SALINITY EFFECTS ON GRAIN YIELD AND QUALITY OF MALT BARLEY IN IRRIGATED SOILS WITH WATER TABLES

by

VIRGINIA NEO MATHINYA

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Department of Soil, Crop and Climate Sciences

Faculty of Natural and Agricultural Sciences,

University of the Free State,

Bloemfontein, South Africa

Supervisor : Dr. J.H. Barnard

Co-Supervisor : Prof. L.D. Van Rensburg

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DECLARATION

I, Virginia Neo Mathinya, declare that the Master's degree research dissertation that I herewith submit for a Master's Degree qualification in Soil Science inter-disciplinary at the University of the Free State is my independent work, and that I have not previously submitted it for any qualification at another institution of higher learning.

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Signature Date

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ABSTRACT

Global water scarcity and salinity of irrigated lands remains a concern. Shallow groundwater tables, often present in irrigation areas, may serve as energy efficient water sources, but they also restrict leaching of salts, especially in arid and semi-arid regions where high evapotranspiration exacerbates salinity. This study aimed at assessing salinity effects on water use, grain yield and grain quality of irrigated malt barley in the presence of a shallow groundwater table.

The experiment was conducted over two seasons in lysimeters filled with a sandy Clovelly soil and a sandy loam Bainsvlei soil in which shallow saline groundwater table was maintained at a constant depth of 1.2 m. Cocktail barley cultivar was irrigated with five different irrigation water quality levels (EC_i), i.e. control, 450, 600, 900 and 1200 mS m^{-1} made up of six different salts in varying amounts. Salinity of the groundwater table corresponded to irrigation water quality. Soil water balance was calculated from soil water measurements and used to determine crop water use. Seasonal salt balance of the root zone was also monitored.

Saline irrigation water had cumulative effects on evapotranspiration, groundwater table depletion and grain yield as well as water productivity. Increasing irrigation water salinity from the control to the1200 mS m^{-1} EC_i reduced grain yield by 91 and 89% for the Clovelly and Bainsvlei soil types, respectively, in the second season. Relationship between grain yield and salinity was better explained by the Van Genuchten & Gupta (1993) (R^2=0.8) sigmoidal curve depicting the effect of EC_e on grain yield of barley to be non-linear.

Salinity (> 600 mS m^{-1}) decreased 1000 seed weight and had no significant effect on germination characteristics. However, grain nitrogen, protein and sugar contents were increased by salinity. Nitrogen significantly increased above the cultivar's inherent mean of 1.87%. Maltose was the only sugar not affected by both salinity and soil types. Increase in salinity reduced malt extract potential as indicated by lower (<7) germination index values for all treatments, seasons and soils with lower (<5.5) germination index values associated with the 900 and 1200 EC_i mS m^{-1} treatments. This outcome may hold direct impact on barley producers as a lower premium is offered for lower quality grains. Therefore, further research is needed to explore interactive effects of salinity and other abiotic stresses on grain quality and the influence of cultivar variations. Furthermore, subsequent financial impact on grain processors need to be assessed.

Key words: Irrigation water quality, shallow groundwater table, water productivity, soil salinity, malt barley, grain quality.

Chapter 1: Introduction

1.1 Background and motivation

Barley is a winter cereal crop ranking only second to wheat in small grains production in South Africa, and principally cultivated for the production of malt (BFAP, 2016). In South Africa production of barley takes place both under dry land farming in the winter rainfall areas of the Western Cape, and under irrigation in the Northern Cape (Douglas) and North West provinces (Taung) (SABBI, 2013).

A substantial portion of irrigated barley producing areas in South Africa have shallow groundwater tables within the potential root zone (Le Roux *et al*., 2007). These shallow groundwater tables are important mainly for three reasons. Firstly, barley is susceptible to water logging and poor drainage conditions (Setter *et al*., 1999; Assefa & Labuschagne, 2007). Secondly, shallow groundwater table soils are in many cases coupled with the occurrence of soil salinity through capillary rise (Wang *et al*., 2015). Thirdly, they lighten the burden on scarce irrigation water resources by significantly contributing towards crop water requirements (Ehlers *et al*., 2003; Ghamarnia *et al*., 2004; Ayars *et al*., 2006; Van Rensburg *et al*., 2012).

Currently only 5% of Africa's potential water resources are developed with an average per capita storage of 200 m^3, compared to 6 000 m^3 in North America (2030 WRG, 2009). This restricted water availability in arid and semi-arid regions of Africa, makes water the most limiting input for irrigated agriculture. The sustainable and economic strategy in irrigated agriculture is to use water with low salinity to foster good yields and quality produce. Unfortunately, this is not always easily achievable since high quality water for irrigation is very scarce (Ayars *et al*., 2006), thus increasing the potential for irrigation-induced salinization.

Around 831 million hectares (ha) of arable land worldwide (5 to 6% of the total land area) are salt-affected to various degrees (Munns & Tester, 2008). In South Africa, salt affected areas are estimated to be between 18 and 28% (Backeberg *et al*., 1996). Recently, Nell (2017) identified areas where waterlogging and salinization are likely (or unlikely) to occur using within-field anomaly detection method to monitor these processes over large areas. Monitoring was done using existing soil maps, terrain data and satellite imagery from which a much lower value of 6.27% was concluded. According to Nell (2017), the 6.27% translates into 94 050 ha that are salt affected and waterlogged on South African irrigation schemes.

Crop production on salt affected soils results in physiological and metabolic disturbances in plants, affecting development, growth, yield, and even quality of produce (Munns, 2002). Subsequently, producers of grains such as barley, may suffer a financial loss because maltsters reject barley grains that do not meet the required quality parameters for malting. Likewise, brewers and distillers of malt have set malt quality requirements. Malting is a process of controlled germination of cereals to ensure given physical and biochemical changes within the grain (Singh *et al*., 2012). Hence, selection of quality barley grains is crucial since all subsequent malting and malt-processing procedures are dependent on it. Grain quality parameters are therefore set to grade barley grains bought by maltsters to ensure that end products are produced in the most economical way possible (Gupta *et al*., 2010).

In 2015, only about 65% of malt barley could be sourced in South Africa (DAFF, 2015) due to production constraints, while the goal was to source 90% of this key ingredient locally (BFAP, 2016). To realize this goal, farmers need to be better equipped with comprehensive knowledge of resolving production challenges. Due to the limited water supply and the ensuing deterioration of its quality, efficiency becomes the key concept in formulating irrigation management strategies. Hence, the then SABMiller, now *Ab-InBev* (Mickle, 2016), had launched a programme (Better Barley Better Beer, 'BBBB'), which encouraged and supported responsible and sustainable farming practices focusing amongst others on reducing water use without sacrificing yield and quality (SAB, 2014).

In support of this effort, research studies have indicated that, properly managed deficit irrigation can help conserve water and reduce irrigation operational costs without significantly affecting barley yields (Bello *et al*., 2017). However, deficit irrigation does not allow for salt leaching beyond the root zone. Consequently, salts accumulates in the root zone threatening present and future malt barley yields and quality. In addition, deterioration of irrigation water quality aggravates the challenges of irrigation through water resource degradation (Du Preez *et al*., 2000), waterlogging (Houk *et al*., 2006) and salt accumulation (Lambert & Karim, 2002; Nagaz *et al*., 2008). Furthermore, irrigation water quality influences the leaching requirements of soils and should therefore be considered in irrigation management practices (Ben-Gal *et al*., 2008; Barnard *et al*., 2010).

With that being said, research regarding effects of irrigation-induced salinity on barley has mostly focussed on the impact on germination (Al-Seedi, 2008; Bagwasi, 2015), vegetative growth (Pessarakli *et al*., 1991; Grewal, 2010; Bagwasi, 2015) and total grain yield (Yazar *et al*., 2004; Dikgwathle *et al*., 2008). Therefore, research on the effects of salinity on grain quality of malt barley in South Africa and implications thereof for end users remains limited.

1.2 Objectives

The overall objective of this research was to investigate the impact of irrigation water salinity (EC_i) on grain yield and quality of malt barley, with the following specific objectives:

i) Quantify the effect of increasing EC_i on water use and grain yield of malt barley.

ii) Quantify the effect of increasing EC_i on grain quality characteristics of malt barley and the expected malt quality.

Chapter 2: Literature review

2.1 Introduction

Upon providing a brief overview of barley production in South Africa and its accompanying challenges, this review provides a summary of effects of salinity on soil chemical, physical and biological properties. Monitoring salinity through the salt and water balance concept is also explained. The review further looks into salinity effects on germination, vegetative and reproductive growth of barley. Additionally, the link between salinity and grain yield, and grain composition of barley is explored by briefly describing grain quality parameters as related to malt quality and their responses to saline conditions. Furthermore, this review highlights the impact of grain quality on malt quality and malt extract potential in the South African context.

2.2 Overview of barley production in South Africa

Barley is a short-seasoned, early maturing winter cereal crop. In different parts of the world, it is used as food for human consumption, feed for animals and for the production of malt. In South Africa, barley is primarily cultivated for malting purposes, as the feed market for barley is insignificant due to large volumes of maize production (DAFF, 2015). In its malted form, barley is a primary ingredient for brewers and distillers.

The main world producers of barley are the European Union (mainly Spain, Germany and France), the Russian Federation and Canada, together accounting for more than half of the world's barley production (DAFF, 2015). South Africa is not a major role player in the global barley industry and has very limited influence on the international market as it ranks 48th in terms of production (DAFF, 2015). However, in the African continent, Morocco, Algeria, Tunisia, South Africa and Egypt are the top five barley producers.

Barley ranks only second to wheat in small grains production in South Africa (SABBI, 2013). It is vital to South Africa's premier brewer, *Ab-InBev* (previously known as the South African Breweries Maltings (SABM)), one of the largest brewers by volume in the world (Mickle, 2016).

Currently, barley is cultivated across a wide range of geographical and climatic conditions in South Africa. Prior to 1997, barley production was exclusive to the winter rainfall areas of the Western Cape surrounding Caledon, Bredasdorp, Riviersonderend, Napier, Heidelberg and Swellendam. Since 1997, production has been extended to irrigation areas of the Northern Cape (Vaalharts, Douglas, Barkley west, and Rietrivier/ Modderrivier) and to small-scale farmers in the North West province (BFAP, 2016). The extension of barley production to the cooler central irrigation areas was necessitated by the unpredictable weather conditions in the

Southern Cape and was aimed at curbing yield fluctuations caused by total production in one geographical area. As per the guidelines for the production of small grains in South Africa (ARC, 2016), there are five cultivars (SabbiErica, SabbiNemesia, SabbiDisa, Agulhas and Hessekwa) recommended for dryland production and only four (Cocktail, Puma, Marthe and Cristalia) for irrigation areas until 2016. In 2017, the cultivars Cristalia and Overture were recommended cultivars for commercial production of malting barley under irrigation (ARC, 2016).

South Africa is a net importer of barley as not all cultivar and quality specifications required by maltsters can be grown locally (BFAP, 2016). Depending on the variability of climatic conditions during the growing season, only between 70 and 90% of locally produced barley grain is suitable for malting purposes. Therefore, malted barley is imported from Canada, the United States, Australia and Argentina to meet production requirements (DAFF, 2015).

The preferred less dependency on foreign imports (Visser, 2011) will only be possible if malting barley cultivars, suitable for local growing conditions and with the required quality specifications, could be produced locally. Therefore, it is imperative that growing conditions for malt barley be maximised to help secure potential yield and quality. It has been suggested that growing conditions associated with location, season, planting dates and environmental stresses such as soil moisture availability significantly affects grain composition and quality of malt barley (Fox *et al.*, 2003; Beckles & Thitisaksakul, 2014). Effect of a combination of some of these factors during grain filling are also known to be very detrimental (Bardner & Fletcher, 1974; Fox *et al.*, 2003). However, few studies have been done in this regard for South African malt barley cultivars.

2.3 Effects of irrigation water salinity on soil properties

Evapotranspiration (ET) process concentrates salts in the soil when pure water is evaporated from soil surfaces and transpired from crop leaves. Salinization of irrigated fields through ET and inadequate leaching changes inherent soil properties (Chaitanya *et al*., 2014). This change affects the ability of the soil to sustain crop production. Salinization is exacerbated by poor drainage quality, concentration of indigenous salts in the soil and a high groundwater table, moving salts high into the root zone and eventually to the soil surface (Horney *et al*., 2005).

