soil that needs irrigation.

There are some farmers who believe that they are growing crops under saline conditions while they are not and those who believe they are growing crops under normal conditions while they are growing under saline conditions. Cabbage farmers appreciate that they are using salty water for irrigation only if the water tastes salty. They also appreciate that the soil is salty if they see the accumulation of the salts on the surface. Those farmers who appreciate that they are working under saline environment do not know any measure to take to reduce the impacts of the salts. Therefore there is need to educate farmers on irrigation under saline conditions.

6.2.2 Infield Irrigation Management

Accumulation of salts in the soil was found to be different depending on the combination of management and soil used therefore to recommend any irrigation management practice for soil salinity control, a study on the infield irrigation status on the farm in question is necessary. The following recommendations are based on conclusions drawn after observing soil salinity due to cases studied in chapter 5. Four distinct soil salinity trends were identified in chapter 5 of which three have a potential for causing problems for cabbage production. Amendments of the infield irrigation management, which produced the two trends, to keep soil salinity below the critical levels are discussed below.

6.2.2.1 Variation of Soil salinity within the Critical Range

Soil salinity variation within the critical range of cabbage will affect some sensitive varieties of cabbage only. In this case, it would be advisable to grow varieties that are more tolerant to salt. If the only available varieties are the sensitive ones, this will mean that salinity will either be always above the critical level or will be above critical level in some years and be below in some as shown in Figure 6.1. In this figure, the trend line named original represent soil salinity due to use of irrigation water salinity of 0.76 dS/m on clay soil in the Gaborone region just as is shown on Figure 5.6. The soil salinity trend in this case varies within the upper and the lower threshold limits (two horizontal brown lines). But considering a cabbage variety with soil salinity threshold that lies at threshold .1, there are some years when soil salinity is a problem for the cabbage.

Therefore, there is a need then to stabililise soil salinity in this trendline. The problem of variability in soil salinity from one year to the other was found to be contributed to by the amount of rainfall in the year. This means that in years of low rainfall water applied to the soil is not enough to leach salts rootzone to keep soil salinity below the critical levels. This problem can be corrected by adding more irrigation water to cater for leaching. This will maintain salinity below critical levels as shown on Figure 6. 1 where 20 % leaching was applied (corrected trendline).

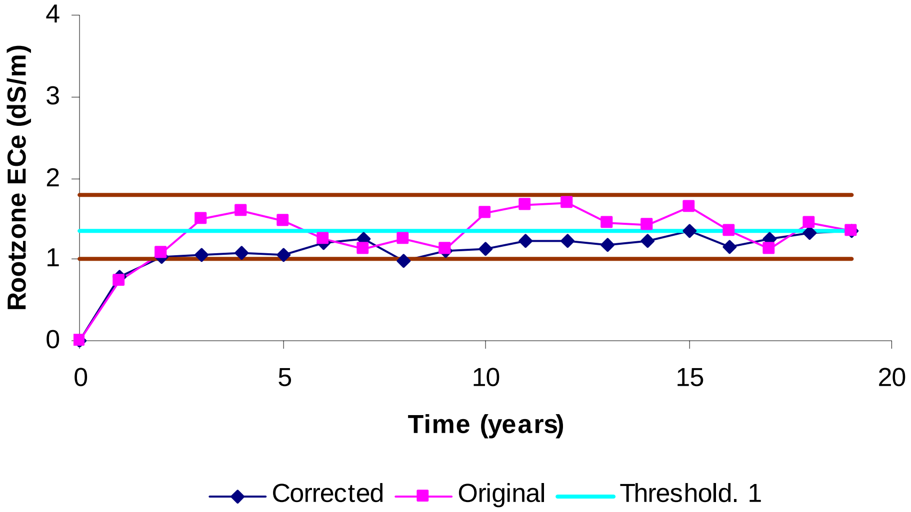


Figure 6. 1 Soil salinity trends due to original infield irrigation management and the corrected management with reference to the cabbage salinity threshold for case A on clay soil in Francistown

6.2.2.2 Soil salinity increasing over the years to values beyond critical levels

Soil salinity increasing continuously to values beyond critical levels occurs when the average salts added into the rootzone is more than the average salt removed. This problem was realised when irrigation with water of 2.65 dS/m at 8 mm in two days was applied on sandy soil (light soil). Figure 6. 2 shows that the problem can be corrected by growing cabbage in dry season and fallowing during the rainy season as it is the only one showing a trend that is within the critical range. Only salt tolerant varieties can be used in this situation.

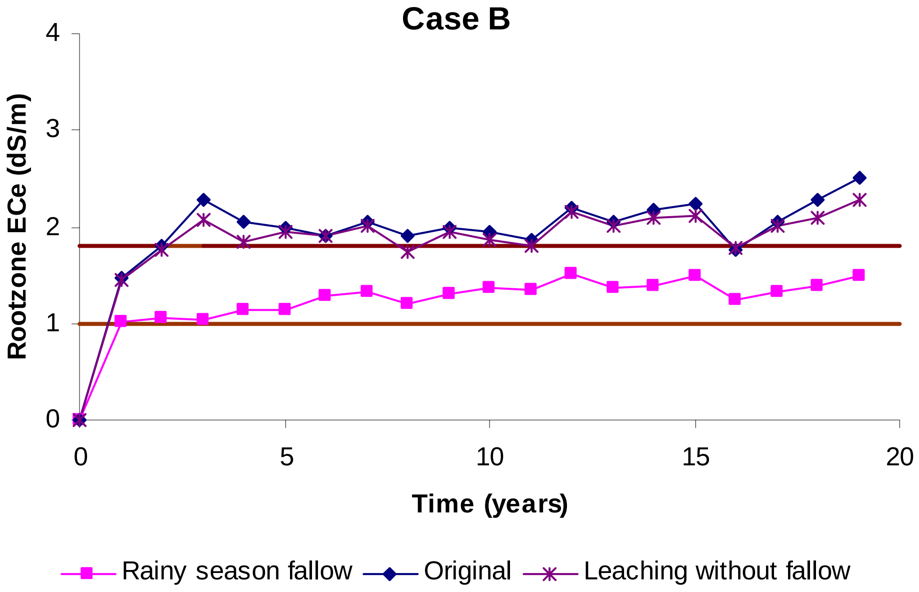


Figure 6. 2 Soil salinity trends for original and amended infield irrigation management for irrigation water salinity of 2.65 dS/m on sandy soil. Two horizontal lines in the graphs represent the lower and the upper levels of rootzone salinity threshold for cabbage varieties

6.2.2.3 Soil Salinity Increasing to Values beyond Critical Levels in the First Year and Remaining Too High

When using Case B (irrigation with water of high salinity at 8 mm in two days irrigation water) on clay soil (heavy soil) it was realised that soil salinity increases to values beyond the critical levels in the first year and continues increasing with time for years after. This problem cannot be controlled by producing cabbage in winter and fallowing during the rainy season as is shown by all the salinity trends are beyond the critical range (Figure 6. 3). It is then recommended that situations like Case B on clay soil should not be used for cabbage production.

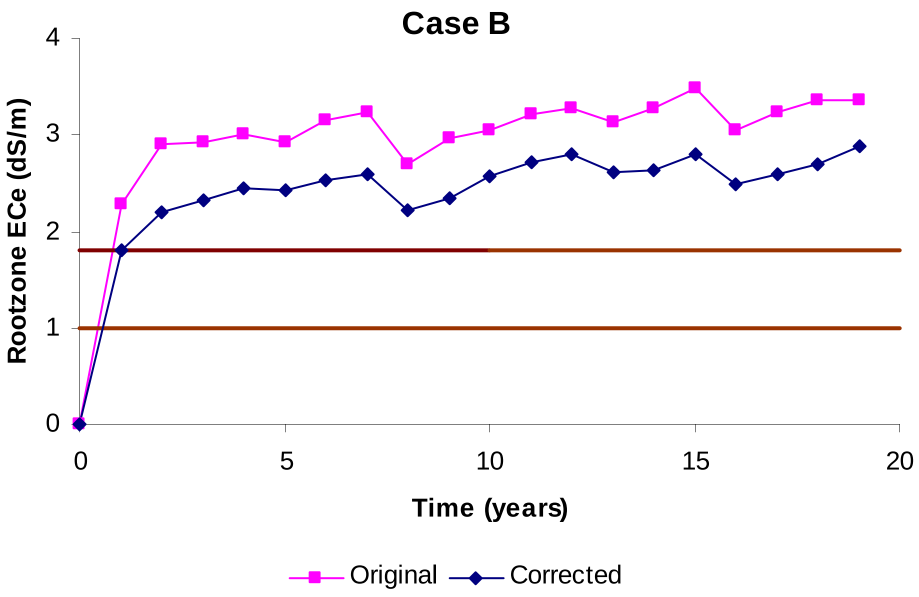


Figure 6. 3 Soil salinity trends for original and amended infield irrigation management for Case B on clay soil. Two horizontal lines in the graphs represent the lower and the upper levels of rootzone salinity threshold for cabbage varieties

6.3 DISCUSIONS

It was found that there are some irrigation management scenarios (that is a combination of management and soil) where soil salinity cannot be kept below critical levels by just varying the amount of water applied to the soil. This might be due to the fact that some soils (heavy) drain slower than the others (light).

6.4 CONCLUSIONS

There is no single recommendation that can be made for all the farmers who have soil salinity problems due to infield irrigation management. This is because the farms differ in soil type, irrigation water salinity and irrigation management wish determine the amount and rate of salt accumulation. An individual farm situation has to be studied separately before any recommendation can be made. Any of the following factors need to be applied either independently or in combination if soil salinity increase due to infield irrigation management by Botswana cabbage farmers has to be contained below the salinity threshold.

- Educating farmers on irrigation under saline conditions
- Reclaiming the already salt affected soils
- Cabbage varieties have a range of soil salinity tolerance therefore more tolerant varieties can be grown
- Adding leaching water when irrigating
- Fallowing the land during the rainy season

There are times when soil salinity cannot be kept below the soil salinity threshold for cabbage. This occurs when the heavy soils are used with irrigation water of high salinity. In such case production of cabbage is not advisable.

Chapter 7

Synthesis and Recommendations for Further Work

7.1 INTRODUCTION

The aim of this chapter was to synthesise the key aspects of the study. The recommendations from the study are also discussed here.

7.2 CONTRIBUTION OF THE STUDY

The study was aimed at recommending infield irrigation management to be used by cabbage farmers in Botswana without increase in soil salinity to levels that would result in yield losses. To achieve this, the study was divided into three objectives answered by running a field survey with Botswana cabbage farmers, simulations of soil salinity using WaSim simulation model and finally using conclusion from the survey and simulations and using WaSim model to make some recommendations on management practices. The research provides a greater understanding of how cabbage farmers in Botswana manage irrigation and the impacts their management have on soil salinity. The understanding of where to start when providing help for farmers on irrigation for soil salinity management was also provided.

7.2.1 Objective 1: To identify the infield irrigation management practices presently used by cabbage farmers in Botswana

The objective was answered through a survey with the farmers. The key aspects in this objective included:

1. Salinity levels of irrigation water used by Botswana cabbage farmers.

2. Rootzone salinity in the Botswana cabbage farmers' fields.

3. Soil type used by the farmers for growing cabbage.

4. Irrigation depth used by cabbage farmers in Botswana

6. Climate in the different agricultural regions of Botswana.

It was found that some of the water used by the farmers is saline (as high as 22 dS/m). Some of the soils used by the farmers are too saline for cabbage and that irrigation water is contributing to the salinity. It was shown that there is no evidence that cabbage farmers in the country are following the recommended methods of irrigation scheduling.

7.2.2 Objective 2: To model impacts brought about by the current irrigation management practices on soil salinity using WaSim model.

This objective was answered by two experiments. The first study was to validate the simulation model used in the study. This first study was divided into the field experiment (where soil salinity was monitored over the growing season in a cabbage field) and the actual testing of the model by testing the field results against the simulated. The experiment found that the model is good enough to be used. The second experiment for answering this objective was using the data collected from objective 1 and the simulation model tested in the first part of objective 2 to simulate the salinity trends due to infield irrigation management by the cabbage farmers. It was established that some infield irrigation management practiced by Botswana cabbage farmers result in increasing soil salinity in the long term. Also it was found that the salinity varies from year to year due to rainfall in such a way that most of the management practices will at one point result in salinity problems.

7.2.3 Objective 3: To recommend irrigation management practices that would keep soil salinity within the levels which will not result in yield loss but conserving water.

This objective was achieved by using the conclusions made under objectives 1 and 2 to recommend the management practices to be used by the Botswana cabbage farmers. Methods of reclaiming the already salt affected land were discussed under this objective. It was realised that there is a need to educate first farmers on how to identify a salt affected soil before giving recommendations.

7.3 RECOMMENDATIONS FOR FURTHER WORK

The study has shown that there are some farms which are affected by salts in the soil, and that each farm is affected in a unique manner. Since it was shown which farms are likely to have some problem with soil salinity, there is a need to review the individual farm situation. WaSim simulation model can then be used to assess the nature/ trend of salinity problem over time so that necessary infield irrigation management amendments and/or reclamation could be done.

It was found that there is a need to do more than increasing irrigation depth in order to keep soil salinity below cabbage critical levels therefore the study recommends that more work be done on other methods such as those that encourage infiltration (especially during the rainy season) and/ or improve soil drainage. This involves installing drainage systems (Armstrong *et al*, 1996) or improving the drainability of the soil by adding manure (FAO/ UNESCO, 1973).

During the study, it was realised that there are situations where excessive amounts of water are used where it does not look like there is a need. The study recommends the need to study irrigation efficiency of the irrigation managements in Botswana. This is important as the country has limited water resources. It is also recommended that a study be done on the impact of infield irrigation management on ground water salinity and depletion. This is important as the recharge of ground water in the country is low.

Reference List

Abbott C. L., Abdel-Gawad S., Wahba M.S., & Cascio A .L. (2001) *Field Testing of Controlled Drainage, and Verification of the WaSim Simulation Model*. OD/TN 102,

Abrol I. P, Yadav J.S.P & Massoud F.I. (1988) Salt-Affected Soils and their Management. *FAO Soils Soils Bulletin* 39 Rome, Italy: FAO Fiat Panos.

Allen R. G., Pereira L. S., Raes D & Smith M. (1998) Crop evapotranspiration - Guidelines for computing crop water requirements . *FAO Irrigation and Drainage Paper* 56 Rome, Italy: FAO Fiat Panos.

Amstrong A. S. B, Hughes E. J., Rycroft D. W., Tanton T. W., Pearce G. R. & Abbott C. L. (1996) *Reclamation of Saline Clay Soils - A manual of the Horizontal Leaching Technique*. England: HR Wallingford and University of Southampton.

Ayers R.S. & Westcot D.W. (1985) Water Quality For Agriculture. *FAO Irrigation and Drainage Paper* 29 Rome, Italy: FAO Fiat Panos.

Barrett-Lennard, E.G. (2002) Restoration of saline land through revegetation. *Agricultural Water Management*, 53 (1-3), 213-226.

Bok I., Madisa M, Machacha D, Moamogwe M, & More K. (2003) *Manual for Vegetable Production in Botswana*, unpublished Manual. Department of Agriculture Research.

Burgess J (2003) *Grassland and pasture crops. Country Pastura/ Forage Resource Profile, Botswana*. Available at: http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGP/AGPC/doc/Co unprof/Botswana/botswana.htm. Accessed 2003.

Cetin, M. and Kirda, C. (2003) Spatial and temporal changes of soil salinity in a cotton field irrigated with low-quality water . *Journal of Hydrology*, 272 (1-4), 238-249.

Chhabra R. (1996) *Soil Salinity and Water Quality*. Old Post Road, Brookfield, VT05036, USA: A.A.Balkema Publishers.

DAR Soils Labs (2002) *Water tests*. DAR, Ministry of Agriculture, Botswana.

Davies B., Eagle D., & Finney B (1993) *Soil management*. 5th ed. Ipswich IP1 4LG United Kindom: Farming press Books and Vedeos.

Doneen L.D. & Westcot D. W. (1984) Irrigation Practice and Water Management. *FAO Irrigation and Drainage Paper* 1 Rev. 1 Rome, Italy: FAO Fiat Panos.

Doorenbos, J. & Kassam A.H. (1986) Yield Response to Water. *Irrigation and Drainage Paper* 33 Rome: FAO.

Doran J. W. & Parkin T. B. (1994) Defining soil Quality for a Sustainable Environment. *In*: Anon. *Defining and assessing Soil quality*. Madison, WI53711 USA: Soil science society of America, Inc, 3-19.

FAO (1973) Mans influence on the hydrological cycle. *FAO Irrigation and Drainage Paper* 17 Rome: FAO.

FAO (1984) *Agroclimatological data: Africa 2*. Viadelle Termedi Caracalla, 00100 Rome, Italy: FAO.

FAO (2004) *FAO Country Profiles and Mapping Information System*. Available at: http://www.fao.org/countryprofiles/Maps/BWA/16/ad/index.html. Accessed

2004.

FAO & Ministry of Agriculture (1998) *Guidelines for Investigation, Design, Construction and Management of Irrigation Schemes*. Gaborone Botswana:

FAO-AGL (2000) *Salt-affected soils*. Available at: http://www.fao.org/WAICENT/FaoInfo/Agricult/agl/agll/prosoil/salt.htm. Accessed 2004.

FAO/ UNESCO (1973) *Irrigation Drainage and Salinity*. Great Britain: PARIS/ UNESCO HUTCHINSON & CO LTD.

Gartley K. (1995) Recommended Soil Testing Procedures for the Northeastern United States . *In*: FAO *Recommended Soluble Salts Tests*. 2nd ed. Northeastern Regional Publication , 70-72.

Gould. J & Nissen-Petersen E. (1999) *Rainwater Catchment System for Domestic Supply. Design construction and Implementation*. 102/105 Southampton Row, London, WC1B 4HH, UK.: Intermediate Technology Publications LTD.

Hess T, Leeds-Harrison P, & Counsell C. (2000) *WaSim Technical Manual*. HR Wallingford Howbery Park Wallingford , Institute of Water and Environment Cranfield University Silsoe.

Hess T and Counsell C. (2000) *A water balance simulation model for teaching and learning– WaSim* . Institute of Water and Environment, Cranfield University, Silsoe, Bedford, MK45 4DT, UK. HR Wallingford, Howbery Park, Wallingford, Oxfordshire OX10 8BA, UK.

Hoinville G., Jowell R, Airey C., Brook L., Courtenay G., Herges B., Kalton G., Morton-Williams J., Walker D., & Wood D. (1978) *Survey Research Practice*. 48 Charles Street, London WIX 8AH: Heinemann Educational

Books.

Anon. (2004) *A20 Soil Sience Practicals Laboratory Workbook*, unpublished Workbook. Cranfield University:

Keller J. & Bliesner R. D. (1990) *Sprinkler and Trickle Irrigation*. New York, USA: Van Nostrand Reinhold.

Merriam J. L. (1968) *Irrigation System Evaluation and Improvement.* 1415 Monetary Street Sun Luis Obispo, California 93401: Blake Printary.

Owens S. (2001) Salt of the Earth: Genetic engineering may help to reclaim agricultural land lost due to salinisation. *EMBO Reports,* 10

Parsons J.E., Thomas D. L., & Huffman R. L. (2004) Agricultural non-point source water quality models: Their and application. *Southern Cooperative Series Bulletin,* 398

Qadir, M. and Oster, J.D. (2004) Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Science of The Total Environment*, 323 (1-3), 1-19.

Rhoades J. D., Kandiah A. & Mashali A. M. (1992) The use of saline water for crop production. *FAO Irrigation and Drainage Paper* 48 5-19. Rome, Italy: FAO Fiat Panos. Rome, Italy.

Scherer T.F, Seelig B., & Franzen D. (North Dakota State Unuversity) (1996) *Soil, Water and Plant Characteristics Important for Irrigation*. EB 66, NDSU Extension Services.

Sharma D.P. and Rao K.V.G.K. (1998) Strategy for long term use of saline drainage water for irrigation in semi-arid regions. *Soil and Tillage Research*, 48 (4), 287-295.

Smedema L.K. & Rycroft D.W. (1983) *Land Drainage: Planning and design of agricultural drainage*. London: Batsford Academic and Educational.

Smedema L.K, Vlotman W.F., & Rycroft D.W. (2004) *Modern Land Drainage; Planning, Design and Management of Agricultural Drainage Systems*. Netherlands: A.A Balkema Publishers.

Smith M. (1992) CROPWAT - A Computer Program for Irrigation Planning and Management. *FAO Irrigation and Drainage Paper,* 46

Snedecor G. W & Cochran W.G. (1989) *Statistical Methods*. 8th ed. Iowa State University:

Tahal Consulting Engineers (2000) *National Master Plan for Agricultural Development*. Volume 1, Ministry of Agriculture, Botswana.

Tedeschi, A. and Menenti, M. (2002) Simulation studies of long-term saline water use: model validation and evaluation of schedules. *Agricultural Water Management*, 54 (2), 123-157.

Withers B. & Vipond S. (1974) *Irrigation: design and practice*. London: Batsford.

Zoldeske D.F, Slomon K.H. & Nuram E.U. (1994.) *Coefficient of Uniformity: What it tells us* , California State University, Fresno, California

Appendix A

A.1 Survey Questionnaire

Survey Questions

<u>Metadata</u>
Name of Farm/farmer ___________________________

Farm size __________________________

Farm location __________________________

Borehole number _______ (For identification when collecting data from the water affairs)

Name of nearest meteorological station ________________________

Distance of farm from meteorological station ________________________________

Location of meteorological Station: Altitude ______ Latitude ___________________

<u>Soil data</u>
Soil type (Identify soil texture) ______________________________

Water table depth _________________

Mulch: Yes _______ No _______

<u>Crop data</u>
Land preparation for planting cabbage: Ridges ____ Flat ____ Beds ____

Cultivation: Deep _______ Light _______

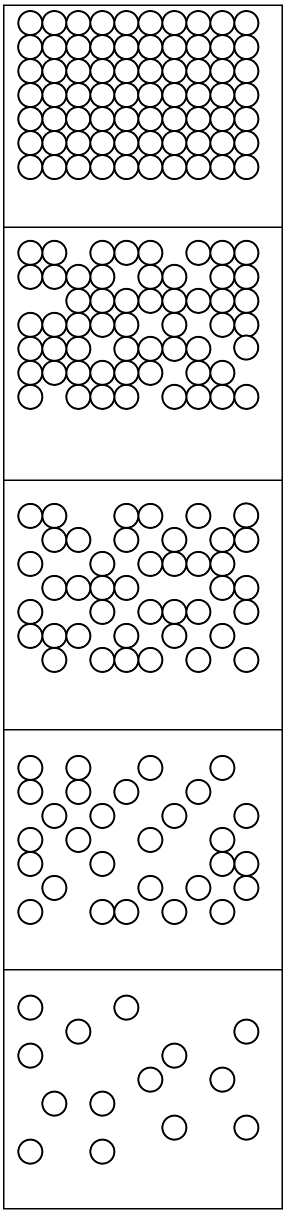
Other crop grown on the same land

Crop	Time grown	Irrigated	No irrigation

Proportion of land allocated to cabbage ________________

Weed control: Mechanical _____ Chemical _____ Biological _____

Ground Cover at maturity



Irrigation data

Schedule Date	Application rate	Sprinkler spacing	Number of sprinklers	Time taken irrigating

Consideration for Irrigation

Consideration	Indicator
Time from last irrigation	
Crop	
Soil	

Water Salinity:
Salty _____ Corrective measure ____
No salty _________
Do not know _________

Soil:
Salty _____ Corrective measure ____
Not salty ______
Do not know _______

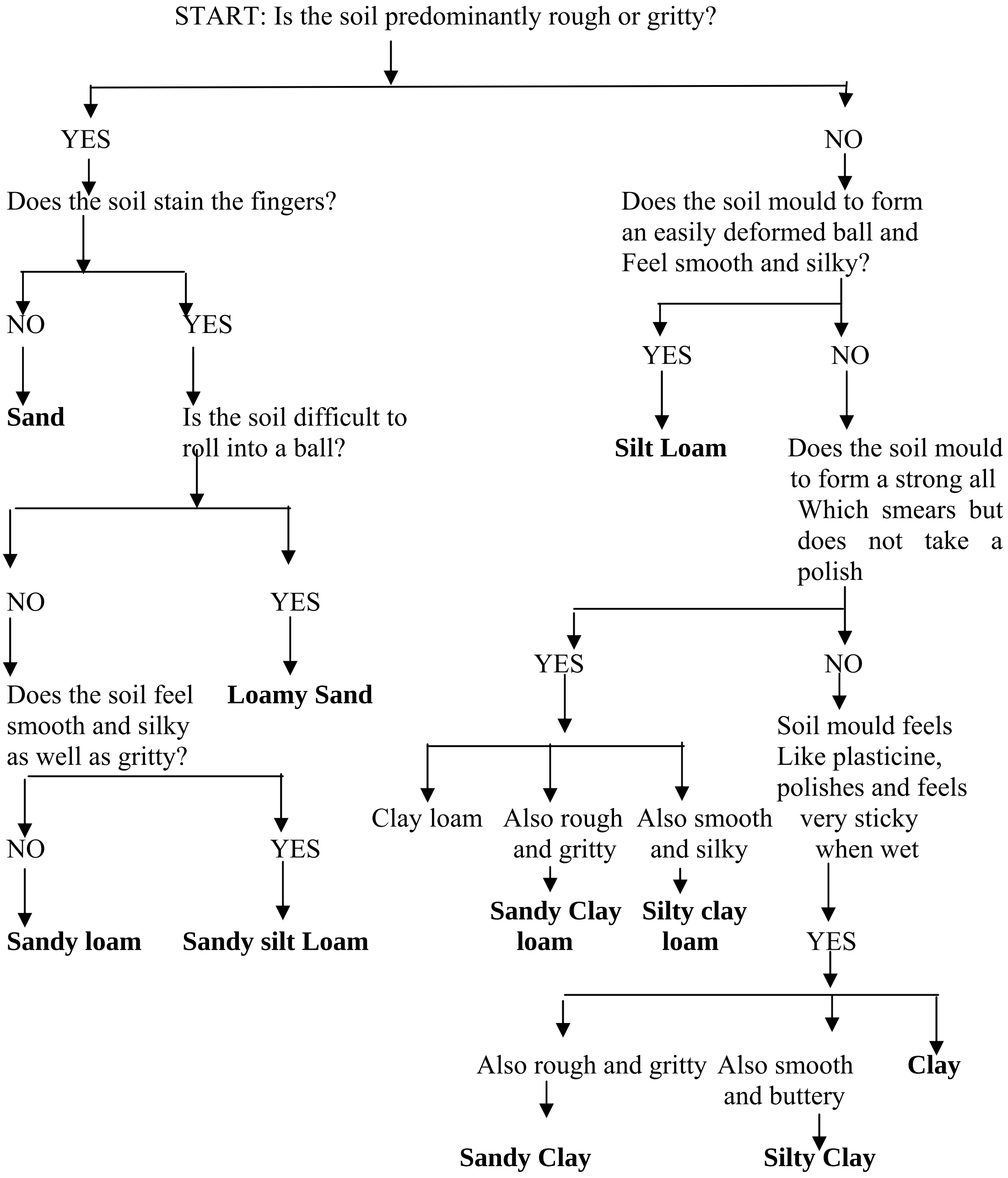
Actual water salinity (measured) ___________