Although salinity may be detected early by monitoring salt concentrations in both irrigation and drainage water, it only becomes a concern to crop producers after a noticeable decline in yields, which can be rather gradual (Chaitanya *et al*., 2014). Managing soil salinity requires knowledge of the magnitude, extent and distribution of the problem in the fields. Of importance is also the knowledge of the trend and changes of the problem over time (Barnard *et al*., 2010) detected by monitoring its effect on soil chemical, physical and biological properties.

In recent years, South African research into soil salinity has been satisfactory with the following areas fairly documented:

I. Quantifying salt balances for salinity assessment (De Villiers *et al*., 2003; Le Roux *et al*., 2007; De Clercq *et al*., 2010; Bugan *et al*., 2015)

II. Sustainability and guidelines for irrigation (Annandale *et al*., 2002; Van Rensburg *et al*., 2012)

III. Remote sensing to quantify salt affected soils (Ojo *et al*., 2011; Mashimbye, 2013; Vermeulen & Van Niekerk, 2016)

IV. Leaching and modelling (Matthews *et al*., 2010; Barnard *et al*., 2010)

V. Irrigation water quality (Du Preez *et al*., 2000; Van der Laan *et al*., 2012)

However, because traditional data collection methods such as soil surveys accompanied by laboratory analyses are time consuming and bear many inconsistencies, monitoring of waterlogging and salinization on a national scale for South African irrigation schemes has been at a disadvantage (Nell *et al*., 2015). Nonetheless, the current rise in the use of modern techniques such as direct and indirect remote sensing approaches holds a promise for the lacking periodic data in waterlogging and salinization monitoring at a national scale. Additionally, Ojo *et al*. (2011) deemed the recent development of the national monitoring system, SANSA, as a step in the right direction for addressing the issue. However, there is still a lack of research linking salinity effects to end users in terms of product quality. This is believed to be a result of the wide variability in texture and salinity status of South African soils in addition to the complex nature of salinity studies (Nell, 2017).

2.3.1 Effects on soil chemical properties

Electrolyte concentration, the type and amount of colloidal particles and cation composition of a soil influence the soil chemistry (type and amount of interaction between soil solution and the soil particles). Calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}) are the most common cations in arid and semi-arid areas (Chaitanya *et al*., 2014). Cations typically dominate the exchange complex of soils, having replaced aluminium (Al^{3+}) and hydrogen (H^{+}). Soils with exchange complexes saturated with Ca, Mg, and Na have a high base saturation and typically high pH values (Brady & Weil, 2008).

The common anions are chloride (Cl^-), sulphate (SO_4^{2-}) and carbonate (CO_3^{2-}). Anions influence soil properties directly and indirectly by increasing salinity and affecting affecting the exchangeable Na^+, Ca^{2+}, and Mg^{2+} ratios respectively. The presence of free electrolytes causes an increase in the ionic strength of the soil solution, which in turn, counteracts the dispersion of clay particles initially caused by repulsive forces because of the hydration of Na and net negative charge on the clay surfaces (Shainberg & Letey, 1984).

Acosta *et al.* (2011) found salinity to favour mobilization of heavy metals by competing for sorption sites at a pH above 7.5. Salinity increases water soluble cations and water dispersible clay thereby changing the chemical composition of soil water (Tedeschi & Dell'aquila, 2005). Additionally, alterations in soil chemistry have been known to affect plant nutrition by:

I. reducing phosphate (PO_4^{3-}) solubility and thus availability to the crop (Paliwal & Gandhi, 1976),

II. Na-induced potassium (K) deficiency (Botella *et al*., 1997) or Ca deficiency (Ehret *et al*., 1990),

III. Cl^- reducing nitrate uptake by crops (Kafkafi *et al.,* 1982) and

IV. Increasing the internal requirement and altering the distribution of nutrients in crops (Hu *et al*., 2007).

Therefore, in saline environments, yield benefits are unlikely from fertilization applications above recommended amounts.

2.3.2 Effects on soil physical properties

Soil physical properties are those related to the size and arrangement of solid particles, and how the movement of liquids and gases through soils is affected by the particles (Brady & Weil, 2008). A relatively high salt concentration in the soil solution essentially pushes adsorbed cations closer to the soil particles surface, keeping soil aggregates together through flocculation (Shainberg & Letey, 1984; Warrence *et al*., 2002). The net result of this aggregation is that pores between the soil aggregates will be relatively larger than in non-flocculated soil thus enhancing permeability. However, flocculation will not be favoured in the often-likely event that Na^+ is the dominant cation causing salinization of the soil.

High concentrations of Na^+ ions in the soil result in dispersion. Unlike Na^+, Ca^{2+} and Mg^{2+} were reported to be beneficial for the development and maintenance of soil structure (The U.S. Salinity Laboratory Staff, 1954). However, other studies have since pointed to the dispersive effect of Mg^{2+} (Shainberg *et al*., 1988; Basak *et al*., 2015). A reason for this was given as the smaller ionic radius of Mg^{2+} compared to Ca^{2+} (0.066 nm vs. 0.099 nm) and the subsequently larger hydration shell that increases the distance between particles of Mg^{2+}-saturated clay and decreases the inter-particle attraction. These characteristics are known to result in a double layer and an increase in dispersion.

Dispersed soil particles clog the pores when they settle out of solution and reduce the hydraulic conductivity of the soil. A sealed or crust layer then develops, which can lead to surface runoff and soil erosion (Shainberg & Letey, 1984; Tedeschi & Dell'aquila, 2005). Sodic conditions also affect important hydraulic soil properties such as infiltration and drainage rates, and aggregate stability.

Tedeschi & Dell'aquila (2005) investigated the long-term impacts of sodium chloride (NaCl) on soil physical and chemical characteristics of a clay-silty soil in an experimental farm in Vutilazio, Italy over a seven-year period. Drip irrigations of three saline concentrations of irrigation water (0.25 to 0.5 and 1% of NaCl) and two irrigation levels (100% and 40% replenishing of ET) were applied. The groundwater table ranged between 0-0.4 m in spring and 4 m in autumn depending on rainfall patterns, which had a salt leaching effect. Results showed that an increase in sodium adsorption ratio (SAR) from 0 to 50 (at electrical conductivity (EC) = 60 mS m^{-1}), decreased the aggregate stability index from 0.63 to 0.19. Emdad *et al*. (2004) had noted similar findings on a uniform clay loam soil.

Salinity reduces the effect of Na on soil physical properties through flocculation of clay particles. Although increasing salinity of the soil solution has a beneficial effect of enhancing soil aggregation (Shainberg & Letey, 1984), high levels of salinity have a negative effect on plants. Hence, one cannot merely increase salinity in order to maintain soil structure without considering the impact on plants.

Dispersion and flocculation phenomena are important factors determining soil hydraulic properties such as permeability, porosity and hydraulic conductivity (Al-Nabulisi, 2001; Emdad *et al*., 2004). Therefore, the disruption of soil hydraulic properties can make a soil either excessively dry or wet for long periods of time, which affects root development and crop growth. For example, Al-Nabulisi (2001) found that decreases in soil bulk density and infiltration rate were greater with saline drainage water irrigations, irrespective of the crop grown and the irrigation frequency.The colloidal dispersion caused by sodicity may harm plants in at least two ways: (I) Oxygen becomes deficient due to the breakdown of soil structure resulting in very limited air movement, and (II) water relations are poor due to the very slow infiltration rates. In addition, when irrigation water of low EC is used, the low structural stability of many semi- arid soils facilitates the dispersion, migration, and deposition of clay particles (Warrence *et al*., 2002).

2.3.3 Effects on soil biological properties

Both the chemical and physical responses of soils to salinity have been greatly explored over the years. However, the biological and biochemical components have only recently gained research attention. Microbial size, composition and activity has been the focus of that attention.

Generally, salinity is known to reduce soil water availability and therefore causes desiccation of microorganisms. It also alters the soil solution composition, affecting catalytic reactions needed for the survival of microorganisms. Some toxic ions in saline soils such as Na^+ and Cl^- may inhibit microbial growth directly (Singh, 2016).

Egamberdieva *et al*. (2010) found a significant impact of irrigation-induced salinity on soil biological properties. The authors sampled soils from long-term cotton monoculture fields with varying degrees of salinity (230, 560 and 710 mS m^{-1}). A 10 and 40% decrease in organic carbon (C) and extractable C, respectively, with an increase in soil salinity was found. The results showed a decrease in microbial biomass ranging from 18 to 42%. Rietz & Haynes had noted similar results (2003) were microbial biomass C, percentage of organic C present as microbial biomass C and indices of microbial activity were negatively exponentially related to EC.

Although other researchers have conducted similar research recently (Mavi *et al*., 2012; Yan & Marschner, 2013; Elmajdoub *et al*., 2014; Min *et al*., 2016), results have been rather contradictory concerning adaptability of microorganisms to salinity stress. Both increases and decreases in mineralization of C and nitrogen (N) have been reported. The contradiction is believed to be a result of differences in soil properties and environmental conditions (Muhammad *et al*., 2008). However, there is a consensus that salinity remains a stressful environment for soil microorganisms. The microbial and enzyme activities in saline and sodic soils were well reviewed by Singh (2016).

2.4 Water and salt balance in the soil

Soil receives water naturally from precipitation or artificially through irrigation. Upon contact with the soil surface under prevailing conditions, water may be absorbed through infiltration or fail to infiltrate the soil but instead accumulate at the surface or flow over it as surface runoff (Hillel, 2004). By calculating the soil water balance of the root zone on a daily basis, timing and depth of future irrigations can be computed (Chanasyk & Naeth, 1996), if the other components of the soil water balance are known.

2.4.1 Water balance

The soil water balance is based on the law of conservation of mass which states that the change in soil water content (ΔW, mm) of a root zone of a crop is equal to the difference between the amount of water added to the root zone (Q_i, mm) and the amount removed from it (Q_0, mm) (Hillel, 2004) in a given time interval (Equation 2.1):

$$\Delta W = Q_i - Q_0 \quad (2.1)$$

Water additions to and losses from the root zone are elaborately explained by Equation 2.2.

$$\Delta W = (I + P) - ET - D + U \pm R \quad (2.2)$$

Both irrigation (I, mm) and precipitation (P, mm) water that manages to infiltrate the soil may be (I) lost through evapotranspiration (ET, mm), (II) seep downwards beyond the root zone as deep drainage(D, mm) and eventually recharge the ground water reservoir or, (III) move from the groundwater through capillary rise into the root zone (U). Water not infiltrated into the soil is lost to runoff ($-R$, mm) or added as run-on ($+R$, mm) (Beltran, 1999; Zeleke & Wade, 2012).

Application of Equation (2.2) requires measurement or estimation of other parameters (Hillel, 2004). Several techniques are available to measure soil water content. A standard and direct procedure for measuring soil water content is the gravimetric method (Hillel, 2004). Soil water content is indirectly measured by a number of instruments ranging from neutron probe meters to automated capacitance, time-domain reflectometer (TDR) probes and electromagnetic induction (EMI) sensors (Brady & Weil, 2008).

Advantages of these instruments include the ability to measure soil water in all its three physical states with depth. Measurements can be done with ease and stored data can be automatically downloaded. They also allow measurements to be made repeatedly and non-destructively at the same site from which rapid changes in soil water can be detected (Brady & Weil, 2008).

Despite the versatility of these instruments, their application is limited due to their high capital requirements (Brady & Weil, 2008). In addition to human error, sources of error in these instruments exist, including instrument error, timing error and location error. Although these instruments are more popular than the direct method, they still require calibration done through the direct method (Edeh, 2017).

2.4.2 Salt balance

A salt balance is the concept of the relationship of the mass of salt entering and leaving the soil system (Beltran, 1999). It is derived by multiplying components of the water balance with their respective salt concentrations (Equation 2.3). However, the amount of salt added through precipitation and fertilization as well as salts precipitated at the soil surface and removed through uptake by crops are considered negligible in this equation.

$$\Delta S = Ic_i + Uc_u - Dc_d \pm Rc_r \qquad (2.3)$$

Where ΔS= change in salt content of the root zone (mg ℓ^{-1}), C_i= salt concentration of irrigation water (mg ℓ^{-1}), C_u= salt concentration of capillary water (mg ℓ^{-1}), C_d= salt concentration of drainage water (mg ℓ^{-1}) and C_r= salt concentration of surface flow (mg ℓ^{-1}).

As described by Thayalakumaran *et al*. (2007), the limitations of the salt balance concept are that "it does not describe the absolute amount of salt or the level of average salinity in a system". However, the salt balance concept is useful in managing soil salinity as it indicates a need for a shift in managerial strategies when the incoming salt becomes increasingly higher than the outgoing and leaving a high salt concentration in the soil.