A.2. Conductivity meter used in the experiment

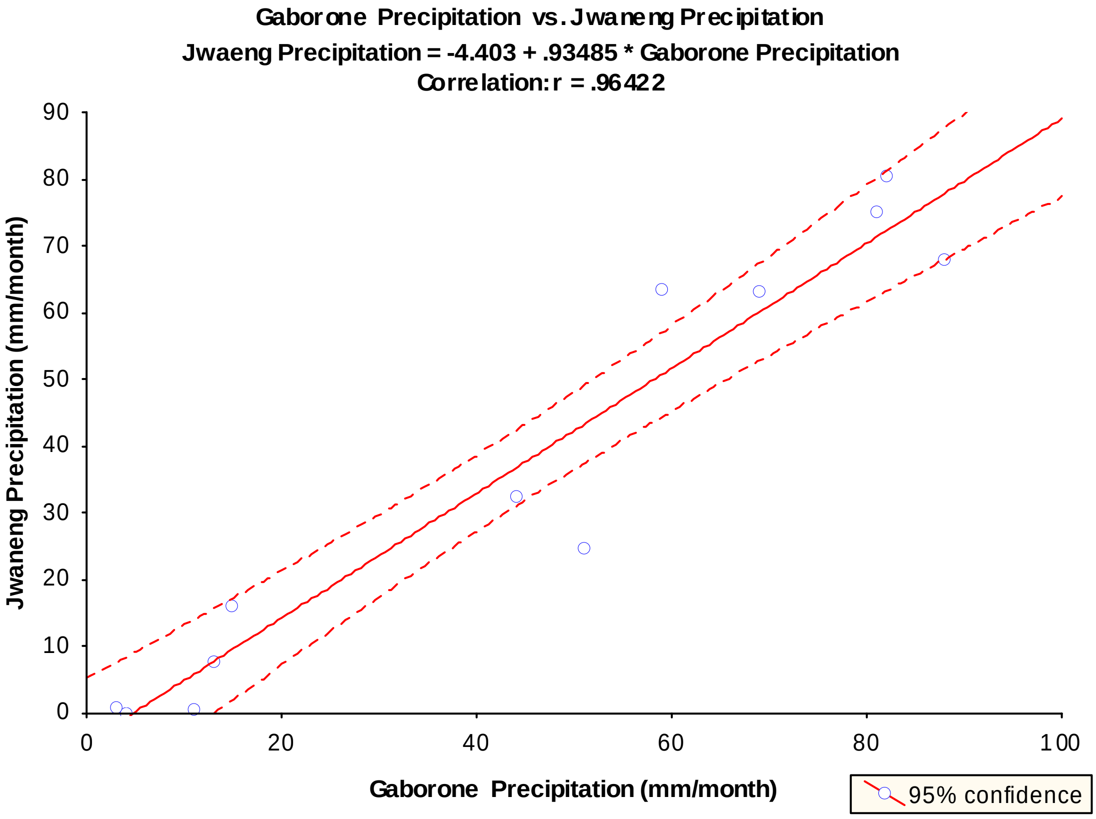
Specifications of model 4070 conductivity meter

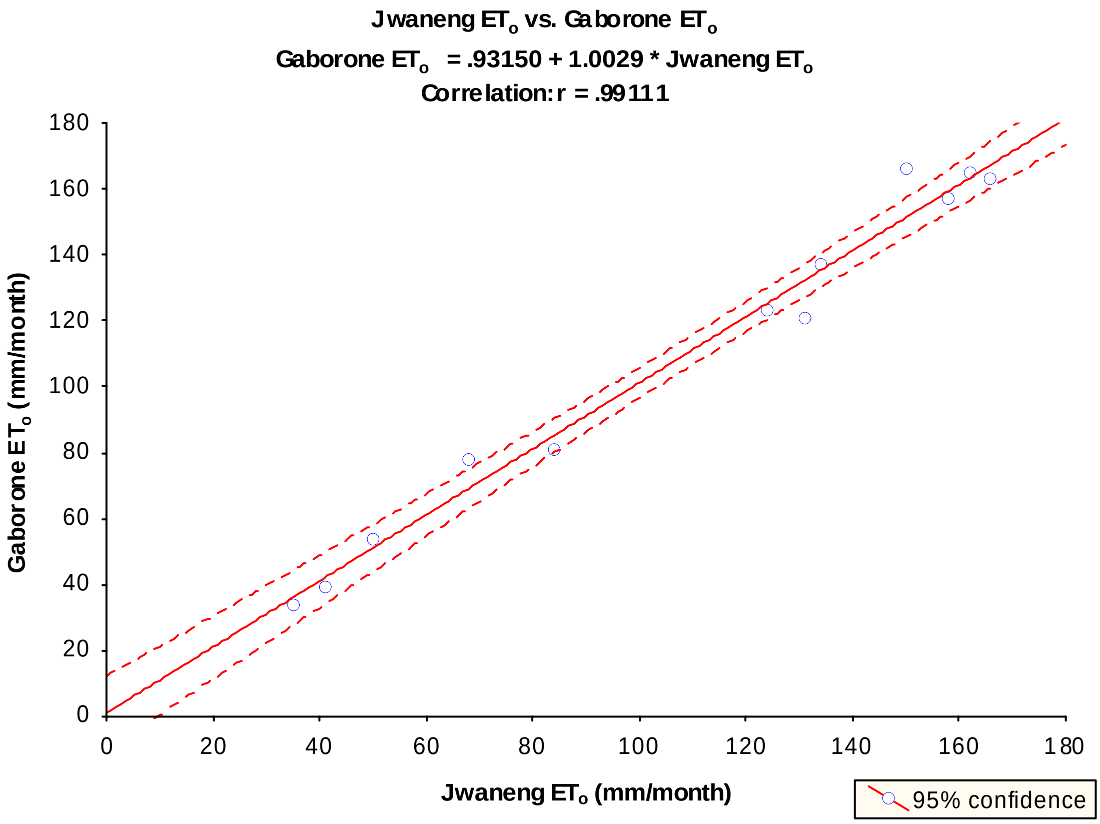
Specification	
Ranges	0 to 19.99mS -30 to +150^{o}C
Resolution	0.01mS 0.1 ^{o}C
Accuracy	±0.5% ±2 digits ±0.5^{o}
Temp. Comp.:	0 to 50 ^{o}C
Slope:	2% per ^{o}C
Cell:	0.75 to 1.50
Constant:	(digitally settable)
Ref. Temp.:	25 ^{o}C

A.3. Soil textural class identification chart

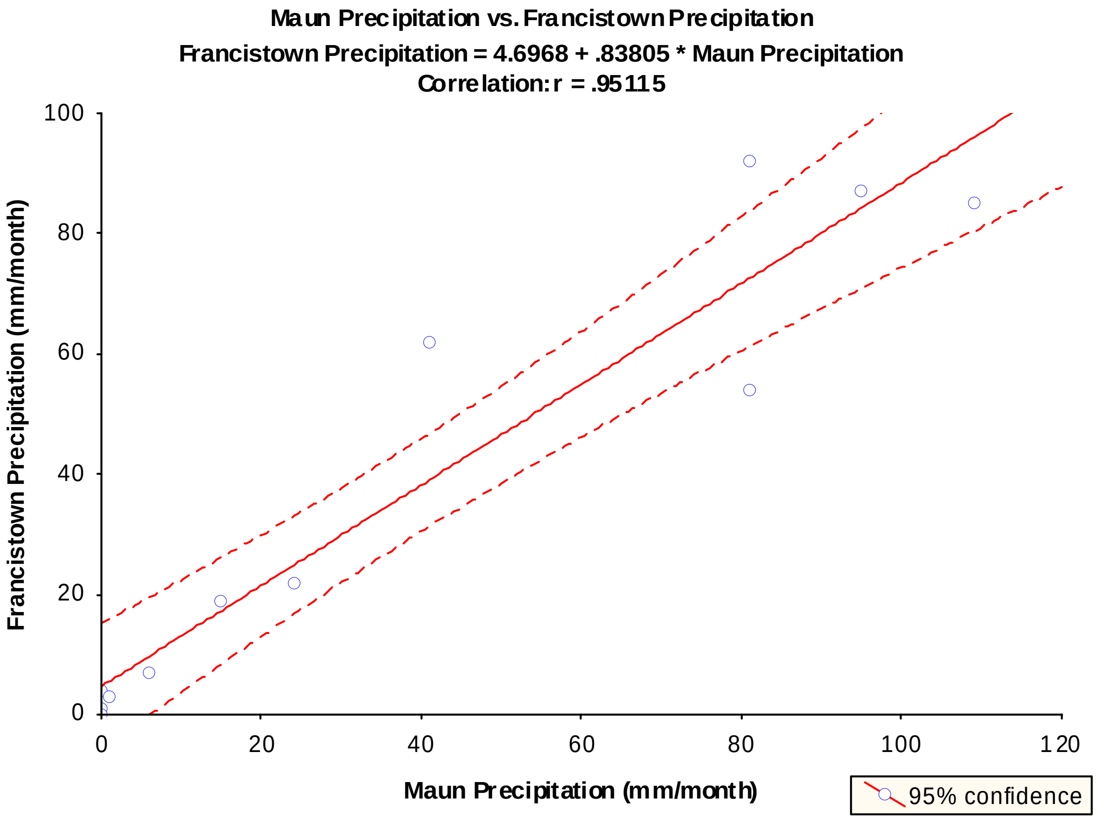


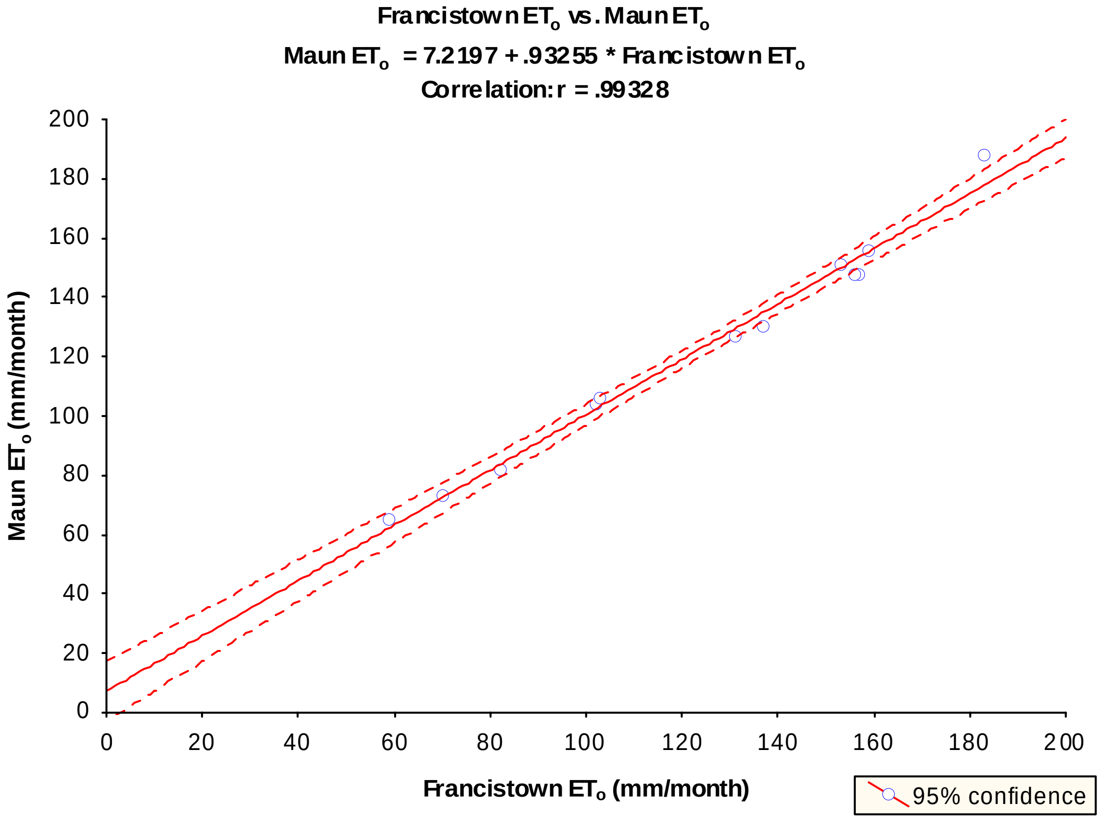
A.4 Relationship between Gaborone and Jwaneng, and Maun and Francistown precipitation and evapotranspiration





Jwaneng ET$_o$ vs. Gaborone ET$_o$
Gaborone ET$_o$ = .93150 + 1.0029 * Jwaneng ET$_o$
Correlation: r = .99111
Gaborone ET$_o$ (mm/month)
0
20
40
60
80
100
120
140
160
180
Jwaneng ET$_o$ (mm/month)
95% confidence


Maun Precipitation vs. Francistown Precipitation
Francistown Precipitation = 4.6968 + .83805 * Maun Precipitation
Correlation: r = .95115
Francistown Precipitation (mm/month)
100
80
60
40
20
0
0
20
40
60
80
100
120
Maun Precipitation (mm/month)
95% confidence


Francistown ET$_o$ vs. Maun ET$_o$
Maun ET$_o$ = 7.2197 + .93255 * Francistown ET$_o$
Correlation: r = .99328
Maun ET$_o$ (mm/month)
200
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200
Francistown ET$_o$ (mm/month)
95% confidence

Appendix B

B.1. Mean relative humidity for the three regions estimated from two different methods

Data collected from all the stations contains relative humidity data recorded at 0800 ad 1400 hours each day. But the FAO Penman-Monteith equation requires average relative humidity. Relative humidity could not be calculated from an equation as the data collected does not contain all the data needed to calculate actual vapour pressure needed for the calculation of relative humidity (Allen *et al.*, 1998). Therefore the average relative humidity was estimated using the following assumptions.

Assumption 1: $RH_{14:00} = RH_{min}$ and $RH_{max} = 100$ then

$$RH_{mean} = (RH_{14:00} + 100) / 2 \qquad \text{(B.1)}$$

Assumption 2: $RH_{mean} = RH_{08:00}$ -- (B.2)

Where:

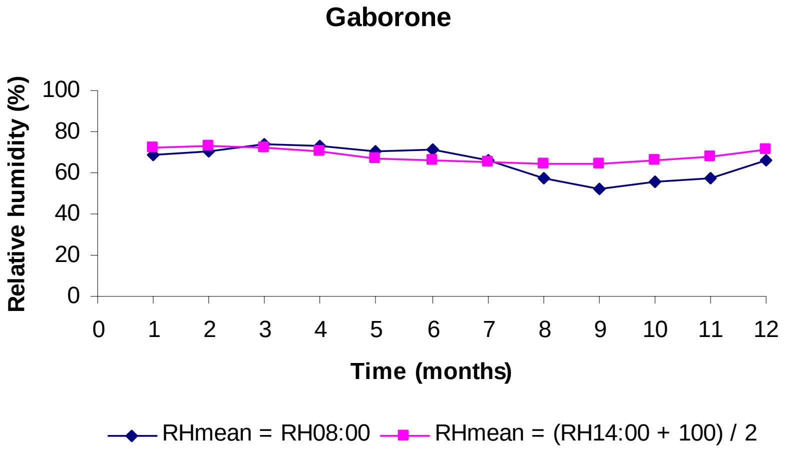
$RH_{14:00}$ – Relative humidity at 14:00 hours
RH_{min} – Minimum relative humidity for the day
RH_{max} – Maximum relative humidity for the day
$RH_{08:00}$ – Relative humidity at 08:00 hours

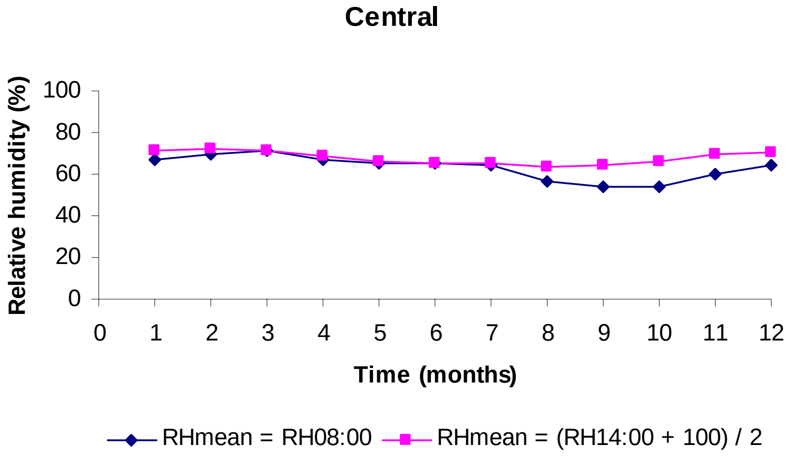
Over 5500, 7000 and 6000 days with both 8 o'clock and 2 o'clock relative humidity data for SSKA (Gaborone/ Southern), Mahalapye (Central) and Francistown (Francistown/ Maun) meteorological stations respectively between the period of 1985 - 2000 for SSKA and 1980 - 2000 for Francistown and Mahalapye

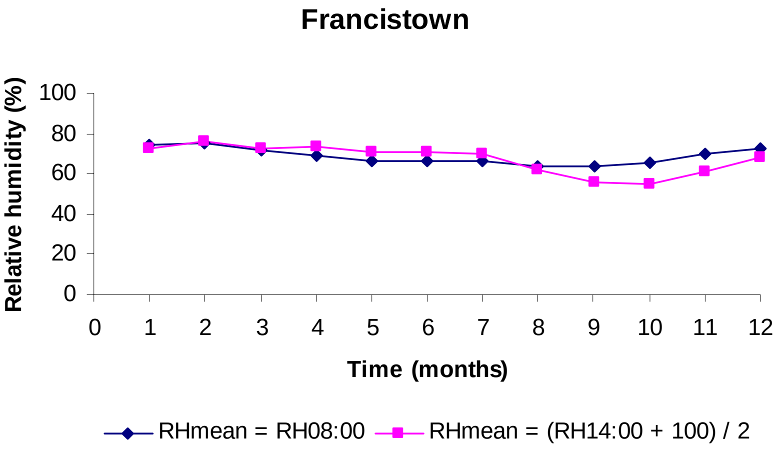
Results

Comparisons between the two methods used in estimating the mean relative humidity are shown in figure 5.2. The two methods, that is

give similar values which mean that assumption 2 $RH_{mean} = RH_{08:00}$ might be applying. Therefore $RH_{08:00}$ can be used as the mean relative humidity in all the regions.






Francistown
Relative humidity (%)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (months)
RHmean = RH08:00
RHmean = (RH14:00 + 100) / 2

B.2 Calculation method for vapour pressure deficit

Vapour pressure deficit is the deficit between the saturation vapour pressure and the actual vapour pressure. Therefore to calculate saturation vapour pressure deficit, mean saturation pressure and actual saturation pressure have to be calculated first.

Saturation vapour pressure is calculated from air temperature as follows:

$$e_s = \frac{e^\circ(T_{max}) + e^\circ(T_{min})}{2} \text{--B.1}$$

Where:

T_{max} - maximum temperature [°C]
T_{min} - minimum temperature [°C]
$e^\circ(T)$ - saturation vapour pressure at the air temperature T [kPa], and is expressed as shown below:

$$e^\circ(T) = 0.6108 \exp\left[\frac{17.27T}{T + 237.3}\right] \text{---B.2}$$

Where:

T - air temperature [°C],

Actual vapour pressure derived from mean relative humidity is expressed as follows:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^\circ(T_{max}) + e^\circ(Tmin)}{2}\right] \text{---B.3}$$

Where:

RH_{mean} is the mean relative humidity

T_{max} - maximum temperature [^oC]

T_{min} - minimum temperature [^oC]

Then:

Vapour pressure deficit = $e_s - e_a$

B.3 Technical report on WaSim simulation model

Appendix C: Raw data

C.1. North West region data

Farmer	**Soil ECe**	**Water EC**	**Depth (mm)**	**Interval (Days)**	**Depth/ Day (mm/day)**	**Ground cover**	**Years on area**	**Irrigation water salt status (farmers' perception)**	**Corrective measure (water)**	**Soil salt status (farmers' perception)**	**Corrective measure (soil)**	**Mulch**	**Irrigation change with season**
1	0.61	0.15	16	2w/1s	8	70		Salty	Nothing	Do not know		No mulch	Between season change
2	0.69	0.15	12	2	6	80	22	Not salty		Do not know		No mulch	No change
3	9.09	0.38	18	3	6	80		Not salty		Do not know		No mulch	No change
4	4.07	1.99	14	2w/1s	7	70	1	Not salty		Do not know		No mulch	Between season change
5	1.89	1.95	14	2	7	50		Not salty		Do not know		Mulch	No change
6	1.18	0.66	20	3	7	90	3	Not salty		Do not know		No mulch	Between season change
7	0.80	0.76	8	2	4	80		Not salty		Do not know		No mulch	No change
8	8.20	0.46	42	7w/ 4s	6	80	3	Not salty		Do not know		No mulch	Between season change
9	2.56	0.1	42	7	6	80	5	Not salty		Do not know		No mulch	No change
10	1.38	0.32	14	2	7	80	30	Not salty		Not salty		No mulch	Within season change

North West region data continued

Farmer	Total area (Ha)	Cabbage area (Ha)	Proportion of cabbage area	Soil type	Bed type	Planting time	Planting season	Region	Irrigation system
1	1	0.49	49	Silt loam	Sunken Beds	All year	All year	North West	Sprinklers
2	3.5	0.125	3.	Silt loam	Flat	All year	All year	North West	Sprinklers
3	1	0.5	50	Sandy silty loam	Sunken Beds	June	Winter	North West	Sprinklers
4	1	0.25	25	Silt loam	Flat	April	Winter	North West	Sprinklers
5	1.5	0.25	16	Silt loam	Sunken Beds	April	Winter	North West	Hand watering
6	1.5	0.5	33	Silt loam	Flat	April	Winter	North West	Sprinklers
7	1	1	100	Silt loam	Sunken Beds	All year	All year	North West	Sprinklers
8	2	0.25	12.5	Sandy silty loam	Flat	All year	All year	North West	Sprinklers
9	1.5	0.04	2	Sandy silty loam	Flat	All year	All year	North West	Sprinklers
10	1.5	0.2	13	Silt loam	Flat	All year	All year	North West	Sprinklers

C.2. Francistown region data

Farmer	**Soil ECe (dS/m)**	**Water EC (dS/m)**	**Depth (mm)**	**Interval (Days)**	**Depth/ Day (mm/day)**	**Ground cover**	**Years on area**	**Irrigation water salt status (farmers' perception)**	**Corrective measure (water)**	**Soil salt status (farmers' perception)**	**Corrective measure (soil)**	**Mulch**	**Irrigation change with season**
11	4.65	3.2	6	1	6	80	4	Do not know		Do not know		No mulch	No change
12	1.84	1.05	20	3	7	80	4	Not salty		Do not know		No mulch	No change
13	3.32	0.65	8	3	3	60	1	Do not know		Do not know		No mulch	No change
14	1.40	0.92	20	2	10	80	1	Not salty		Do not know		No mulch	No change
15	1.71	0.6	24	7	3	80	2	Not salty		Do not know		No mulch	No change
16	2.74	1.25	12	2	6	80	4	Salty	Nothing	Do not know		No mulch	No change
17	2.90	1.23	4	2	2	80	3	Salty	Nothing	Do not know		No mulch	No change
18	4.46	1.66	8	2	4	80	4	Salty	Nothing	Salty	Nothing	No mulch	No change
19	2.20	0.69	6	3	2	80	1	Salty	Nothing	Do not know		No mulch	No change
20	5.21	1.22	6	2	3	80	5	Salty	Nothing	Do not know		No mulch	No change

Francistown region data continued

Farmer	**Total area (Ha)**	**Cabbage area (Ha)**	**Proportion of cabbage area**	**Soil type**	**Bed type**	**Planting time**	**Planting season**	**Region**	**Irrigation system**
11	4	0.28	7	sandy loam	Raised beds	All year	All year	Francistown	Drip
12	0.5	0.016	3	sand	Sunken Beds	All year	All year	Francistown	Hand watering
13	0.6	0.03	5	loamy sand	Sunken Beds	May	Winter	Francistown	Hand watering
14	0.6	0.02	3	sandy loam	Sunken Beds	May	Winter	Francistown	Hand watering
15	2.5	0.25	10	sandy loam	Flat	May	Winter	Francistown	Sprinklers
16	0.1	0.03	30	sandy loam	Flat	May	Winter	Francistown	Hand watering
17	6	0.01	0	sandy loam	Flat	May	Winter	Francistown	Sprinklers
18	6	1	16	sandy loam	Sunken Beds	All year	All year	Francistown	Hand watering
19	1.5	0.5	33	sandy loam	Flat	May	Winter	Francistown	Sprinklers
20	0.12	0.006	5	sandy loam	Sunken Beds	May	Winter	Francistown	Hand watering

C.3. Central region data

Farmer	Soil ECe (dS/m)	Water EC (dS/m)	Depth (mm)	Interval (Days)	Depth/ Day (mm/day)	Ground cover	Years on area	Irrigation water salt status (farmers' perception)	Corrective measure (water)	Soil salt status (farmers' perception)	Correctiv e measure (soil)	Mulch	Irrigation change with season
21	11.50	2.12	15	4	4	90	2	Not salty		Do not know		No mulch	No change
22	5.27	2.96	13	1s/2w	13	90	2	Salty	Nothing	Do not know		No mulch	Between season change
23	4.78	2.55	8	7	1	40	13	Salty	Nothing	Do not know		No mulch	No change
24	3.95	1.55	5	1	5	80	3	Not salty		Do not know		No mulch	No change
25	9.70	1.34	8	1	8	80	4	Salty	Nothing	Do not know		No mulch	No change
26	1.95	0.79	8	2	4	20	2	Not salty		Do not know		No mulch	No change
27	12.12	2.98	5	2w/1s	3	80		Salty	Nothing	Not salty		No mulch	Between season change
28	3.00	1.24	4	2	2	60	5	Salty	Nothing	Do not know		No mulch	No change
29	2.99	1.17	8	4	2	80	3	Not salty		Do not know		No mulch	Between season change
30	2.77	0.46	3	1	3	90	2	Salty	Nothing	Do not know		No mulch	No change

31	1.28	0.72	3	1	3	80	2	Not salty		Do not know		No mulch	No change
32	4.59	1.35	8	3	3	80	3	Not salty		Do not know		Mulch	No change
33	8.04	1.09	6	2	3	80	3	Salty	Nothing	Do not know		Mulch	No change
34	10.43	1.21	3	1	3	80	4	Salty		Not salty		No mulch	No change
35	22.20	2.64	6	1	6	20	3	Not salty		Do not know		Mulch	No change
36	5.43	1.15	6	1	6	80	3	Salty	Nothing	Do not know		Mulch	No change
37	2.31	0.9	6	2	3	80	5	Salty	Nothing	Do not know		Mulch	No change
38	2.75	2.65	4	1	4	80	4	Salty	Nothing	Do not know		Mulch	No change
39	4.77	2.13	15	4	4	80	20	Salty	Nothing	Do not know		Mulch	No change
40	7.50	1.43	24	7	3	80	4	Salty	Nothing	Do not know		Mulch	No change