A system with a net accumulation in the salt balance is considered to be at risk of salinization (Thayalakumaran *et al*., 2007). Salt leaching may be applied to such a system as a preventative or curative measure.

2.5 Salt leaching

Leaching is both a preventative and a curative measure that removes dissolved salts from the root zone aiming to prevent excessive salt accumulation in irrigated soils (Brady & Weil, 2008). Traditionally, additional irrigation required to leach salts and keep soil salinity below a level that would significantly reduce crop yield under steady-state conditions has been expressed as the leaching requirement (LR) (U.S. Salinity Laboratory Staff, 1954; Rhoades, 1997).

Salts play a role in the total charge of water and are measured as total dissolved solids (TDS), expressed as milligrams of salt per litre (mg ℓ^{-1}) of water. Electrical conductivity of irrigation water (EC_i) and TDS are directly proportional, and according to Ehlers *et al*. (2007), Equation 2.4 gives this relationship where Cf is the conversion factor.

$$TDS = EC \times Cf \qquad (2.4)$$

The exact value of the conversion factor depends on the ionic composition of the water. Therefore, for a more accurate computation of TDS, the conversion factor should be determined for specific conditions (Ehlers *et al*., 2007). Ehlers *et al*. (2007) has since determined this factor to be higher (7.831) than the 6.5 determined by the DWAF in 1996.

The amount of salts added (S, kg ha^{-1}) to the soil through irrigation can therefore be calculated as the product of EC_i, the depth of the cumulative irrigation (I, mm) over a growing season and Cf (Equation 2.5).

$$S = EC_i(Cf)(I) \quad (2.5)$$

Conversely, the dividend of this value and soil depth (z) gives the salt accumulation per mm rooting depth, which can be multiplied by 69.918 to obtain the estimated increase in the mean EC_{sw} (Electrical conductivity of the soil water) of the root zone (Equation 2.6).

$$EC_e = \frac{S}{(I)(Z)(Cf)} \quad (2.6)$$

This is based on the assumption that all of the salts added through the irrigation water will accumulate in the root zone and that the relative decrease in yield for any given crop is related to an increase in EC_{sw}. (Ehlers *et al.*, 2007).

The fraction of infiltrated water that must pass through the root zone to keep soil salinity within an acceptable level is referred to as leaching ration (LR). However, under field conditions, not all the extra amount of applied water passes through the root zone. Therefore, the fraction of infiltrated irrigation water that percolates below the root zone is called leaching fraction (LF). In the absence of effective rainfall to leach the soil, the *LR* must be calculated as the ratio of EC of irrigation water (EC_{iw}) to the EC of drainage water (EC_{dw}) (Equation 2.7) (Qadir *et al*., 2000).

$$LR = \frac{EC_{iw}}{EC_{dw}} \quad (2.7)$$

The *LF* is then calculated as a ratio of volume of drainage water (V_{dw}, mm) to the volume of infiltrating irrigation water (V_{inf}, mm).

$$LF = \frac{V_{dw}}{V_{inf}} \quad (2.8)$$

For example, EC_{dw} maximum allowable values are 200 mS m^{-1} for sensitive crops such as bean; 400 mS m^{-1} for moderately sensitive crops such as maize; 800 mS m^{-1} for moderately tolerant crops such as sorghum, and 1200 mS m^{-1} for tolerant crops such as barley (Maas & Hoffman, 1977).

Due to the functional relationship between EC_i and crop yield, *LF* is influenced by environmental factors and dynamic interactions within the soil– water–plant system (Letey *et al*., 2011).

Ben-Gal *et al*. (2008) found the *LF* to be highly influenced by plant feedback, as transpiration depended on root zone salinity. The higher the salinity level, the greater the relative benefit from increased leaching. The *LF* needed to maximize yields when irrigating with saline water may make such a practice highly unsustainable. Yurtseven & Demir (2004) concluded that effect of *LF* on ion leaching is highly influenced by ion type as increase in the *LR* caused increase in the leaching of Cl^- through the soil profile.

Optimal amounts of water required to efficiently leach excess salts was studied by Barnard *et al*. (2010). The lysimeter experiment leached salts from the root zone of maize irrigated with water of 750 mS m^{-1}. It was found that excess amounts of irrigation water (20% and 30% of the pore volume for sandy and loam soil respectively) were needed to efficiently leach 70% of the excess salts from the root zone. However, the experiment pointed to a lack of economic feasibility as the salinity of the soil solution approached EC_i only after leaching with a volume comparable to 90% of the pore volume of the soils. This finding was also highlighted by Blanco & Folegatti (2002) where *LF* and its management had no significant effect on soil salinization with time.

The *LR* approach is based on steady-state conditions that do not normally exist under most field situations and its applicability is therefore limited. Steady-state models assume that the salt concentration of the soil solution at any point in the soil profile is constant at all times and that ET is constant over the growing season. It also specifies that applied irrigation water is continuously flowing downwards at a constant rate, irrespective of irrigation frequency (Corwin *et al*., 2007).

Because steady-state flow analysis do not include a time variable, development of new models to address transient conditions came to be. These models incorporate temporal changes in crops; crop salt tolerance changes through the growing season, water salinity including rain, and the amount of irrigation and rain that are consistent with actual conditions including processes of salt precipitation and mineral weathering. Corwin *et al*. (2007) reviewed several of these models.

Corwin *et al*. (2007) reported that calculated *LR* was lower when determined using a transient-state approach than when using a steady-state approach. It is therefore empirical that the appropriate model be used to determine the *LR* for the benefit of both irrigation and salinity management.

Although leaching may also be achieved with saline water (Ahmed *et al*., 2012), the more sustainable strategy when managing irrigation for salt leaching is to use water with low salinity. However, the complex interactions involved in irrigation management with saline water requires the determination of the trade-off between allocating water for leaching vs. crop production. Matthews *et al.* (2010) developed a robust non-linear optimisation model to study the impact of deteriorating irrigation water quality on the economic efficiency of maize production under different irrigation water supply scenarios. The model allowed for explicit simulation taking the opportunity cost of water under limited water supply conditions into consideration as well as salinity of the soil solution and crop yield production. The model showed that in terms of time and location, there is an economic benefit of leaching by reducing the size of the irrigated area and allocating water for leaching.

2.6 Influence of the groundwater table

Apart from limiting leaching efficiencies, groundwater tables may be advantageous as a potential water resource for crops provided up-flow does not contribute to processes of soil degradation, such as salinization or acidification, nor limit crop growth through waterlogging (Streutker *et al*., 1981). This advantage was indicated by several studies showing that crops are able to extract as much as 60% of their water requirements from shallow groundwater tables (Table 2.1). However, crop benefits from subsurface water resources are shown to depend on crop type, soil type, depth to the groundwater table, groundwater salinity and climatic conditions (Wallendas *et al*., 1979; Ehlers *et al*., 2003; Ghamarnia *et al*., 2004; Ayars *et al*., 2006; Gowing *et al*., 2009).

Table 2.1: Groundwater table (wt) contributions towards crop water requirements

Crop	Growth conditions	Soil class	wt depth (m)	% Contribution	Source
Wheat	Controlled	Sandy loam	1	40	Gowing *et al*., 2009
	Field lysimeters	Sandy loam	1	63	Ehlers *et al*., 2003
			1.5	51	
Maize	Field lysimeters	Silty loam	0.58	18	Babajimopoulos *et al*., 2007
Sorghum	Lysimeters	Silty loam	1	10	Kahlown *et al*., 2005
Barley	Glass house lysimeters	Sandy silty loam	0.6	27	Hassan ,1990
			0.9	16	
			1.2	11	

When groundwater tables are very shallow, the rate of upward flow depends entirely on climatic conditions affecting ET from the soil. When the groundwater table is deep, upward flow is limited instead by soil properties. Ehlers *et al*. (2003) demonstrated this where capillary rise increased with an increase in the silt-plus-clay content of the soil.

It is estimated that shallow groundwater tables, in or just below the potential rooting depth of annual crops, can be found in at least 20% of irrigated soils in South Africa (Backeberg *et al.,* 1996). Mismanagement of shallow groundwater tables may contribute to salinization of the root zone and water logging (Streutker *et al*., 1981; Meyer *et al.,* 1994; Hornbuckle *et al*., 2005). When irrigation scheduling is adapted to enhance crop water uptake from shallow groundwater tables the risk of accelerating soil salinization is increased, because of less leaching and the accumulation of salts within the groundwater table (Ehlers *et al*., 2003). It is therefore advisable to monitor the salinity status of the soil on a continuous basis.

2.7 Barley growth in saline conditions

Response to stress is a complicated attribute of plants that is a result of interactive factors like physiology, morphology and chemistry (Munns, 2002). These interactions are difficult to accurately determine, making it difficult to scale salinity tolerance of crops. Salinity reduces the ability of plants to take up water, causing reductions in growth rate, along with a suite of metabolic changes identical to those caused by water stress. Agriculturalists define salt tolerance as the extent to which the relative growth or yield of a crop is decreased when the crop is grown in a saline soil, compared to its growth or yield in a non-saline soil (Munns, 2002). Crops can tolerate soil salinity to a given threshold, which is the maximum salinity level at which yield is not reduced. Beyond this threshold value, yield generally declines linearly as soil salinity increases.

2.7.1 Germination and emergence

Germination is a major factor limiting crop establishment under saline conditions. This is of particular importance in cereal grains, as they have been known to be more susceptible to salinity during germination and seedling establishment (Pessarakli *et al*., 1991; Lauchli & Grattan, 2007). Al-Karaki (2001) found that salinity reduced imbibition of barley seeds by close to 5% for each 100 mM increase in NaCl when the seeds were incubated with NaCl solutions. However, this approximate decrease was only noted after reaching a higher concentration of 100 mM NaCl.

Al-Seedi (2008) used a laboratory experiment with petri dishes to study salinity effects on germination and emergence of barley. Treatments were salt solutions prepared to give a concentration of 300, 600, 900, 1200 and 1500 mS m^{-1} of NaCl. Twenty-five seeds were germinated on a filter paper moistened with 5ml of each treatment and incubated at 25 ^{0}C. After five days, germinated seeds were recorded and the percentage of germination was calculated. The experiment showed that salt concentration levels of 600, 900, 1200 and 1500 mS m^{-1} of NaCl decreased germination percentage by 2, 3, 5 and 8% respectively when EC was above 300 mS m^{-1}. Compared to the control of distilled water, salinity levels of 300 and 1500 mS m^{-1} had high (100%) and low (92%) germination percentages respectively. These results were corroborated by Adjel *et al*. (2013) who noted a decrease from 86.0 to 50.9% in germination percentage with an increase in salinity from none to 150mM NaCl. Similar results had been noted by Al-Tahir *et al*. (1997) who recorded seedling emergence ranging from 96 to 100% for both canal (EC_i of 310 mS m^{-1}) and mixed waters (EC_i of 790 mS m^{-1}).

Bagwasi (2015) compared the response of South African spring wheat and South African spring barley at germination, seedling growth, vegetative growth, reproductive growth and maturity stage to irrigation induced salinity. The study was conducted both in the laboratory (Trial 1) and under controlled glasshouse conditions (Trial 2 & 3). Five EC_i levels of NaCl solutions (400, 800, 1200, 1600 and 2000 mS m^{-1}) and a control (0 mS m^{-1}) of distilled water were treatments for trial 1 & 2. Three wheat cultivars (SST 027, SST 056 and SST 087) and three dry land barley cultivars (Nemesia, Erica and Hessekwa) were used.

Trial 1 investigated the response of final germination percentage (FGP), salt tolerance (ST) and germination rate (GR) measured at 7 days after incubation. Results showed that FGP, ST and GR of all wheat and barley cultivars tested decreased with an increase in salinity. Notably, wheat cultivars had faster GR compared to barley cultivars and showed less sensitivity to salinity in the germination stage.

2.7.2 Vegetative growth

The process of plant growth involving cell division and expansion is greatly dependant on water. Cellular expansion takes place as divided cells absorb water. The process results in increased internal pressure called turgor. The absence of this pressure results in physiological drought, a condition of which plants are unable to take up water because the available water holds substances in solution, which impedes absorption (Munns, 2002).