Central region data continued

Farmer	Total area (Ha)	Cabbage area (Ha)	Proportion of cabbage area	Soil type	Bed type	Planting time	Planting season	Region	Irrigation system
21	0.5	0.5	100	loamy sand	Flat	All year	All year	Central	Drip
22	4	1	25	sandy loam	Flat	All year	All year	Central	Drip
23	0.24	0.09	37	loamy sand	Sunken Beds	May	Winter	Central	Hand watering
24	1	0.02	2	sand	Flat	April	Winter	Central	Sprinklers
25	0.4	0.025	6	loamy sand	Flat	June	Winter	Central	Drip
26	0.25	0.025	10	loamy sand	Flat	All year	All year	Central	Sprinklers
27	1	0.036	3.6	sandy loam	Flat	March	Winter	Central	Hand watering
28	1	0.0075	0.75	sandy loam	Sunken Beds	May	Winter	Central	Hand watering
29	4	1	25	sandy loam	Flat	April	Winter	Central	Sprinklers
30	0.81		27	loamy sand	Ridges	May	Winter	Central	Hand watering
31	4	1	25	sandy loam	Ridges	March	Winter	Central	Drip
32	0.25	0.125	50	sand	Sunken Beds	March	Winter	Central	Sprinklers
33	4	1	25	loamy sand	Sunken Beds	May	Winter	Central	Drip
34	3	1	33	loamy sand	Flat	April	Winter	Central	Drip
35	0.66	0.1	16	sandy loam	Flat	April	Winter	Central	Drip
36	0.8	0.025	3	sandy loam	Raised beds	May	Winter	Central	Drip
37	1	0.5	50	sandy loam	Flat	May	Winter	Central	Drip
38	1	0.25	25	sandy loam	Sunken Beds	All year	All year	Central	Hand watering
39	5	1	20	sandy loam	Flat	May	Winter	Central	Sprinklers
40	4	1	25	sand	Flat	May	Winter	Central	Sprinklers

C.4. Gaborone region data

Farmer	Soil ECe (dS/m)	Water EC (dS/m)	Depth (mm)	Interval (Days)	Depth/ Day (mm/day)	Ground cover	Years on area	Irrigation water salt status (farmers' perception)	Corrective measure (water)	Soil salt status (farmers' perception)	Corrective measure (soil)	Mulch	Irrigation change with season
41	3.22	1.53	11	2w/1s	6	60	4	Salty	Nothing	Do not know		No mulch	Between season change
42	2.60	1.18	5.5	2	3	80	4	Salty	Nothing	Do not know		No mulch	No change
43	2.13	0.83	24	4w/3s	6	40	2	Do not know		Do not know		No mulch	Between season change
44	0.70	0.79	24	2w/1s	12	90	3	Do not know		Not salty		No mulch	Between season change
45	0.44	0.13	20	4s/7w	5	80	20	Not salty		Not salty		No mulch	Between season change
46	1.60	0.78	5.5	1	6	80	4	Do not know		Not salty		Mulch	No change
47	1.09	0.22	24	7	3	90	5	Not salty		Not salty		No mulch	No change
48	1.83	0.63	16	7w/4s	2	60	20	Not salty		Not salty		No mulch	Between season change
49	0.81	0.28	11	1	11	60	2	Do not know		Salty		No mulch	No change
50	2.02	1.2	10	2	5	90	25	Do not know		Do not know		No mulch	No change

Gaborone region data continued

Farmer	Total area (Ha)	Cabbage area (Ha)	Proportion of cabbage area	Soil type	Bed type	Planting time	Planting season	Region	Irrigation system
41	5.7	1.5	26	Clay loam	Flat	All year	All year	Gaborone	Sprinklers
42	4	2	50	sandy loam	Flat	March	Winter	Gaborone	Sprinklers
43	1	0.03	3	Silt loam	Flat	All year	Winter	Gaborone	Sprinklers
44	1.3	0.09	6	sand	Flat	April	Winter	Gaborone	Sprinklers
45	6	1	16	sandy loam	Ridges	March	Winter	Gaborone	Sprinklers
46	0.46	0.0125	2	Silt loam	Flat	May	Winter	Gaborone	Drip
47	4	1	25	Sandy clay loam	Flat	March	Winter	Gaborone	Sprinklers
48	30	4	13	Clay	Flat	May	Winter	Gaborone	Sprinklers
49	0.36	0.05	13	Silt loam	Raised beds	May	Winter	Gaborone	Drip
50	4	1	25	sandy loam	Flat	May	Winter	Gaborone	Sprinklers

C.5. Southern region data

Farmer	Soil ECe (dS/m)	Water EC (dS/m)	Depth (mm)	Interval (Days)	Depth/ Day (mm/day)	Ground cover	Years on area	Irrigation water salt status (farmers' perception)	Corrective measure (water)	Soil salt status (farmers' perception)	Corrective measure (soil)	Mulch	Irrigation change with season
51	2.47	0.76	20	2	10	90	5	Not salty		Not salty		No mulch	No change
52	3.15	0.55	8	3	3	60	3	Salty	Nothing	Salty	Nothing	No mulch	No change
53	1.82	0.88	11	3	4	80	5	Not salty		Not salty		No mulch	No change
54	1.64	0.79	8	3	3	80	5	Not salty		Do not know		No mulch	No change
55	1.62	1.7	8	5	2	60	10	Salty	Nothing	Salty	Nothing	No mulch	No change
56	2.04	0.86	10	3	3	60	6	Do not know		Do not know		No mulch	No change
57	1.30	0.75	45	7	6	90	5	Not salty		Not salty		No mulch	No change
58	0.86	0.81	7	2	4	80	4	Not salty		Not salty		No mulch	No change
59	1.68	0.85	4	2	2	60	5	Not salty		Not salty		No mulch	No change
60	1.05	0.59	25	7	4	90	30	Not salty		Not salty		No mulch	No change

Southern region data continued

Farmer	Total area (Ha)	Cabbage area (Ha)	Proportion of cabbage area	Soil type	Bed type	Planting time	Planting season	Region	Irrigation system
51	8	5	62	sand	Flat	April	Winter	Southern	Sprinklers
52	2	0.05	2.5	sandy loam	Flat	April	Winter	Southern	Sprinklers
53	2	1.5	75	loamy sand	Raised beds	April	Winter	Southern	Sprinklers
54	1	0.04	4	loamy sand	Flat	April	Winter	Southern	Sprinklers
55	8	4	50	sandy loam	Flat	May	Winter	Southern	Sprinklers
56	4	0.03	0.75	sandy loam	Flat	May	Winter	Southern	Sprinklers
57	2	0.04	2	sand	Flat	April	Winter	Southern	Sprinklers
58	1	0.05	5	loamy sand	Sunken Beds	April	Winter	Southern	Sprinklers
59	1	0.5	50	loamy sand	Flat	May	Winter	Southern	Sprinklers
60	6	3	50	sandy loam	Flat	May	Winter	Southern	Drip

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WaSim
Technical Manual

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List of variables

Symbol	Description	Units
α	soil evaporation constant, mm $d^{-½}$	mm $d^{-½}$
τ	drainage coefficient	dimensionless
θ	volume water fraction	dimensionless
ϕ	ditch water level or drain diameter	m
μ	drainable porosity	dimensionless
Δr	daily root growth	m d^{-1}
θ_{SAT}	volume water fraction at saturation	dimensionless
a	empirical constant	dimensionless
b	empirical constant	dimensionless
bs	reduction in yield due to salinity	% (dS $m^{-1})^{-1}$
B	bare soil fraction	dimensionless
c	empirical constant	m^{-1}
C	crop cover fraction	dimensionless
d	Hooghoudt's equivalent depth	m
d_0	depth from the drain to the impermeable layer	m
e	the potential contribution of groundwater to ET	mm d^{-1}
EC	electrical conductivity of soil water	dS m^{-1}
EC_I	electrical conductivity of irrigation water	dS m^{-1}
ECs	electrical conductivity of saturation extract	dS m^{-1}
ECs'	Threshold electrical conductivity of saturation extract	dS m^{-1}
Egw	contribution from water table to soil evaporation	mm d^{-1}
Em	evaporation from mulch cover	mm d^{-1}
Eo	open water evaporation	mm
Es	soil evaporation	mm d^{-1}
Es_o	potential soil evaporation	mm d^{-1}
ET	actual evapotranspiration	mm d^{-1}
ET_o	reference evapotranspiration	mm d^{-1}
f	fraction of drain flow from below drain depth	dimensionless
FC	water content of root zone at field capacity	mm
θ_{FC}	volume water fraction at field capacity	dimensionless
f_s	relative saturation	dimensionless
h	height of the mid-drain water table above the drain depth	m
I	irrigation water applied	mm d^{-1}
Ie	effective irrigation water applied	mm d^{-1}
K	saturated hydraulic conductivity	mm d^{-1}
Kc_{max}	ratio of potential transpiration to reference evapotranspiration at full cover	dimensionless
Kp	open water evaporation (pan) coefficient	dimensionless
Ks	transpiration reduction factor for salinity	dimensionless
Ky	yield response factor due to water stress	dimensionless
L	drain spacing	m
Le	leaching efficiency	dimensionless
M	fraction mulch cover	dimensionless

M_0	cover fraction of mulch at planting	dimensionless
n	duration of root growth	d
N	Curve number	dimensionless
N_1	Curve number for dry antecedent conditions	dimensionless
N_2	Curve number for average antecedent conditions	dimensionless
N_3	Curve number for wet antecedent conditions	dimensionless
p	fraction of total available water that is easily available	dimensionless
P	gross rainfall	mm d^{-1}
P’	available precipitation	mm d^{-1}
P_e	effective rainfall	mm d^{-1}
Pond	ponding depth	mm
Pond’	maximum allowable ponding depth	mm
PWP	water content of root zone at permanent wilting point	mm
Q	drain flow	mm d^{-1}
q	drainage from compartment	mm d^{-1}
Q’	fraction of drain flow from below drain depth	dimensionless
q_s	daily addition to water table from canal seepage	mm d^{-1}
R	surface runoff	mm d^{-1}
r	root depth	m
r_0	planting depth	m
r_{max}	maximum root depth	m
s	maximum storage	mm
S	mass of salt	mm dS m^{-1} d^{-1}
Sd	mass of salt in the water leaving compartment j	mm dS m^{-1} d^{-1}
S_I	mass of salt added by irrigation water	mm dS m^{-1} d^{-1}
SWD	soil water deficit of root zone	mm
t	time since the start of stage 2	d
Ta	actual transpiration	mm d^{-1}
TAWC	total available water capacity of root zone	mm
Tgw	contribution from water table to transpiration	mm d^{-1}
To	potential transpiration	mm d^{-1}
t_p	time since planting	d
U	maximum cumulative evaporation	mm d^{-1}
Vs	net flux from the water table to the root zone	mm d^{-1}
W	water content	mm
z	compartment thickness	mm
z_w	depth to the water table	m
β	exponent dependant on depth to the impermeable layer	m^{-1}

1. THE WATER BALANCE MODEL

The model carries out a one-dimensional, daily, soil water balance. It aims to simulate the soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage) of water in response to climate, irrigation, and canal seepage where relevant.

The upper boundary is the soil surface and the lower boundary is the impermeable layer[1]. Water is stored between these two boundaries in five stores (compartment):

- Compartment 0. The surface (0 – 0.15m) layer,
- Compartment 1. The active root zone (0.15m – root depth),
- Compartment 2. The unsaturated compartment below the root zone (root depth – water table),
- Compartment 3. The saturated compartment above drain depth (water table – drain depth),
- Compartment 4. The saturated compartment below drain depth (drain depth – impermeable layer).

The boundary between compartments 1 and 2 will change as the roots grow. Before plant roots reach 0.15m, compartment 1 will have zero thickness. Similarly the boundary between compartments 2 and 3 will fluctuate with the water table.

1.1 Inputs of water

Inputs of water are from net rainfall, net irrigation and lateral seepage, where relevant. Net rainfall and irrigation are defined as the gross amounts, less interception losses, and surface runoff. Irrigation may, or may not, be subject to interception, depending on the application method.

1.2 Outputs of water

The outputs of water from the profile are;

1. Open water evaporation, Eo, occurs only if there is ponding on the soil surface. In this case, there is no transpiration.
2. Soil evaporation, Esoccurs from compartment 0 only.
3. Plant transpiration,Ts_0, Ts_1 occurs from compartments 0 and 1.

---

[1] The model is insensitive to an impermeable layer >10m.

4. Capillary rise from the groundwater. Rather than redistribute water from the water table to the unsaturated compartments and then to evaporation or transpiration, the model simulates a direct ‘shortcut’ from the groundwater to evaporation, *Egw* and transpiration, *Tgw*.

5. Drain flow occurs from the lower compartments if the water table is above the drain depth. The rate of drain flow is a function of the height of the water table above the drain.

6. Pumped drainage. A constant daily output can be taken directly from the water table. This can be used to simulate pumped drainage.

1.3 Redistribution of soil water

Soil water moves from upper compartments to compartments below only when the soil water content of the compartment exceeds field capacity. In this case, the rate of drainage, q_0 to q_2, is a function of the amount of excess water.