In trial 2 of Bagwasi (2015), wheat cultivar SST 027 and barley cultivar SVG 13 were subjected to five EC_i levels of NaCl solutions (400, 800, 1200, 1600 and 2000 mS m^{-1}) and a control (0 mS m^{-1}) in pots and grown until the tillering stage. Shoot length (SL), root length (RL), shoot fresh weight (SFW), root fresh weight (RFW), shoot dry weight (SDW) and root dry weight (RDW) were measured at 35 days after planting (DAP). The study concluded that salinity had a significant effect on seedling growth for all measured parameters of both wheat and barley.

2.7.3 Reproductive growth

Lack of plant available water during the flowering and grain forming stages induce stomatal closure, rise in plant temperature and reduced photosynthesis in plants (Naseer, 2001; Bello *et al*., 2017). During grain filling, water stress leads to reduced translocation of photosynthetic assimilates to the developing grain and decreased yields.

Dikgwathle *et al*. (2008) found that at EC_i levels of 300 and 600 mS m^{-1} grain yield of wheat was reduced by 18 and 36%, respectively. Naseer (2001) also found significant reduction of barley grain yield of up to 46% when EC_i was 1600 mS m^{-1}. Similar results were noted by Bagwasi (2015) were salinity had a significant effect on the reproductive growth and grain yield of wheat and barley.

A field experiment by El-Desoky *et al*. (2007), evaluated effects of irrigation management treatments of saline ground water (EC of 536 mS m^{-1}) on barley grown on a sandy calcareous soil with an EC_e of 262 mS m^{-1}. Treatments were continuous irrigations of fresh water, alternation of fresh water and saline ground water and continuous irrigations of saline ground water. The study indicated that continuous irrigation with fresh water (EC_i of 61 mS m^{-1}) gives the highest yields for both straw and grain yield. Yield was reduced by up to 34% and 38% for grain and straw respectively when saline ground water was used for irrigation. From the study, it was noted that uptake of nutrients such as N, phosphorus (P), K and Ca by both straw and grain decreased with an increase in water quality deterioration.

2.8 Crop yields and salinity relationships.

The two barley studies (Ayers *et al*., 1952; Hassan *et al*., 1970) used by Maas & Hoffman (1977) when compiling the salt tolerance of agricultural crops are summarised below.

Ayers *et al*. (1952): Equal weights of NaCl and calcium chloride ($CaCl_2$) were used to obtain EC_i ranging from 800 to 2000 mS m^{-1}. This water was used to flood irrigate four varieties of barley and two varieties of wheat cultivated on 4 m by 4 m field plots. Soil heterogeneity was eliminated by mixing the soil with a bulldozer. The main observations of the study included:

I. Salinity delayed emergence by up to 5 days when EC_i was 1000 mS m^{-1}.

II. Crop establishment was minimally affected by salinity as it exceeded 98% across all treatments.

III. Salinity had minimal effect on the weight of the heads per unit area.

IV. Varietal differences were noted for all measured parameters.

The study was concluded with an important note that with a change in experimental locality, climate and variety, salt response could yield different results.

Hassan *et al*. (1970): Sodium sulphate ($NaSO_4$), magnesium sulphate ($MgSO_4$) and $CaCl_2$ were used to obtain eight levels of soil salinities ranging from 200 to 3000 mS m^{-1}. Barley seedlings grown in the greenhouse were thinned to 10 plants per pot containing silt loam soils. 75% of the treatment solution required to produce a given level of soil salinity was added three weeks after germination and the remaining 25% of the salt solution was added one week later. Distilled water was used for irrigation when soil moisture was below 50% field capacity. Soil analyses were made from composited air-dried soil material. The main observations of the study included:

I. Dry matter production decreased at salinities above 1200 mS m^{-1} with bigger decreases noted in grain heads and not stems and leaves.

II. There was a significant negative relationship between soil salinity levels and dry matter production.

III. Salinity decreased soil pH, which influenced the solubility and uptake of minerals in the soil.

IV. Uptake of Na, Mg, Mn and zinc (Zn) increased while the uptake of phosphorus (P), K, Ca, iron (Fe), and cobalt (Co) decreased.

The study concluded that, excess salts associated with salinity greatly influences the mineral nutrition and composition of crops cultivated on saline soils.

Although performed under different conditions, the two studies painted a similar picture of barley response to salinity stress. However, the authors concluded differently regarding the effect of salinity on the weight of the heads. Ayers *et al*. (1952) observed minimal effect of salinity on weight of the heads while Hassan *et al*. (1970) noted bigger decreases in grain heads with an increase in salinity. Salinity effects on grain composition and quality have since been elusive and not easy to conclude (Halford *et al*., 2015).

Nonetheless, Maas & Hoffman (1977) laid the foundation for salinity studies by establishing Equation 2.9 to calculate the effects of soil salinity on the relative yield of crops. This linear relationship between relative yield and soil salinity was also observed for relative yield and EC_i. Although the equation was formulated from results obtained under steady-state conditions with uniform salt distribution with depth and time, uniform water distribution achieved by flood irrigation, and unrestricted water supply, it has been the basis in many crop salinity studies.

$$Y_r = 100 - B(EC_e - A) \qquad (2.9)$$

Where *Yr* = Relative yield of the various crops grown under specific saline conditions compared to those crops grown under non saline conditions, EC_e = Electrical conductivity of the saturated paste (dS m^{-1}), *A* = Threshold value of EC_e (dS m^{-1}), starting point of yield decrease and B = Slope of the percentage yield loss due to surpassing threshold values.

With this linear equation, grain barley was shown to be able to tolerate soil salinity of 800 mS m^{-1} before any yield declines (Table 2.2). Accordingly, the same straight line is found with increasing EC_e as with EC_i. Maas & Hoffman (1977) acknowledged that this simple relationship does not always hold given the dependence of salinity tolerance on many plant, soil, water and environmental variables.

After the 800 mS m^{-1} threshold, grain barley yields are expected to decrease by 5.0% for every unit increase in salinity. Therefore, at EC_e of 1200 mS m^{-1}, relative yield of barley will be 80%. Pal *et al*. (1984) had noted that, if a criterion for uneconomic yield was 50% reduction from the potential yield, then barley could be grown successfully up to 1600 mS m^{-1}.

Table 2.2: Crop tolerance and yield potential of cereal grains as influenced by irrigation water salinity (EC_i) or soil salinity (EC_e) (Adapted from Ayers & Westcot, 1985)

	100%		90%		75%		50%		0%	
	EC_e	EC_i	EC_e	EC_i	EC_e	EC_i	EC_e	EC_i	EC_e	EC_i
	EC (mS m^{-1})									
Barley	800	530	100	670	130	870	1800	1200	2800	1900
Sorghum	680	450	740	500	840	560	990	670	1300	870
Wheat	600	400	740	490	950	630	1300	870	2000	1300
Rice	300	200	380	260	510	340	720	480	1100	760
Maize	170	110	250	170	380	250	570	390	1000	670

Problems associated with this linear model include the relatively poor definition of the salinity threshold value for data sets, which are poorly defined, erratic or have limited observations, and the inability to accurately reproduce many salt tolerance data sets at relatively high soil salinities (Van Genuchten & Gupta, 1993). Furthermore, as the model is variety-specific, and may depend, among other things, on the unique soil, environmental and water management conditions of an experiment, it holds limitations on extrapolation of threshold values. These shortfalls encouraged the development of the alternative S-shaped response model by Van Genuchten & Gupta (1993). The authors vouched for this dimensionless curve based on better description of experimental data and a more stable and unbiased statistical fit to many experimental data sets.

The curve is given by

$$y_r = \frac{1}{1+(\frac{c}{c_{50}})^p} \quad (2.10)$$

Where Y_r is the relative yield, c the average salt concentration of the root zone, and, c_{50} a parameter that describes the degree of salt tolerance of the crop (the average root zone salinity at which the yield has declined by 50%) while p is the empirical constant. This function has then been adapted for many salinity models including but not limited to the Analytical model (Shani *et al*., 2007), HYSWASOR (Dirksen *et al*., 2015) and ORYZA v3 and APSIM-Oryza (Radanielson *et al*., 2018).

Plants vary in their ability to tolerate different EC_e levels and yield decline starts at different salinity. This holds a direct impact on management decisions regarding the use of marginal soil and water resources as well as the modelling thereof.

2.9 Water use of barley in saline soils

Water infiltration into the soil is a key to crop production and salinity control. Normally, root cell solute concentration is higher than soil water solute concentration and this difference allows free water movement from the soil solution into the plant root. However, as the salinity of the soil solution increases, the difference lessens, making soil water less available to the plant (Ragab *et al*., 2008). Salts have an affinity for water, therefore, additional energy is required for the crop to extract water from a saline soil.

The process of soil water loss through ET depends on energy supply and interception, vapour pressure gradient and wind. Therefore, ET will differ with type of crop, crop development, environment and management practices. Small expanses of tall vegetation surrounded by shorter cover cause a "clothesline effect" where the interchange between air and vegetation is much more efficient than with the logarithmically shaped boundary layer profiles established over large fields and that are assumed in essentially all aerodynamically based ET equations. In these cases, ET from the isolated stands, on a per unit area basis, may be significantly greater than the corresponding ET_{ref} computation and will not represent large expanses (Allen *et al.,* 2011).

As the crop develops, visible changes such as percentage ground cover, crop height and the leaf area occur. Just as well, water use values change together with changes in crop growth phases or stages namely: tillering, stem extension, heading and ripening phase (Figure 2.1). The tillering phase extends from planting date to approximately 10% ground cover (Allen *et al*., 2011). During the initial period, the leaf area is small, and evapotranspiration is predominately in the form of soil evaporation. It is understood that the crop or plant can continue to grow in both height and leaf area after the time of effective full cover. As the crop develops and shades more and more of the ground, evaporation becomes more restricted and transpiration gradually becomes the major process.

The heading phase runs from effective full cover to the start of maturity. The start of maturity is often indicated by the beginning of the ageing, yellowing or senescence of leaves, leaf drop, or the browning of fruit to the degree that the crop evapotranspiration is reduced relative to the reference ETo. The ripening phase runs from the start of maturity to harvest or full senescence. The calculation for ETc is presumed to end when the crop is harvested, dries out naturally, reaches full senescence, or experiences leaf drop (Allen *et al*., 2011).

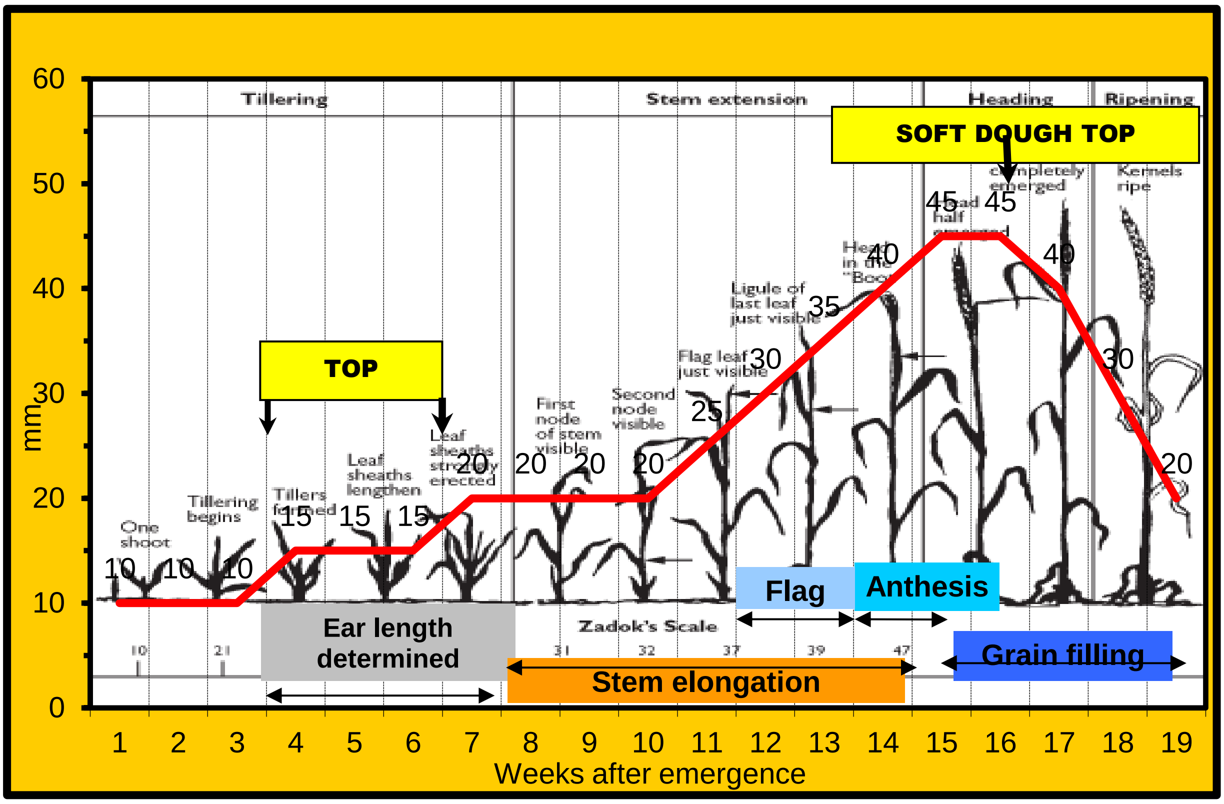

Figure 2.1: Water requirement of barley according to the growth phases (Kotze, 2018).