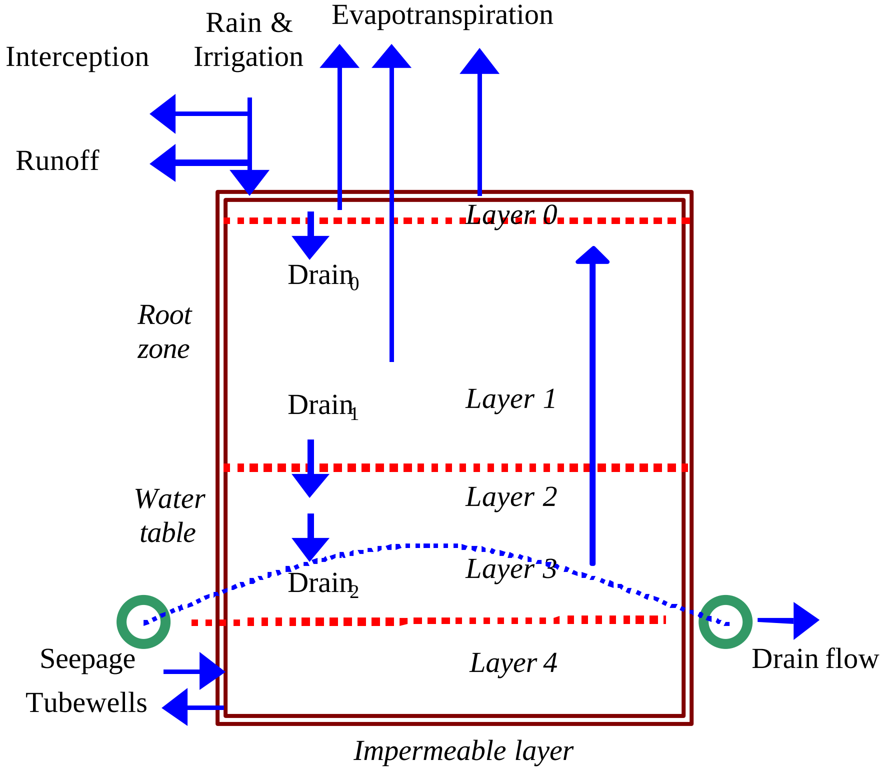

Figure 1. Overview of the soil water balance

2. SURFACE CONDITIONS

The soil surface is divided into three components – plant cover, bare soil and mulch - and the evapotranspiration from each is modelled separately.

2.1 Crop cover fraction

The crop cover fraction on a particular day is determined by linear interpolation between the dates of emergence, 20% cover, maximum cover, maturity and harvest (Figure 2). If the maximum cover fraction is less than 20%, then the first stage is ignored. Senescence is simulated by a linear reduction in crop cover fraction between maximum cover at maturity and zero at harvest.

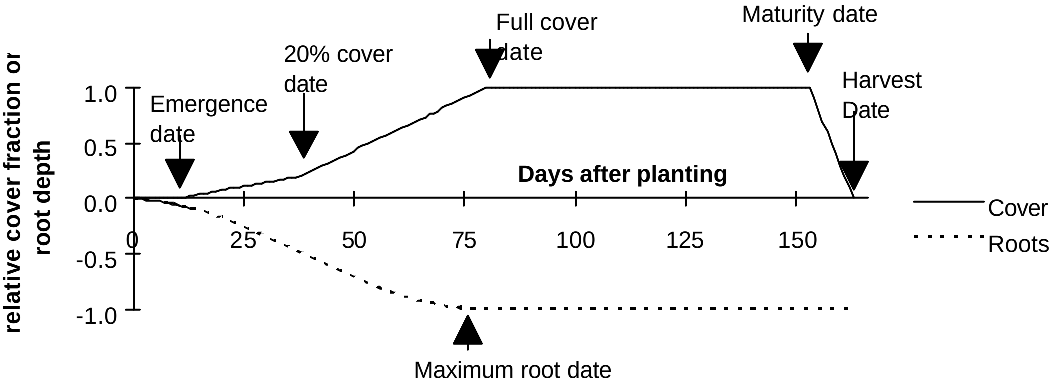

Figure 2. Crop cover and root depth development

2.2 Mulch cover fraction

The fraction of the ground covered by mulch each day is determined by;

$$M_i = (1 - C_i)\, M_0 \qquad (1)$$

where

M_i	cover fraction of mulch on day i
M_0	cover fraction of mulch at planting
C_i	cover fraction of crop on day i

i.e. the mulch is assumed to cover the entire surface areas, but M_0 reflects the permeability of the mulch.

2.3 Bare soil fraction

The fraction of the ground covered by bare soil each day is determined by;

$$B_i = 1 - M_i - C_i \qquad (2)$$

where

B_i bare soil fraction on day i

2.4 Ponding

If the water table reaches the soil surface, ponding occurs. Once ponding occurs, the surface is treated as open water and there is no transpiration or soil evaporation loss.

3. AVAILABLE WATER AND SOIL WATER DEFICIT

3.1 Root depth

The root depth on a particular day is calculated from;

Table 1 Calculation of root depth

Condition	Root depth
a) Planting date	r_0
b) Planting to maximum root date	$r_{i-1} + \Delta r$
c) Maximum root date to harvest	r_{max}
d) After harvest	0

where

r_i	root depth on day i, m
Δr	daily root growth, m
r_0	planting depth, m
r_{max}	maximum root depth, m

The root growth on a particular day is determined from a sigmoidal root growth curve (Borg and Grimes, 1986)

$$Dr = [0.5 + 0.5 * SIN (3.03 * (t_p / n) - 1.47)] * (r_{max} - r_0) \qquad (3)$$

where

t_p	time since planting, days
n	duration of root growth, days

The root growth is limited by the water table, but is not reduced if a water table rises into an established root zone.

3.2 Available water capacity

The total, and easily, available water capacity are calculated each day from;

$$TAWC = FC - PWP \qquad (4)$$

$$FC = q_{FC} * r_i * 1000 \qquad (5)$$

$$PWP = q_{PWP} * r_i *1000 \qquad (6)$$

$$EAWC = TAWC \; x \; p \qquad (7)$$

where

$TAWC$	total available water capacity of root zone, mm
EAWC	easily available water capacity of root zone, mm
FC	water content of root zone at field capacity, mm
PWP	water content of root zone at permanent wilting point , mm
θ_{FC}	volume water fraction at field capacity
q_{PWP}	volume water fraction at permanent wilting point
p	fraction of total available water that is easily available, dimensionless
r_i	root depth on day i, m

All soil parameters are weighted according to the fractions of the root zone in the top soil and subsoil where the physical characteristics may be different.

3.3 Root zone deficit

The soil water deficit of the root zone is calculated from:

$$SWD = (q_{FC} - q) * r *1000 \qquad (8)$$

where

SWD	soil water deficit of root zone, mm
r	root depth, m
q_{FC}	volume water fraction at field capacity, dimensionless
q	volume water fraction of root zone, dimensionless

4. INPUTS

4.1 Gross rainfall and irrigation

Gross rainfall on each day is read from the input data file and irrigation may be given, or determined by the model according to scheduling rules. The irrigation plan determines whether irrigation applications are subject to interception loss or not. For example, drip irrigation would not be subject to interception, whereas sprinkler irrigation would.

4.2 Interception loss

Net rainfall (or irrigation), i.e. that part not intercepted by the crop canopy and directly evaporated, is estimated from

$$P_n = P\,(1\text{-}C) + (a + b\,P)\,C \qquad (P > a)$$

$$P_n = P \qquad (P \text{ £ } a) \qquad (9)$$

where

P_n	net rainfall, mm
P	gross rainfall, mm
C	crop cover fraction (dimensionless)
a, b	empirical constants (dimensionless)

Thus, interception loss = $P - P_n$

4.3 Surface runoff

Surface runoff is comprised of two components; runoff due to intense rainfall (infiltration excess) and runoff due to saturated soil. As the rainfall data used to drive the water balance model is only available on a daily timestep, daily surface runoff due to the intensity of rainfall, R_1, is estimated using the US SCS Curve Number method,

$$R_1 = \frac{(P - 0.2s)^2}{(P + 0.8s)} \qquad (10)$$

where

R_1	surface runoff, mm d^{-1}
P	gross rainfall, mm d^{-1}
s	maximum storage for the given antecedent conditions, mm

The maximum storage, s, on a particular day is estimated from the storage at dry antecedent conditions, s_1, the relative saturation of the top 0.15 m of the soil and two weighting factors, W_1 and W_2. (Hawkins *et al*., 1985).

$$s = s_1\left(1 - \frac{f_s}{f_s + \exp(W_1 - W_2 f_s)}\right) \qquad (11)$$

f_s	relative saturation of the surface compartment, dimensionless
s_1	maximum storage under dry antecedent conditions, mm
W_1	weighting factor, dimensionless
W_2	weighting factor, dimensionless

$$f_s = q \big/ q_{sat} \qquad (12)$$

where

q	volume water fraction of surface soil
q_{SAT}	volume water fraction at saturation

W_1 and W_2 are weighting factors, calculated from the curve number for dry, N_1, average, N_2, and wet, N_3, antecedent conditions (Garen, 1996).

$$N_1 = \frac{N_2}{2.281 - 0.01281 N_2} \qquad (13)$$

$$N_3 = \frac{N_2}{0.427 + 0.00573 N_2} \tag{14}$$

where

N_n Curve number for antecedent condition n

and,

$$s_n = 250\left(\frac{100}{N_n} - 1\right) \tag{15}$$

where

s_n maximum storage under antecedent condition n, mm

then,

$$W_1 = \ln\left(\frac{1}{1 - {}^{s_3}\!/_{s_2}} - 1\right) + W_2 \tag{16}$$

$$W_2 = 2\left[\ln\left(\frac{0.5}{1 - {}^{s_2}\!/_{s_1}} - 0.5\right) - \ln\left(\frac{1}{1 - {}^{s_2}\!/_{s_1}} - 1\right)\right] \tag{17}$$

Surface runoff due to saturated soil, R_2, is calculated from;

$$R_2 = Pond + P - Pond' \tag{18}$$

where

R_2 runoff due to saturated soil, mm

P gross rainfall, mm

$Pond$ ponding depth, mm

$Pond'$ maximum allowable ponding depth, mm

Total surface runoff, R, is the sum of the two components.

$$R = R_1 + R_2 \tag{19}$$

5. OUTPUTS

5.1 Open water evaporation

Open water evaporation occurs only if there is ponded water on the surface. The rate of open water evaporation is proportional to the reference evapotranspiration;

$$Eo_i = ETo_i / Kp \qquad (20)$$

where

Eo_i open water evaporation on day i, mm

ETo_i reference evapotranspiration on day i, mm

Kp open water evaporation (pan) coefficient, dimensionless, = 0.80

5.2 Soil evaporation

5.2.1 Potential soil evaporation

The potential soil evaporation on any day is given by;

$$Eso_i = ETo_i \qquad (21)$$

where

Eso_i potential soil evaporation on day i, mm

ETo_i reference evapotranspiration on day i, mm

5.2.2 Actual soil evaporation

The evaporation from bare soil is calculated as a two stage process, following the method of Richie (1972).

Stage 1 starts on the first day after wetting[2] and lasts until a maximum cumulative evaporation, U. During stage 1, evaporation is limited by the atmosphere, therefore;

$$Es_i = Eso_i \qquad (22)$$

where

Es_i soil evaporation on day i, mm d^{-1}

During stage 2, evaporation is limited by the wetness of the soil, and the evaporation rate is determined from the time since wetting,

$$Es_i = a\, t_2^{1/2} - a\, (t_2-1)^{1/2} \qquad (23)$$

where

Es_i soil evaporation on day i, mm

a constant, mm $d^{-1/2}$

t_2 time since the start of stage 2, d

Methods used to calculate t_2 following partial wetting and adjustment of soil evaporation on rain days are given in Richie (1972).

---

[2] Wetting = rain in excess of potential soil evaporation.

5.3 Crop transpiration

5.3.1 Potential crop transpiration

The potential crop transpiration on any day is given by;

$$To_i = ETo_i * Kc_{max} \qquad (24)$$

where

To_i potential transpiration on day i, mm

Kc_{max} ratio of potential transpiration to reference evapotranspiration at maximum cover

5.3.2 Actual crop transpiration

Actual plant transpiration per unit area of plant, is assumed to occur at the potential rate whilst the root zone soil water content is between field capacity (FC) and the easily available water capacity (EAWC). For excess water, it decreases linearly to zero when the root zone soil water content reaches saturation (SAT). For restricted water supply, it decreases linearly to permanent wilting point (PWP) and remains zero thereafter (Figure 3). This has been shown to be an acceptable simplification for irrigated conditions (Brisson, 1998).

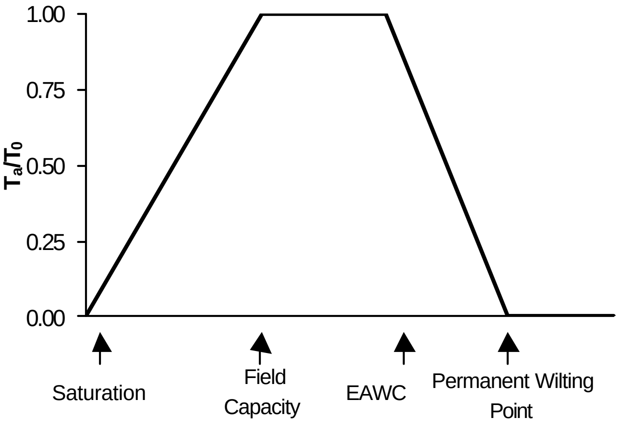

Figure 3. Relative plant transpiration as a function of soil water content.

Actual plant transpiration is then,

$$Ta_i = To_i \frac{Ta_i}{To_i} \qquad (25)$$

where

Ta_i actual transpiration on day i, mm

To_i potential transpiration on day i, mm

5.3.3 *Adjustment for available precipitation*

When rain falls on dry soil, a proportion of the rainfall will be readily available to the crop, even if the soil profile is at an otherwise limiting deficit. Therefore, a pool of ‘available precipitation’ is maintained in the soil that will be depleted preferentially, at the potential rate.