There is considerable scope for improving water use efficiency of crops by proper irrigation scheduling which is essentially governed by crop ET (Tyagi *et al*., 2000). However, partitioning of evapotranspiration (ET) into its components of evaporation (E) and transpiration (T) is difficult, although important for managing water losses under irrigated agriculture (Dlamini *et al*., 2017).

When managing water for irrigation, the concept of crop water productivity (CWP) referred to in older literature as water use efficiency (WUE), has also proven very useful (Zoebel, 2006).

It gives the relationship between the amount of marketable crop output and its water consumption as actual ET (Molden *et al*., 2010). Although its usefulness in agricultural water management has been questioned (Zoebel, 2006), it has also gained praises for the ability to help cab the gap between irrigation water supply and demand (Molden *et al*., 2010). A detailed review on salt and water dynamics in saline environments is available in Li *et al*. (2014). The review highlights the importance of efficient use of water to overcome the setback of decreasing tendency of water availability for irrigation purposes.

Hussain & Al-Jaloud (1998) noted variation in WUE of barley as influenced by irrigation water sources and application of N fertilizers. The highest WUE was 8.74 and 11.53 kg ha^{-1} mm^{-1} with well water and aquaculture effluent irrigations respectively. Ehlers *et al*., 2007 observed similar trends of a reduction in transpiration with an increase in EC_i for maize, wheat, beans and peas. The author attributed the trends to the osmotic effect that reduces the availability of soil water to crops. With that being said, the actual and practical feasibility of water productivity of barley under saline conditions is yet to be explored. Under increasing saline conditions, crop roots have to compete with salts for water. Salt accumulation in the soil also reduces the profile available water content over the growing season as was indicated through a simulation study by Barnard *et al*. (2015).

2.10 Growth promotion of salt stressed barley

In an elaborate review by Plaut *et al*. (2013), approaches to mitigate salinity effects in agricultural crops were broadly grouped into: (I) development of salt-tolerant cultivars by screening, conventional breeding or genetic engineering and, (II) the traditional approach dealing with treatments and management of the soil, plants, irrigation water, and plant environment. The review noted the limited success of the first approach because of the complex nature of salt-tolerance traits in plants.

The possible mitigation of salinity stress in barley through accumulation of compatible solutes has been investigated. The added solutes are believed to counteract the deleterious effects of Na^+ by lowering Na^+ and Cl^- uptake by the plants (Liang, 1999).

In a greenhouse study with two salinity levels (75 and 1300 mS m^{-1}) and five levels of K^+ (0, 0.2, 0.4, 0.6, and 0.8 g K^+ per pot as potassium chloride (KCl)), Endris & Mohammed (2007) found that K^+ applications significantly alleviated salinity stress and improved dry matter yield and yield components of barley. Other solutes such as manganese (Mn) (Pandya *et al*., 2005) and potassium nitrate (KNO_3) (Fayez & Bazaid, 2014) have been shown to be just as effective.

Gad *et al*. (2011) found an antagonistic relationship between Co and Fe in field grown salt stressed barley grown at varied concentrations of Co. Even so, Co had significant promotive effects on the growth and all yield parameters of barley. However, the promotive effect decreased with an increase in Co concentrations higher than 10 ppm. Ragab *et al*. (2008) also noted similar findings where increasing salinity caused nutrient imbalances in wheat grains. Silicon (Si) was found to have a positive effect on net photosynthetic rate of barley grown in a solution containing 120 mM NaCl ℓ^{-1} (Liang, 1999). Several studies have raised the possibility of increasing plants' salinity tolerance trough seed priming (Anwar *et al*., 2011) and inoculation (Bagheri, 2011).

2.11 Effect of salinity on barley grain quality

Halford *et al*. (2015) reviewed effects of abiotic stress and crop management on cereal grain composition and their implications for food quality and safety. The review noted that relatively fewer studies have researched the effects of abiotic stress on cereal grain composition since many have focused on general plant growth. It further went on to stress the limited research exploring the link in stress effects on grain quality and the implications for end users. Additionally, the review noted that most of the research in this regard has been done by plant breeders in single controlled environmental stress experiments. Therefore, little is known about whether the results of such experiments can be extrapolated to multifactorial and large-scale settings.

As with other cereal grains, like wheat (McGoverin *et al*., 2011), quality characteristics of barley are also influenced by both the environment and the biochemical components of the grain (Wang & Frei, 2011; Coventry *et al*., 2003). Exposure to saline environments induces osmotic stress (Munns, 2002) in barley that leads to intensified competition among grains for photosynthetic assimilates because of reduced leaf area (Coventry *et al*., 2003). This changes the source-sink relationship by intensifying the demand for source assimilate and thereby hindering grain development. Thitisaksakul *et al*. (2012) notes that the changes in starch biosynthetic enzyme activity of grains under salinity stress (as opposed to other abiotic stresses like drought and extreme temperatures) is still not fully comprehended and more research in this regard is needed.

When reviewing effects of environmental stress on starch composition and functionality in cereal endosperms, Beckles & Thitisaksakul (2014) noted that research in this area has been primarily focusing on heat, cold and drought stress. Only little effort has been put to understanding effects of salinity stress in endosperm composition. Additionally, available research in this regard has been widely directed to rice and triticale. Nonetheless exposure to stress leads to a number of physiological changes in crops including changes in the photosynthetic gas exchange; translocation of assimilates; water and nutrient uptake and translocation (Wang & Frei, 2011). Unfavourable growth conditions usually induce higher protein concentration in crop harvests. Although different stresses impose different physiological reactions in crops (Munns, 2002), the common negative effects on dry matter accumulation (accelerated leaf senescence and shortened grain development) is suggested as a main factor related to higher protein concentrations (Wang & Frei, 2011).

Accelerated leaf senescence remobilizes N from vegetative tissue and amino acids derived from protein degradation compensates for the stress-induced decrease in grain filling time and the N shortage due to a significant reduction of N uptake from soil by plant roots under stressed conditions (Clarke *et al*., 1990). Protein synthesis is less affected by stress than other components due to this enhanced amino acid remobilization; In contrast, carbohydrate synthesis in seeds depends primarily on concurrent carbon fixation during grain filling. Drought and salinity in general increases soluble sugar concentrations. However, concentration of sugars do not follow a stable model as it varies with genotype and stress factor (Rosa *et al*., 2009). This is because soluble sugar fluctuations under abiotic stresses also involve changes in CO_2 assimilation, in source-sink carbon partitioning and in activity of related enzymes as well as in the expression of specific genes.

In a greenhouse study, Izadi *et al*. (2014) investigated the effect of salinity on soluble protein content of four wheat ('Bam', 'Kavir', 'Hirmand', and 'Khalij') and four barley ('Nimrooz', 'Kavir', 'Jonoob', and 'Riehan 03') cultivars. The treatments included no salt (control), and two salinity levels, 700 and 1300 mS m^{-1} obtained by mixing NaCl and sodium sulphate ($NaSO_4$) in a 1:1 ratio. Seeds were sown 4 cm deep in a clay loam soil. From the study, protein content was shown to increase with an increase in salinity. It ranged from 6.8 to 13.4% in mealy grains and steely grains respectively. Variability among the barley cultivars and the wheat cultivars, as well as between barley and wheat was noted. The higher protein content in barley was believed to be one of the factors that offer barley the tolerance to saline conditions.

A greenhouse experiment was conducted by Bagheri (2011) to evaluate the effect of *Azosprillium brasilense* inoculation on barley grown in saline clay loam soil. NaCl was used to obtain four EC levels of 100, 500, 1000 and 1500 mS m^{-1}. Water-soluble carbohydrates content of the flag leaf at anthesis were extracted with 80% ethanol. Sucrose was measured by sucrose kit and the Kjeldahl digestion was used to determine the total N content of dry shoots. Results showed that grain weight was reduced by salinity. Al-Tahir *et al*. (1997) who found that 1000-grain weight was significantly reduced from 42.6 g to 38.8 g when ECi increased from 310 to 1400 mS m-1 had also noted this finding.

Another finding observed by Bagheri (2011) was the higher starch content in the inoculated treatments in comparison with the uninoculated one under salinity (435 mg g^{-1} DW and 340 mg g^{-1} DW respectively). Soluble saccharides were increased by salinity in the shoots. While fructan levels increased, sucrose levels were decreased by inoculation. Salinity effect on protein content was insignificant although the highest plant N was observed in the inoculated treatment under salinity condition. The study concluded that continuous growth in saline conditions could lead to acclimatisation and result in constant grain weight across treatments and only a little reduction in very high salinities. Similar results had been noted by Pal *et al*. (1984) were salinity increases significantly decreased the N content of barley that was grown on a sandy loam soil.

2.12 Barley grain quality for malting

A typical barley grain consists of the hull, endosperm and the embryo, making it a preferred cereal for malting (Holopainen, 2015). Its glumes and hulls are firmly cemented to the kernel and remains attached to the grain after threshing (Gupta *et al*., 2010). During processing for malt, the coleoptile grows and elongates under the protection of the hull (Singh *et al*., 2012). The hull also acts as a filter for separation of soluble materials during malting.

Barley grain composition affects malt-processing properties such as extract yield, colour, and aroma (Halford *et al.,* 2015). Therefore, various grain quality parameters have been defined by different end users for selecting barley with better malt quality to meet their needs (Yesmin *et al*., 2014). In South Africa, quality of malt barley is determined on a sliding scale with multiple intervals (GG 36587, 2013). Producers are rewarded for better quality grain and penalised for grain outside the required intervals.

The grain quality parameters for malting quality set out in the Production Guidelines for Small Grains in the Summer Rainfall areas of South Africa (ARC, 2017) are summarised in Table 2.3. Some of these grain parameters and their relation to malt quality are briefly discussed below.

1000 seed weight: Grains for malting are screened as they should be uniform in shape and size (Coventry *et al*., 2003) for consistent germination during processing (Kumar *et al*., 2013). Size and mass are the most readily identifiable characteristics of the grain, and large and plump kernels (indirectly indicated by the 1000 seed weight) have a higher proportion of endosperm or starch and are therefore preferred for malting as opposed to steely or flinty grains (Magliano *et al*., 2014). The malt extract potential from smaller grains is generally lower due to lower starch contents and higher protein levels.

Nitrogen content: This characteristic is both genetically and environmentally influenced and affects the quality of malt. The quality increases as the N content increases from 1.50% to 1.74%. The average N content is between 1.75% and 1.85%. The quality decreases as the N content increases from 1.86% to 2.00%. Grain N content is positively correlated to the enzyme content of malt and negatively correlated to extract yield and should therefore be maintained within the specified range (Table 2.3) to preserve malt quality (Agu *et al*., 2007; Magliano *et al.,* 2014). Once determined, the N content of the grain can be multiplied by a factor of 6.25 to give the crude protein content (Dendy & Dobraszczyk, 2001).

Protein content: Protein content is an important determinant of grain quality with a highly complex interaction with malt quality (Li *et al*., 2008; Halford *et al*., 2015). A high protein content grain yields a low malt extract and negatively affects the malting process by slowing down imbibition during steeping (Fox *et al*., 2003). However, grains with a very low protein content result in a lack of enzymes necessary for malting and brewing. Soluble protein content was shown to cause the most variation (79%) in malt extract yield under different modification levels (Li *et al*., 2008).

Carbohydrate concentration: Malt extract is influenced by the starch content of the grain. It is of great economic importance as it indicates the cultivar's potential for beer yield (Fox *et al*., 2003).

Table 2.3: Barley grain evaluation parameters for malting (Dendy & Dobraszczyk, 2001; GG 36587, 2013; GTA, 2014)

Parameter	Limits
Endosperm appearance	Mealy & floury not steely
Germination %	> 97% after 3 days
Germinative capacity	Min 98%
Germinative energy	Min 95%
Grain nitrogen content:	1.5 – 2.0%
Protein	> 9% < 11.5% (N * 6.25)

Endosperm texture: Endosperm is a major part of the grain and its texture and chemical composition is directly related to malt quality (Ferrari *et al*., 2010). Steely grains are high in protein content and display a slower rate of water infiltration and distribution at the steeping stage during malting. This results in slower modification (overall enzymatic action in the endosperm) rate during malting (Figure 2.2).

Studies have indicated that steely grains are excessively nitrogenous and they therefore erratically acquire rootlets and shoot growth during malting, resulting in malting losses (Chandra *et al*., 1999; Beckles & Thitisaksakul, 2014). As a result they malt un-homogeneously and achieve a low degree of modification during malting (Ferrari *et al*., 2010). On the other hand, mealy grains allow rapid imbibition and uniform hydration of the endosperm, resulting in quicker and more uniform modification.

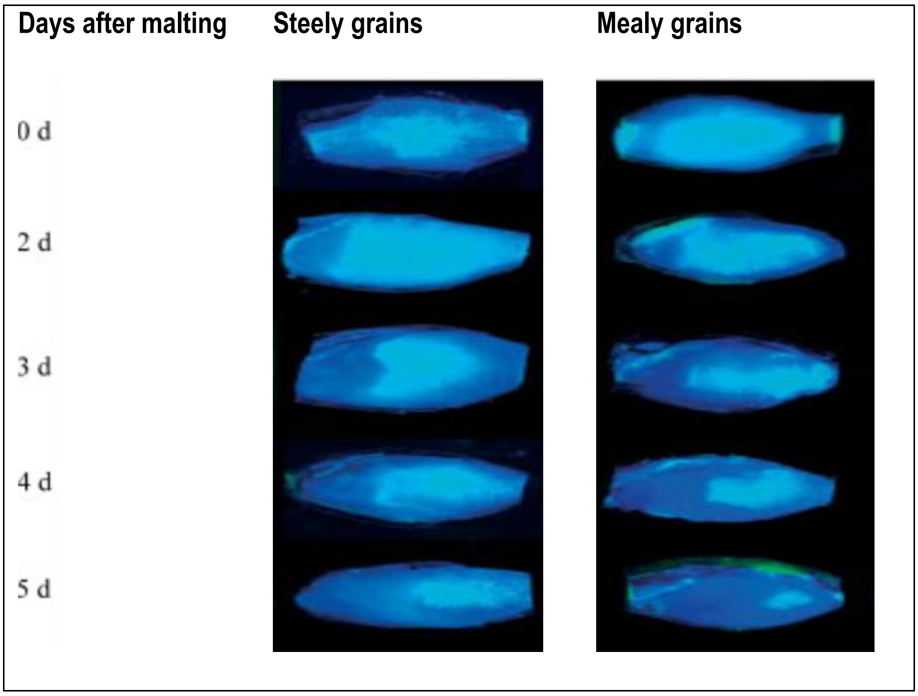

Figure 2.2: Extent of grain modification in steely and mealy samples (Adapted from Ferrari *et al*., 2010).

2.13 Malt extract potential of barley

Malt extract is perhaps the most important malt quality parameter for maltsters and brewers when selecting or purchasing malting barley. Literature notes few equations useful in determining and predicting malt extract potential yield (Blazewicz *et al*., 2007; Li *et al*., 2008; Francakova *et al.,* 2012).

Malt extraction potential can be calculated by the Bishop's equation where the extract potential (E) is given by the relationship between the total nitrogen content of the grain (TN, % dry weight) and the weight of a 1000 kernels (TKW) (Blazewicz *et al*., 2007).

$$E = A - 11.0TN + 0.22TKW \quad (2.11)$$

Varietal constant (A) represents the capability a particular variety has for achieving good extract. Maltsters read hot-water extract in litre-degrees per kilogram (E x 2.96 = l°kg^{-1}), expressing how many litres of wort each kilogram of malt will yield.

Li *et al.*, 2008 concluded that, under the same modification level, barley protein (Pr), TKW, and diastatic power (DP) explains about 74.3% of variation in extract yield (E). Therefore, the predicted extract equation takes the form:

$$E = 89.3 - 1.64Pr + 0.16TKW + 0.019DP \qquad (2.12)$$

Francakova *et al.* (2012) determined that germination index (GI) (Equation 2.13) is a good physiological parameter to predict the malting potential of barley as it was significantly positively correlated to the malt extract yield (r = 0.57). High values of GI indicates high quality and homogeneity of malt (Francakova *et al.,* 2012).

$$GI = 10[\frac{n_{24}+n_{48}+n_{72}}{n_{24}+2n_{48}+3n_{72}}] \qquad (2.13)$$

Where:

n_{24}, n_{48}, n_{72} – numbers of germinated kernels at 24, 48, and 72 h.

In South Africa, the malt extract calculator based on the total soluble nitrogen (TSN) of malted barley is used (Appendix 1). Drawbacks of such a calculator is that, a sample must be malted first for the potential extract to be calculated. Therefore, GI could work best when extract predictions must be based solely on grain quality characteristics.

As grain quality standards determines the malt yield and quality, malt quality in turn determines its potential to use for different purposes (Li *et al*., 2008). Malts with high extract yield values are essential to increase the efficiency of brewing and it therefore makes sense that the malt extract yield that a cultivar can produce will always be of crucial economic importance. Hence, maltsters supply malt to brewers and distillers, each with set characteristics for quality. Therefore, “quality" can often be entirely determined by the specific needs of a particular end user (Kumar *et al*., 2013).

2.14 Conclusions

While trying to produce quality barley required by maltsters, farmers are faced with the challenge of very limited water resources that are not even of desirable quality. Research has indicated that, that situation can be lightened by incorporating groundwater tables as additional water sources. Properly managed deficit irrigation has also been shown to help save water and reduce irrigation costs without significantly affecting barley yields. However, mismanagement of these water saving techniques leads to waterlogged and saline conditions.

Together with irrigation water quality considerations, soil indicators and crop growth may be used to estimate the possible extent of salinization and expected decrease in yields may also be calculated according to crop's salinity threshold values.

Barley and hence malt, are derived from living materials and so are subject effects of genetic and environmental variations. Therefore, achievement of malt specifications will not only depend on the maltster's expertise but on the environment under which the barley grains were produced as well.

Although salinity effects on growth and yield of barley are well documented, knowledge of effects of saline environments on grain quality of malt barley remains sketchy. This includes the possible interaction of salt stress with other stressful conditions such as waterlogging, drought and heat stress on barley grain composition for malting. It is therefore imperial that influence of such environmental factors on grain quality be investigated. The aims of this study therefore seek to bridge this gap in knowledge

Chapter 3: Effect of saline irrigation water and shallow groundwater tables on malt barley water-use and grain yield

3.1 Introduction

Shallow groundwater tables within or just below a potential root zone of 2 m contributes positively to crop water use in semi-arid climates provided capillary rise does not lead to soil degradation by salinization or acidification, nor limit crop growth through waterlogging (Streutker *et al*., 1981). Capillary rise from shallow groundwater tables bring dissolved salts into the root zone that remain behind when evapotranspiration (ET) occurs (Wallendas *et al*., 1979; Ehlers *et al*., 2003; Ghamarnia *et al*., 2004; Ayars *et al*., 2006; Gowing *et al*., 2009). Saline irrigation water (EC_i) also add salts to the root zone thereby exacerbating the salinity problem that decreases crop growth and yield.

Since salt movement in the soil is primarily in solution, its distribution in the profile is dependent on the water flow gradient (Hillel, 2004). High solute concentration gradient causes dissolved salts to move behind the wetting front of infiltration water. When groundwater tables are very shallow (Ayars *et al*., 2001), the capillary or upward flux depend entirely on climatic conditions determining ET. When the groundwater table is deep, upward flow is limited instead by soil properties (Salama *et al*., 1999; Ehlers *et al*., 2003, Mengistu *et al*., 2017). The clay plus fine silt content is one of the soil physical parameters influencing capillarity (Bennie, 1994). Capillary rise from groundwater and subsequent ET result in the build-up of salts in the topsoil. As such, salt accumulation, movement and distribution in soil profiles vary with the depth of groundwater table, soil type, and salt composition (Ehlers *et al*., 2003; Ayars *et al*., 2006). On irrigated fields, salt distribution would also depend on mode of water application, depth of infiltrated water and water quality (Le Roux *et al*., 2007).

Saline environments are detrimental to crop growth and development. Increasing salts in the root zone may expose crops to physiological water-stress and possible wilting even when supplementary water of higher quality is provided (Munns & Tester, 2008). The water-stress is induced by the affinity of salts to water, which reduce the soil solution osmotic potential and profile available water (Barnard *et al*., 2015). To counteract the lower osmotic potential, plant tissues respond by mobilising organic and inorganic solutes (Pessarakli *et al*., 1991). Such physiological adjustments are energy intensive and under persistent saline conditions may result in stunted crop growth and development (Chabbra, 1996).

According to the internationally accepted salinity threshold values developed by Maas & Hoffman (1977), an initial decrease in grain yield of malt barley is to be expected when the electrical conductivity of the saturated paste extract (EC_e) is 800 mS m^{-1}. After this threshold, a 5% linear decline in yield can be expected with every unit increase in salinity on a homogeneous freely drained silt-loam profile. The limitations of the linear model as acknowledged by Maas & Hoffman (1977), led to a proposed alternative *S-shaped response model* by Van Genuchten & Gupta (1993). The authors vouched for this dimensionless curve due to its better description of experimental data and a more stable and unbiased, statistical fit. Both the linear and sigmoid functions have been adapted for a number of salinity models including but not limited to the *SWB* (Annandale *et al*., 1999); *SALTMED* (Ragab *et al*., 2005); Analytical *model* (Shani *et al*., 2007); *HYDRUS* (Simunek *et al*., 2008); *SWAMP* (Bennie *et al*., 1998; Barnard *et al*., 2015); *HYSWASOR* (Dirksen *et al*., 2015) and *ORYZA v3 and APSIM-Oryza* (Radanielson *et al*., 2018).

Given the ever-changing cultivar developments and improvements as well as the heterogeneity of soils especially in arid and semi-arid regions in Southern Africa, it is critical to find a function that properly predicts yield responses to salinity. Additionally, the likelihood of salinization of both water and soil resources in arid and semi-arid regions deems this investigation necessary. The main objective of this chapter is therefore to determine the effect of increasing EC_i on water use and grain yield of malt barley in the presence of a saline shallow groundwater table. The chapter has the following specific objectives: Firstly, to quantify the effect of EC_i on ET, groundwater table depletion (WTD) and grain yield of barley and secondly, to determine the relationship between relative grain yield and EC_e, thirdly, to assess crop water productivity as influenced by irrigation water salinity.

3.2 Materials and methods

3.2.1 Description of the experimental site

The trial was conducted at the lysimeter facility of the Department of Soil, Crop and Climate Sciences, University of the Free State at Kenilworth near Bloemfontein (29°01'00"S, 26°08'50"E), South Africa. This facility was constructed in 1999 to study the contribution of root accessible groundwater tables towards the irrigation requirements of crops (Ehlers *et al*., 2003). The facility covers an area of 70 m x 35 m and consists of 30 round plastic lysimeters (2 m deep and 1.8 m in diameter) set out in two parallel rows of 15 each with their rims 5 cm above the soil surface (Figure 3.1).

Figure 3.1 Layout of the lysimeter facility of the Department of Soil, Crop and Climate Sciences, University of the Free State at Kenilworth near Bloemfontein (29°01'00"S, 26°08'50"E), South Africa as set out by Ehlers *et al.* (2003).

During construction each lysimeter was lined with a layer of gravel, covered with a plastic mesh and filled with apedal soils of the Clovelly (orthic A / yellow-brown apedal B / unspecified) and Bainsvlei (orthic A / red apedal B / soft plinthic B) forms (Soil Classification Working Group, 1991) or Quartzipsamment and Plinthustalf, respectively (Soil Survey Staff, 2003). Particle size distribution of these soils was carried out using the pipette method of Day (1965) by Ehlers *et al*. (2003) and the results are shown in Table 3.1.