As the start of each day any rainfall or irrigation on that day is added to the pool of available precipitation,

$$P'_i = P'_{i-1} + P_i + \mathrm{I}_i \qquad (26)$$

During that day, all rainfall and irrigation will therefore be available at the potential rate. However, at the end of the day, the pool of available precipitation will have been depleted by an amount equal to the actual evapotranspiration. Also a fraction of the day’s rainfall and irrigation will have been redistributed through the soil profile and will be available at the limited rate. Thus, at the end of the day,

$$P'_i = P'_{i-1} + \frac{P_i + \mathrm{I}_i - ET_i}{2} \qquad (27)$$

where

P'_i	available precipitation on day i, mm
P_i	rainfall on day i, mm
I_i	irrigation on day i, mm
ET_i	actual evapotranspiration on day i, mm

The upper and lower limits of the pool of available precipitation are the easily available water capacity of the root zone and zero respectively.

Actual transpiration is adjusted for rain days and available precipitation by the following;

Condition	*Ta*	
$(Ta + P')\ ^{3}\ To$	To	
$(Ta + P') < To$	$Ta + P'$	(28)

where

Ta	actual transpiration, mm
To	potential transpiration, mm
P’	available precipitation, mm

5.4 Effect of salinity on crop transpiration

The impact of soil salinity on transpiration is simulated using the method of Allen *et al*. (1998).

$$K_s = \left(1 - \frac{bs}{100Ky}\left(ECs - ECs'\right)\right) \qquad (29)$$

where

Ks	transpiration reduction factor for salinity, dimensionless
Ky	yield response factor due to water stress, dimensionless
bs	reduction in yield due to salinity, % (dS $m^{-1})^{-1}$
ECs	Average electrical conductivity of saturation extract for the root zone, dS m^{-1}
ECs'	Threshold electrical conductivity of saturation extract, dS m^{-1}

Typical values of ECe', b and Ky are given in Allen et al. (1998).

5.4.1 *Partitioning of transpiration between compartments*

If the root depth is greater than the depth to the water table (i.e. part of the root zone is below the water table), all transpiration is assumed to take water from the capillary fringe, hence it is taken from the water table. Otherwise, plant transpiration is partitioned between the upper compartment (compartment 0) and the remainder of the root zone (compartment 1) in proportion to the depth of available water (i.e. in excess of permanent wilting point) in each compartment.

5.5 Evaporation from mulch

Evaporation is assumed to occur from the mulch cover only on days when it is wetted by rainfall or irrigation. Taking a maximum storage on the mulch surface of 2.0 mm, the following conditions are set;

Condition	Em
$(P + I) = 0$	0
$(P + I)$ £ 2	$P + I$ or ETo whichever is the smaller
$(P + I) > 2$	2.0 or ET_o whichever is the smaller

where

Em	evaporation from mulch cover, mm d^{-1}
ETo	reference evapotranspiration, mm d^{-1}

5.6 Actual evapotranspiration

If the soil is not ponded, the actual evapotranspiration from the soil is taken as the weighted average of actual crop transpiration, soil evaporation and evaporation of intercepted water from the mulch cover.

$$ETa = T_a \times C_i + E_s \times \left(1 - C_i - M_i\right) + E_m \times M_i \qquad (30)$$

where

C_i	crop cover fraction on day i, dimensionless
M_i	mulch cover fraction on day i, dimensionless

If the surface is ponded then

$$ETa = Eo_i \tag{31}$$

5.7 Drain flow

5.7.1 Flow to drains

The flow to the drains is a function of the mid-drain water table height (after Youngs *et al.*, 1989).

$$q_d = 1000 \frac{K}{\left(L/2\right)^b} \left(\left(\frac{f}{2} \right)^b - h^b \right) \tag{32}$$

where

q_d	flow to the drains, mm d^{-1}
K	saturated hydraulic conductivity, m d^{-1}
L	drain spacing, m
ϕ	ditch water level or drain diameter, m
h	mid-drain water table position, m above drain depth
β	exponent dependant on the depth to the impermeable layer, dimensionless

and,

$$b = 2 \left(\frac{d_0}{L/2} \right)^{\frac{d_0}{L/2}} \quad for \ \frac{d_0}{L/2} < 0.35 \tag{33}$$

$b = 1.36$ otherwise

where,

d_0	depth from the drain to the impermeable layer, m

5.7.2 Capillary rise

The maximum contribution of groundwater to transpiration, *Tgw*, and evaporation, *Egw*, are functions of the difference between the root depth (for transpiration) or soil surface (for evaporation) and the water table position and the hydraulic properties of the soil (Gardner, 1958).

If the water table is below half of the root depth, ($z > r / 2$) then

$$e = 1000\left(\frac{K}{\exp\left(c\left(z_w - \frac{r}{2}\right)\right) - 1}\right) \qquad (34)$$

where
e the potential contribution of groundwater to ET, mm d^{-1}
K saturated hydraulic conductivity, m d^{-1}
c empirical parameter, m^{-1}
r root depth, m
z_w depth to water table, m

If the water table is above half the root depth, the soil is not limiting and, e = 1000 mm d^{-1}.

The parameter, *c*, is a soil texture / structure parameter that represents the relative importance of gravity and capillary forces during water movement in unsaturated soil. Where movement is dominated by gravity, *c* is large and where movement in dominated by capilarity, *c* is small (Reynolds and Elrick, 1991, Pullan, 1990). As *c* is difficult to estimate, it has been related to the hydraulic conductivity of the soil (Gilbert, Pers. Comm.);

$$c = 8.85K + 2.72 \qquad (35)$$

where
c empirical parameter, m^{-1}
K saturated hydraulic conductivity, m d^{-1}

The effect of depth to water table (z – r/2) and hydraulic conductivity is shown in Figure 4.

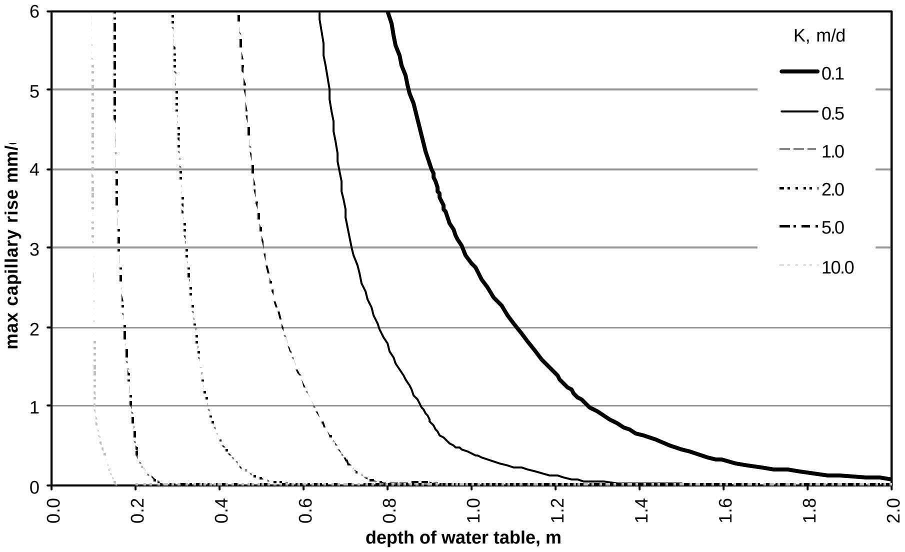

Figure 4 Maximum capillary rise in relation to depth from water table to mid-root zone and hydraulic conductivity.

The actual contribution from groundwater is the maximum of ET_{max} and ET_o. If the water table is above half the drain depth, all the transpiration is taken from the water table.

5.7.3 Additions to the water table from seepage

Seepage from irrigation canals, q_s, is assumed to supply a constant addition to the water table.

5.7.4 Losses from the water table due to tubewell drainage

Tubewell drainage, q_t, is assumed to extract water from the water table at a constant rate.

5.7.5 The net flux from the water table

The net flux from the water table is

$$V_s = E_{gw} + T_{gw} + q_t - q_u - q_s \qquad (36)$$

where

Vs	net flux from the water table to the root zone, mm d^{-1}
E_{gw}	contribution from water table to soil evaporation, mm d^{-1}
T_{gw}	contribution from water table to transpiration, mm d^{-1}
q_t	daily extraction by tubewells, mm d^{-1}
q_u	drainage from the lower unsaturated compartment, mm d^{-1}
q_s	daily addition from seepage, mm d^{-1}

5.7.6 Calculation of water table position

$$h_i = h_{i-1} - \frac{q_d + V_s}{1000m} \qquad (37)$$

where

h_i	height of the mid-drain water table position above drain depth on day i, m
q_d	flow to drains, mm d^{-1}
Vs	net flux from the water table to the root zone, mm d^{-1}
m	drainable porosity, dimensionless

and,

$$m = q_{SAT} - q \qquad \textit{for a rising water table} \qquad (38)$$
$$m = q_{SAT} - q_{FC} \qquad \textit{for a falling water table}$$

6. SOIL WATER RE-DISTRIBUTION

6.1 Drainage from compartment to compartment

If the volume water fraction of any compartment is brought above saturation any excess is assumed to be transferred to the compartment below immediately by drainage.

If the volume water fraction is between the field capacity and saturation then the drainage released from the compartment is calculated from (Raes and van Aelst, 1985);

$$q = t \left(q - q_{FC}\right)\left(e^{(q - q_{FC})} - 1\right) / \left(e^{(q_{SAT} - q_{FC})} - 1\right) \times 1000 mm/m \qquad (39)$$

where

q	drainage from compartment, mm / m of compartment thickness / d
τ	drainage constant, dimensionless
q	volume water fraction, dimensionless
q_{FC}	volume water fraction at field capacity, dimensionless
q_{SAT}	volume water fraction at saturation, dimensionless

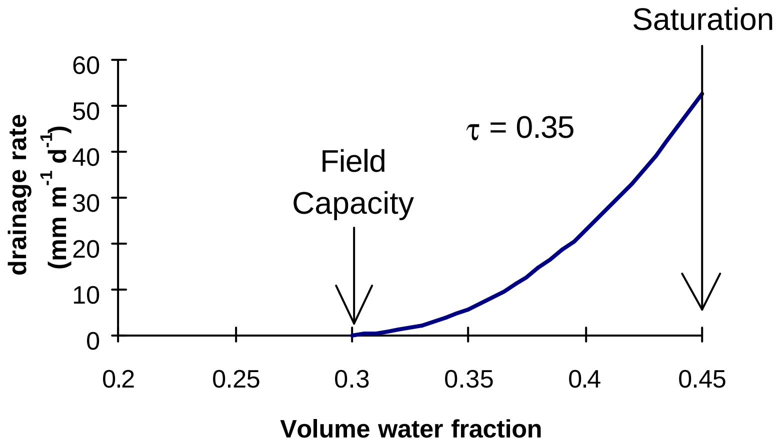

Figure 5. Example of drainage rate function

6.2 Soil water content

Store	Gains	Losses
Compartment 0	Effective rainfall & irrigation	Soil evaporation Plant transpiration Drainage
Compartment 1	Drainage from compartment 0	Plant transpiration Drainage
Compartment 2	Drainage from compartment	Drainage

	0 or 1	
Compartment 3	Drainage from compartment 1 or 2	Capillary rise Drain flow

6.2.1 Compartment 0

The soil water content of compartment 0 is calculated from the water content of the previous day, plus additions of effective rainfall and irrigation and minus losses of ET and drainage.

6.2.2 Compartment 1

The soil water content of compartment 1 is calculated from the water content of the previous day, plus additions of drainage from the surface compartment and the extension of the root zone into compartment 2, less losses due to evapotranspiration and drainage to compartment 2.

$$W_{1,i} = W_{1,i-1} + q_{0,i} + (r_i - r_{i-1}) * 1000 * q_{2,i-1} - Ta_{1,i} - q_{1,i} \qquad (40)$$

where

$W_{j,i}$	water content of compartment j on day i, mm
r_i	root depth on day i, m
$\theta_{2,i}$	volume water fraction of compartment 2 on day i
Ta_{j,i_i}	actual transpiration from compartment *j* on day i, mm
$q_{j,i}$	drainage from compartment *j* on day i, mm

6.2.3 Compartment 2

The soil water content of compartment 2 is calculated from the water content of the previous day, plus additions of drainage from above, less drainage out of compartment 2.

$$W_{2,i} = W_{2,i} + q_{1,i} - q_{2,i} \qquad (41)$$

where

$W_{j,i}$	water content of compartment *j* on day i, mm
$q_{j,i}$	drainage from compartment *j* on day i, mm

6.2.4 Volume water fraction

The volume water fraction of either compartment is calculated from;

$$q = W / z \qquad (42)$$

where

θ	volume water fraction of compartment, dimensionless

W water content of compartment, mm
z compartment thickness, mm

7. THE SALT BALANCE MODEL

The model is a salt mass balance of a one-dimensional profile with boundaries and compartments as for the water balance model (see page 1).

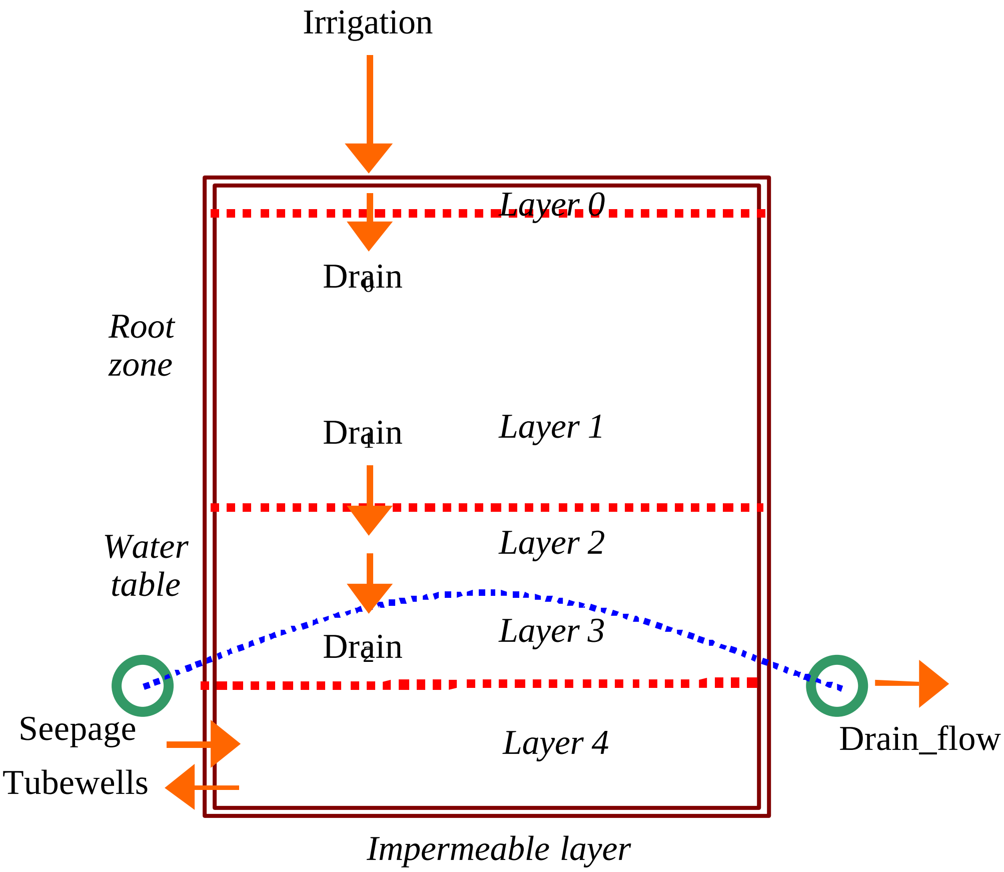

Figure 6 Overview of the salt balance model.

7.1 Inputs

The two inputs of salt to the systems are from irrigation water applied at the surface and seepage from canals. Seepage is assumed to contribute directly to the water table below drain depth. The daily input to the surface is calculated from;

$$S_I = I * EC_I \qquad (43)$$

Where

S_I	mass of salt added by irrigation water, mm dS m^{-1} d^{-1}
I	depth of irrigation water applied, mm d^{-1}
EC_I	electrical conductivity of irrigation water, dS m^{-1}.

The input from seepage is,

$$Ss = Qs * EC_I \tag{44}$$

where

Ss	mass of salt added by seepage, mm dS m^{-1} d^{-1}
Qs	depth of seepage, mm d^{-1}
EC_I	electrical conductivity of irrigation water, dS m^{-1}.

7.2 Outputs

The outputs of salt are in the drainage water and water pumped from tubewells.

The quality of the drain water is a weighted average of the water quality above and below the drain depth. The daily output from the drains is calculated from;

$$S_d = Q * (f * EC_4 + (1 - f) * EC_3) \tag{45}$$

Where

S_d	salt removed in drain water, mm dS m^{-1} d^{-1}
Q	drain flow, mm d^{-1}
f	fraction of drain flow from below drain depth, dimensionless
EC_j	electrical conductivity of soil water in compartment j, dS m^{-1}

Assuming that the hydraulic conductivity above and below the drains is the same, then,

$$f = \frac{8hd}{8hd + 4h^2} \tag{46}$$

where

h	height of the mid-drain water table above the drain depth, m
d	Hooghoudt's equivalent depth, m

and Hooghoudt's equivalent depth may be approximated from (Wesseling, 1979),

$$d = \frac{d_0}{1 + \left(\frac{8}{p}\frac{d_0}{L}\right)\ln\left(\frac{d_0}{\frac{1}{4}p f^2}\right)} \tag{47}$$

where

d_0	depth from the drain to the impermeable compartment, m
L	drain spacing, m
f	drain diameter, m

Salt remove by tubewell drainage is,

$$S_T = Q_T * EC_4 \qquad (48)$$

where

S_T	salt removed by tubewells, mm dS m^{-1} d^{-1}
Q_T	rate of pumping from tubewells, mm d^{-1},

7.3 Salt redistribution between compartments

The transfer of salt between soil compartments is driven by the transfer of water. A complete mixing model is assumed, such that;

$$S_{j,i} = S_{j,i-1} + Sd_{j-1,i} - Sd_{j,i} \qquad (49)$$

where

$S_{j,i}$	mass of salt in compartment j on day i, mm dS m^{-1} d^{-1}
$Sd_{j,i}$	mass of salt in the water leaving compartment j on day i, mm dS m^{-1} d^{-1}

$$Sd_j = q_j * EC_j * Le \qquad (50)$$

Where

Sd_j	mass of salt in the water leaving compartment $_j$, mm dS m^{-1} d^{-1}
q_j	rate of drainage from compartment $_j$, mm d^{-1}
EC_j	electrical conductivity of soil water in compartment $_j$, dS m^{-1}
Le	leaching efficiency, dimensionless

7.4 Electrical conductivity of saturation extract

The electrical conductivity of the saturation extract, *ECs*, is often used as a measure of soil salinity. The *ECs* of the unsaturated compartments is calculated from;

$$ECs = EC\frac{q}{q_{paste}} \qquad (51)$$

where

ECs	electrical conductivity of saturation extract, dS/m
EC	electrical conductivity, dS/m
q	volume water fraction, dimensionless
q_{paste}	volume water fraction of saturated paste, dimensionless

7.5 Target salinity

It is possible to increase irrigation to provide leaching to a target salinity. The irrigation requirement is calculated as follows;

Total salt in profile before irrigation (dSm^{-1} mm),

$$S = \sum_{i=2}^{i=0} S_i \tag{52}$$

where

S_i = salt in compartment i, dSm^{-1}

Water content before irrigation (mm),

$$WC = \sum_{i=2}^{i=0} WC_i \tag{53}$$

where

WC_i = water in compartment i, mm

Drainage (mm),

$$D = WC + I - (z.q_{FC}) \tag{54}$$

where

z = depth to drains, mm

q_{FC} = volume water fraction at field capacity, mm

I = Irrigation application, mm

Salt removed in drainage water (dSm^{-1} mm),

$$S_d = D\frac{(S + I.EC_w)}{(WC + I)}Le \tag{55}$$

where

Le = leaching efficiency, dimensionless

EC_w = electrical conductivity of irrigation water, dSm^{-1}

Salt remaining after irrigation (dSm^{-1} mm),

$$S' = S + I.EC_w - S_d \tag{56}$$

Electrical conductivity of soil saturation extract after irrigation (dSm^{-1}),

$$EC'_e = \frac{S'}{zq_{paste}} \tag{57}$$

where

q_{paste} = volume water fraction of saturated soil paste

Combining the above, the electrical conductivity of soil saturation extract after irrigation (dSm^{-1}),

$$EC'_e = \frac{S + I.EC_w - D\dfrac{(S + I.EC_w)}{(WC + I)}le}{z.q_{paste}} \qquad (58)$$

The initial estimate of irrigation requirement is set at the soil water deficit = $z.q_{FC} - WC$, and the irrigation amount is increased until EC'_e = target salinity.

8. GENERATION OF DEFAULT SOIL HYDRAULIC PARAMETERS

A range of soil hydraulic parameters are given in Rawls *et al.* (1982). Most of what follows is taken from that paper.

> θ_{sat} is the volume water fraction at saturation is taken to be the porosity given in Rawls *et al.* (1982).
>
> θ_{pwp} is the volume water fraction at permanent wilting point is taken to be the water retained at -15bar tension given in Rawls *et al.* (1982).

The field capacity volume water fraction and the drainage parameter, τ, were determined by simulation. A saturated soil was simulated and allowed to drain freely under gravity over a 20 day period (with a zero flux boundary at the soil surface) using the model SWATRE (Belmans, *et al.* 1983). In SWATRE, the soil hydraulic properties are represented by the parameters of the van Genuchten method (van Genuchten, 1980).

- θ_{sat} was taken from above.
- $\theta_{res} \approx$ zero.
- Saturated hydraulic conductivity was taken from Rawls *et al.* (1982).
- $a = 1/y_{bub}$ (59)
- where ψ_{bub} is the bubbling pressure given in Rawls *et al.* (1982).
- $n = l + 1,$ (60)
- where λ is the pore size distribution factor given in Rawls *et al.* (1982).
- $m = 1 - {}^{1}\!/_{n}$ (61)
- (van Genuchten, 1980)
- $L = m \times 2.5$ (62)
- (van Genuchten, 1980)

The values of τ and θ_{fc} were determined by optimisation and minimising the sum of the squares of the difference between the soil water content predicted by SWATRE and that predicted by;

$$q_i = q_{i-1} - dr_{i-1}, \text{ and,} \tag{63}$$

$$dr = t\ \left(q_{i-1} - q_{FC}\right)\left(e^{(q - q_{FC})} - 1\right) / \left(e^{(q_{SAT} - q_{FC})} - 1\right) \times 1000mm/m \tag{64}$$

where

dr_i	drainage on day i, mm / m
τ	drainage constant
θ_i	volume water fraction on day $_I$
θ_{fc}	volume water fraction at field capacity
θ_{sat}	volume water fraction at saturation

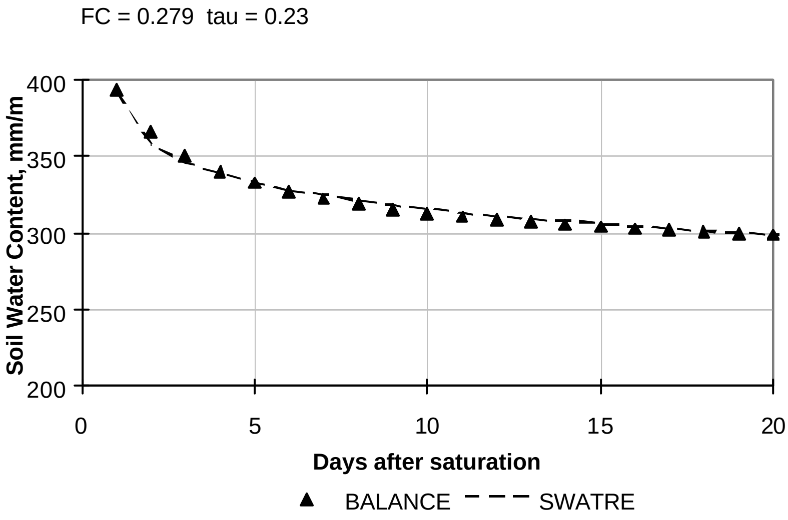

Figure 7 Example of fitted drainage parameters for a loam soil

Table 2 Default soil physical parameters

Texture Class	θ_{sat}	θ_{fc}	θ_{pwp}.	U mm	α	τ	N2	K_{sat}
Sand	0.437	0.115	0.033	10	3.5	0.69	67	5.040
Loamy Sand	0.437	0.168	0.055	10	3.5	0.51	67	1.464
Sandy Loam	0.453	0.245	0.095	10	3.5	0.37	67	0.624
Loam	0.463	0.279	0.117	10	3.5	0.23	81	0.312
Silt Loam	0.501	0.324	0.133	10	3.5	0.17	81	0.163
Sandy Clay Loam	0.398	0.241	0.148	10	3.5	0.17	89	0.103
Clay Loam	0.464	0.321	0.197	10	3.5	0.11	89	0.055
Silty Clay Loam	0.471	0.350	0.208	10	3.5	0.09	89	0.036
Sandy Clay	0.430	0.311	0.239	10	3.5	0.09	89	0.029
Silty Clay	0.479	0.371	0.250	10	3.5	0.08	89	0.022
Clay	0.475	0.368	0.272	10	3.5	0.06	89	0.014

REFERENCES

Allen, R., L. S Pereira, Raes, D and Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements, Irrigation and drainage paper 56. FAO, Rome.

Belmans, C., 1983. Simulation model of the water balance of a cropped soil: SWATRE. *J. Hydrol.* 63:271-286.

Borg, H. and Grimes, D. W,. 1986. Depth development of roots with time: An empirical description. Trans. ASAE 29:194-197.

Brisson, N., 1998. An analytical solution for the estimation of the critical available soil water fraction for a single layer water balance model under growing crops. Hydrology and Earth Science Systems, 2:221-231.

Gardner, W. R., 1958. Some steady state solutions of the unsaturated moisture flow equation with an application to evaporation from a water table. Soil Sci. 85:244-249.

Garen, D., 1996. "Technical description for logical module: Curve_Number_Parameters" and "Technical descripton for logical module: runoff." Draft chapters. Natural Resources Conservation Service, National Water and Climate Center, Portland, OR., USA.

Hawkins, R. H., Hjelmfelt, A. T. and Zevenbergen, A.W., 1985. Runoff probability, storm depth, and curve numbers. J. Irrig. and Drain. Engrg., ASCE 111(4):330-340.

Pullan, A.J., 1990. The quasilinear approximation for unsaturated porous media flow. Water Resources Research, 22:1219-1066.

Raes, D. D. and van Aelst, P., 1985. The field parameters of the BUDGET model. Internal note, Lab of Soil & Water Engng, University of Leuven, Belgium.

Rawls, W. J., Brakensiek D. L. and Saxton K. E., 1982. Estimation of soil water properties. *Trans. ASAE* 25:1316-1320

Reynolds, W.D. and Elrick, E.E., 1991. Determination of hydraulic conductivity using a tension infiltrometer. Soil Science Society of America Journal, 55:633-639.

Ritchie J. T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Res., 8:1204-1213.

van Genuchten M. Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Am. J.* 44:892-898.

Wesseling, J., 1979. Subsurface flow into drains. In, Drainage Principles and Applications. ILRI. 16 Vol.II pp1-56.

Youngs, E. G., Leeds-Harrison, P.B. and Chapman, J.M., 1989. Modelling water-table movement in flat low-lying lands. Hydrological Processes 3:301-315.

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