Table 3.1: Particle size distribution of the two soils located in the lysimeters for different depths

Form	Soil depth (mm)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
Clovelly	0-300	1.3	10.7	79.0	4.0	5.0
	300-600	1.4	25.5	65.0	3.0	5.0
	600-900	1.4	25.6	65.0	3.0	5.0
	900-1200	1.4	25.6	65.0	3.0	5.0
	1200-1500	1.4	25.6	65.0	3.0	5.0
	1500-1800	1.4	25.6	65.0	3.0	5.0
Bainsvlei	0-300	0.3	6.4	83.3	2.0	8.0
	300-600	0.2	4.1	77.8	4.0	14.0
	600-900	0.1	3.5	78.4	4.0	14.0
	900-1200	0.1	5.7	76.2	4.0	14.0
	1200-1500	0.1	5.1	70.8	4.0	20.0
	1500-1800	0.2	5.2	70.7	4.0	20.0

An underground access chamber (1.8 m wide, 2 m deep and 30 m long) allows access to the inner walls of the lysimeters. Each lysimeter is equipped with two neutron probe access tubes, while an opening at the bottom is connected to a manometer and a bucket to recharge and regulate the depth of the groundwater table. The groundwater table depth was maintained at 1200 mm by recharging daily the constant head device with water of the same EC as the irrigation water. Water table depth was maintained at 1200 mm because Saline ground water tables occurring at depths between 600 and 1200 mm under irrigated conditions are common among the windblown sandy soils of the central Free State province, underlying a restrictive horizon forming a perched water table during drainage or under irrigation (Hensley *et al*., 2007).

Five 2500 ℓ reservoirs were used to mix irrigation water of different salinity classes. A tap from each reservoir was installed below ground to recharge the groundwater tables. The lysimeters were protected from rainfall events with a movable shelter to prevent any dilution of the soil solution during rainfall events.

3.2.2 Climate

Bloemfontein area is classified as semi-arid with a mean annual rainfall of approximately 543 mm and an aridity index of 0.23 (Bothma *et al*., 2012). The closest weather station with available recorded data for the two seasons (2015 and 2016) was Bloemfontein-Glen station (Comp. no. 30144) with a latitude of -28.9°29’57”S, longitude of 26.3°26’33”E and altitude of 1227 m. Data from this station is summarised in Table 3.2.

Table 3.2: Monthly mean minimum (Tn) and maximum (Tx) temperatures, reference evapotranspiration (ET_0) and minimum (RHn) and maximum RHx relative humidity for the first (S1) and second (S2) season

	Tn (˚C)		Tx (˚C)		ET_0 (mm)		RHn (%)		RHx (%)	
Month	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
July	2.2	0.8	19.5	18.3	2.5	4.2	24.1	24.8	78.7	79.4
August	4.1	3.2	25.6	22.6	3.6	5.2	12.5	10.2	60.1	51.7
September	8.3	6.9	27.4	26.4	4.5	7.1	18.0	15.0	70.9	64.2
October	12.7	9.8	33.0	30.0	5.9	7.9	10.6	12.4	64.2	60.4
November	12.2	15.0	31.3	32.0	6.9	6.3	10.9	18.0	60.8	77.8
December	16.7	11.6	36.3	34.5	7.5	7.8	10.1	16.3	63.3	73.7
Seasonal mean	9.4	7.9	28.9	27.3	5.2	6.4	14.4	16.1	66.3	67.9
Long-term (16 years)	6.6		25.0		4.3		20.6		77.6	

A summary of the long-term mean weather parameters is presented in Appendix 2. Although similar, these two seasons were drier and hotter compared to the long-term means. The mean minimum temperature during the first and second seasons were 42 and 20% higher than the long-term mean. The mean maximum temperature was 16 and 9 % higher and the reference evapotranspiration 21 and 49 % higher, respectively.

3.2.3 Experimental design and treatments

The experiment was laid out as a completely randomised split plot design with three replications for each treatment (Figure 3.2).

The two soil types, Clovelly and Bainsvlei, were each subjected to five different irrigation water quality treatments (Table 3.3). The on-farm borehole water with a mean EC of 150 mS m^{-1} was used as the control treatment. For the remaining four irrigation water treatments, EC was increased to 450, 600, 900 and 1200 mS m^{-1}. These were prepared using a combination of six salts: NaCl, $CaCl_2$, $MgSO_4$, Na_2SO_4, KCl and magnesium chloride ($MgCl_2$). The ratios and combination of salts to obtain the required EC and sodium adsorption ratio (SAR) values were established through laboratory experimentation based on long-term values of the Lower Vaal River and its tributaries (Du Preez *et al*., 2000).

BORDER															
Clovelly	T2	T0	T4	T0	T2	T3	T1	T3	T1	T2	T3	T4	T0	T4	T1
BORDER															
Bainsvlei	T2	T0	T3	T2	T3	T1	T3	T0	T1	T2	T4	T1	T4	T0	T4
BORDER															

Figure 3.2: Schematic layout of the experiment and allocation of treatments: T0 the control and T1-T4 increasing EC_i treatments with an EC of 450, 600, 900 and 1200 mS m^{-1} respectively.

Table 3.3: Sodium adsorption ratio (SAR), total dissolved solids (TDS), and amounts of the different salts used to prepare the four required irrigation water quality treatments (EC_i)

Parameter	Units	EC_i (mS m^{-1})			
		450	600	900	1200
SAR		5	5	5	5
TDS	g ℓ^{-1}	3.6	5.1	8.2	11.3
NaCl	g ℓ^{-1}	1.14	1.42	1.94	2.34
$CaCl_2$	g ℓ^{-1}	0.50	0.83	1.54	2.27
$MgSO_4$	g ℓ^{-1}	1.19	1.74	2.9	4.04
Na_2SO_4	g ℓ^{-1}	0.02	0.05	0.03	0.04
KCl	g ℓ^{-1}	0.53	0.75	1.06	1.45
$MgCl_2$	g ℓ^{-1}	0.09	0.25	0.67	1.10
Ca:Mg		1:1.32	1:1.31	1:1.32	1:1.31
SO_4:Cl		1:1.33	1:1.32	1:1.34	1:1.33

3.2.4 Agronomic practices

Cultivars, planting date, sowing density and fertilizer applications were based on the production guidelines for small grains in the summer rainfall regions in South Africa (ARC, 2014). The barley cultivar Cocktail was planted and allowed to grow until maturity. This cultivar was chosen because of its higher yielding capacity as compared to Puma, the only other cultivar recommended for irrigation areas at the inception of the study. The barley cultivars Cristalia and Overture are currently the only two cultivars recommended for commercial production of malting barley under irrigation (ARC, 2017). The planting and harvesting dates, row width, planting density, fertilizer application rates and pesticide application for the two growing seasons are summarised in Table 3.4.

Table 3.4: Agronomic practices and decisions made regarding cultivar, planting date, planting depth, row width, seeding rate and fertilization

Parameter	Season 1	Season 2
Cultivar	Cocktail	Cocktail
Planting date	06 July 2015	04 July 2016
Harvesting date	25 November 2015	21 November 2016
Planting depth	2.5 cm	2.5 cm
Row width	25 cm	25 cm
Planting density	60 kg ha^{-1}	60 kg ha^{-1}
Nitrogen Fertilization	128 kg ha^{-1}	128 kg ha^{-1}
	Pre-plant = 68 kg ha^{-1}	Pre-plant = 68 kg ha^{-1}
	Top dressing 1 = 30 kg ha^{-1}	Top dressing 1 = 30 kg ha^{-1}
	Top dressing 2 = 30 kg ha^{-1}	Top dressing 2 = 30 kg ha^{-1}
Phosphorus	21 kg ha^{-1}	21 kg ha^{-1}
Potassium	10 kg ha^{-1}	10 kg ha^{-1}
Pest control	Demeton EC (500 mℓ ha^{-1})	Demeton EC (500 mℓ ha^{-1})

Equal amounts of irrigation water was applied weekly in all treatments by manually flooding the surface of every lysimeter with 60 ℓ of water, equivalent to a 23 mm irrigation (60 ℓ / 2.55469 m^2), to create optimum water conditions for crop growth and maximum yield based on the water use of wheat. Although a total of 465 mm per season is recommended for barley (Kotze, 2018), a total of only 312 and 240 mm were applied for the first and second seasons, respectively, to allow for groundwater utilisation which can contribute more than 50% of crop water requirements (Ehlers *et al*., 2003; Ghamarnia *et al*., 2004; Ayars *et al*., 2006; Gowing *et al*., 2009). The groundwater table was kept constant at 1200 mm by recharging it almost daily, depending on depletion rate, through the manometer tube. Application of irrigation treatments commenced as soon as the seedling establishment reached the four-leaf stage.

It was unfortunate that Russian wheat aphid (*Diuraphis noxia*) infestation at 85 DAP in the first season led to yield variation instabilities between the treatments and that led to some replications performing poorer than others do. These outlier replications were taken to be a result of aphid infestation as it occurred during the critical stages of grain forming and filling (Bardner & Fletcher, 1974). Therefore, treatment means were adjusted with covariance analysis before running the statistical analysis (Gomez & Gomez, 1984).

3.2.5 Measurements and calculations

Single soil samples were collected from each lysimeter at six depths, *viz.* 300, 500, 700, 900, 1200 and 1500 mm, using a hand auger at the beginning and end of every season. Composite soil sampling was not done as minimum disturbance to the lysimeters was desired. Samples were prepared for laboratory analysis by oven drying at 40°C, grinding and sieving through a 2 mm diameter sieve. To analyse for EC ($EC_{e,}$ mS m^{-1}), a saturated paste extract was made using standard procedures (The Non-affiliated Soil Analysis Work Committee, 1990). Seasonal mean $EC_{e,}$ (mS m^{-1}) was then calculated as the average $EC_{e,}$ between the two soil types.

A neutron soil water meter (CPN 503 DR Hydroprobe) was used to determine the volumetric soil water content at 300 mm depth intervals to a depth of 1800 mm. The evapotranspiration (*ET*, mm) or water use from each lysimeter was calculated using Equation 3.1:

$$ET = I + U \pm \Delta W \quad (3.1)$$

Where *I*= irrigation (mm), *U*= upward capillary rise into the root zone (mm) and ΔW= change in the soil water content. Mean cumulative *ET* over the season was used to calculate the water productivity of barley (*WP*, kg ha^{-1} mm^{-1}) with Equation 3.2:

$$WP = Grain\ yield/cumulative\ ET \quad (3.2)$$

The aboveground biomass of each lysimeter was manually harvested after the crop reached physiological maturity and yield was obtained by weighing the grain per lysimeter and expressing it in kg per lysimeter after drying at 70°C for three days in a ventilated oven. Dry matter results were unfortunately not included in the study due to animal damage during the weighing process. Nonetheless, grain yield was converted to kg ha^{-1} and used to calculate WP. After yield determinations, grain was kept in a ventilated storage at 0 to 1˚C. The increase in soil salinity was calculated as the difference between the mean EC_e of every lysimeter at the beginning and end of the growing season.

3.2.6 Statistical analysis

Treatment means and standard deviations were calculated for all results. Data was tested for normal distribution before analysis of variance. The analysis revealed no justification to log-transform the data as it was normally distributed. Significance tests were carried out through analysis of variance (ANOVA) using SAS software version 9.2® designed for Windows. A mixed ANOVA model was fitted with soil, treatment, soil*treatment as fixed effects, and replicate and soil*replicate as random effect. The model was fitted separately for the two seasons. Means were separated by the least significant difference ($LSD_{0.05}$) and different letter symbols represented means that were different. To fit the van Genuchten & Gupta (1993) sigmoidal function to relative grain yield results, the non-linear regression analysis procedure as explained by Brown (2001) was followed.

Comparison of two linear regression lines:

Two parallel linear regression lines (same slope but potentially different intercepts) were to be compared. It was assumed that the reference regression line was fixed, that is, had a fixed intercept a_2. The first regression line was written as:

$$y = a_1 + b_1 x + e \quad (3.3)$$

Where y is the relative yield, and x is the EC_e. Subtracting the constant a_2 from both sides of the above equation, the new equation became:

$$y - a_2 = a_1 - a_2 + b_1 x + e \quad (3.4)$$

The comparison of the regression line 1 against the fixed parallel line therefore reduced to test for the intercept $a = a_1 - a_2$ in a linear regression of $y - a_2$ against x, where $a_2 = 1.4$

Comparison of two nonlinear regression lines:

The nonlinear regression lines to be compared were written as

$$y_r = \frac{1}{1+(\frac{c}{c_{50}})^p} \quad (3.5)$$

Where Y_r is the relative yield, c the average root zone salinity, and c_{50} the average root zone salinity at which the yield has declined by 50%.

3.3 Results

3.3.1 Water use

The mean daily ET during four growth phases for the EC_i treatments of the Clovelly and Bainsvlei soil types during the first and second growing seasons is illustrated in Figure 3.3. The four growth phases (1-tillering; 2-stem extension; 3-heading and 4-extension) were determined according to the irrigation curve of barley (Kotze, 2018). As expected, mean daily ET increased with increase in growth phase with maximum ET values recorded during the heading phase. Generally, mean daily ET declined with an increase in EC_i treatments during all growth phases for both soil types and seasons.

In the first season, the 450 mS m^{-1} EC_i treatment had the highest mean daily ET of 7 mm day^{-1} on the Clovelly soil type. From the same soil type in the second season, control treatment recorded the highest mean daily ET of 9 mm day^{-1}. On the Bainsvlei soil type, the control treatment produced the highest mean daily ET of 7 and 9 mm day^{-1} for the first and second season, respectively. The 900 and 1200 mS m^{-1} EC_i treatments similarly had the lowest records for mean daily ET from both soil types in both seasons. Overall, for both soil types, higher daily ET was recorded in the first season. A detailed record of mean daily ET corresponding to irrigation scheduling intervals for the soil types and seasons is presented in Appendix 3.2.

Figure 3.4 showed mean cumulative groundwater table depletion (WTD) per growth phase under different EC_i treatments. The WTD per growth stage reflected a similar trend to ET. For all growth phases, the figure illustrates a higher cumulative WTD from the control treatment in the second season in particular. The 450 mS m^{-1} EC_i treatment also had a greater WTD, especially in the first season.

Total cumulative WTD is presented in Table 3.5 together with total ET and percentage contribution of WTD to total ET. Significantly higher ($P<0.05$) WTD was from the control and 450 mS m^{-1} EC_i treatments. The Clovelly soil type recorded lower WTD and corresponding contribution to ET in all EC_i treatments especially in the second season. This soil type for the 900 and 1200 mS m^{-1} treatment had respective total cumulative WTD of 192 and 136 mm in first season and 50 and 0 mm in the second season. Uptake from the groundwater table, expressed as a percentage of ET, ranged between 30 and 46% on the Clovelly soil type and was lower than the 42 to 50% from the more clayey Bainsvlei soil type in the first season. For the second season, the corresponding ET ranges were between 0 and 38% for the Clovelly soil and between 0 and 63% for the Bainsvlei soils.

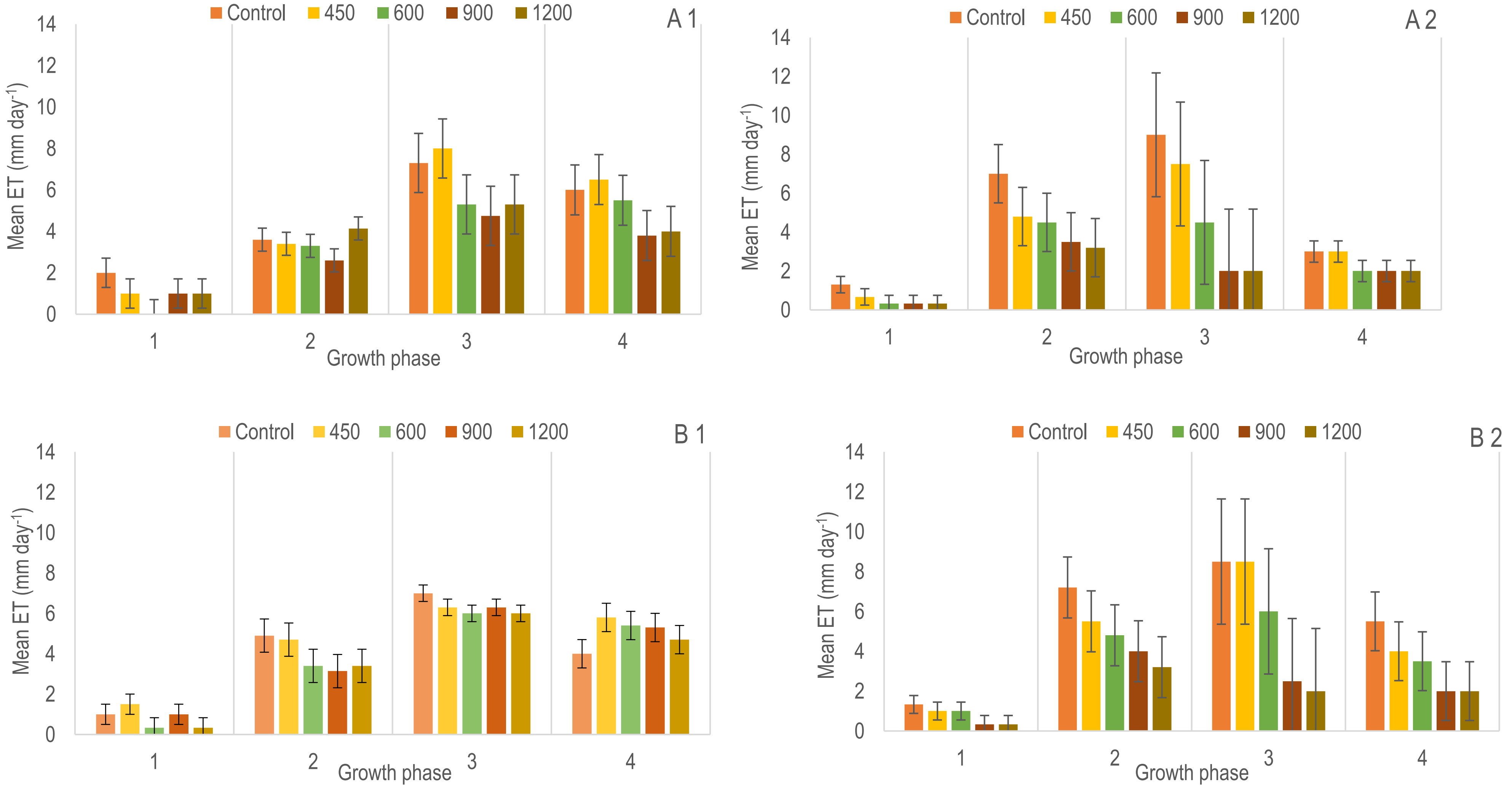

Figure 3.3: Mean ET (mm day^{-1}) per growth phase (1-tillering; 2-stem extension; 3-heading and 4-extension) for all the EC_i treatments (mS m^{-1}) on (A1) Clovelly soil in the first season and (A2) Clovelly soil in the second season, (B1) Bainsvlei soil in the first season and (B2) Bainsvlei soil in the second season.

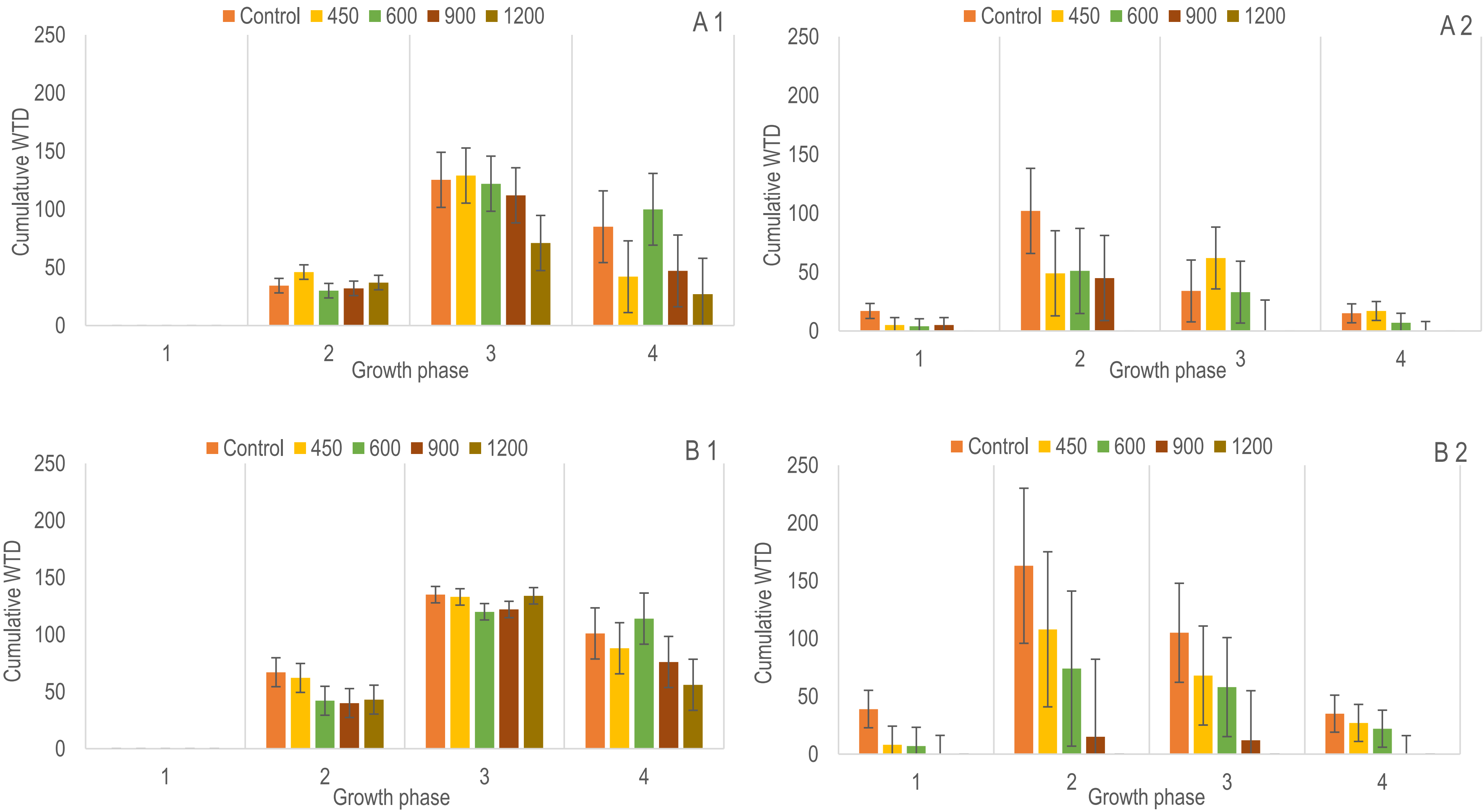

Figure 3.4: Cumulative groundwater table depletion (WTD, mm) per growth phase (1-tillering; 2-stem extension; 3-heading and 4-extension) for all the EC_i treatments (mS m^{-1}) on (A1) Clovelly soil in the first season and (A2) Clovelly soil in the second season, (B1) Bainsvlei soil in the first season and (B2) Bainsvlei soil in the second season.

Table 3.5 Total groundwater table depletion (WTD), cumulative evapotranspiration (ET) and the percentage contribution of the groundwater table as a source of total ET for the different EC_i treatments on the two different soils over the two seasons

Soil	EC_i (mS m^{-1})	Season 1			Season 2		
		ET (mm)	WTD (mm)	% of ET	ET (mm)	WTD (mm)	% of ET
Clovelly	Control	530 bc	245 c	46	492 b	179 c	36
	450	501 c	218 d	44	353 d	134 e	38
	600	488 d	215 de	44	294 e	94 f	32
	900	441 e	192 e	44	218 fg	50 g	23
	1200	456 e	136 f	30	214 f	0 i	0
Bainsvlei	Control	595 a	304 a	49	539 a	342 a	63
	450	573 ab	282 ab	42	450 c	211 b	47
	600	559 b	277b	50	373 d	161 d	43
	900	545 b	239 c	44	245 f	27 h	11
	1200	515 c	234 cd	45	223 fg	0 i	0
LSD		27	21		26	10	

Means in each column followed by different letters are significantly different according to Fisher's LSD ($P < 0.05$).

3.3.2 Salt accumulation

Table 3.6 summarises the mean root zone salt build up for the different EC_i treatments over the two seasons for the Clovelly and Bainsvlei soil types. The EC_e increased over the two seasons with a sharp rise between the beginning and end of the first season. From a mean of 200 mS m^{-1} at the beginning of the first season, EC_e increased by 506 mS m^{-1} to a mean of 706 mS m^{-1} by the end of the first season. EC_e increased by only 213 mS m^{-1} to a mean of 919 mS m^{-1} by the end of the second season. Nonetheless, salt accumulation was higher in the Bainsvlei soil with a seasonal mean of 771 and 995 mS m^{-1} for the first and second season respectively. For the Clovelly soil, the seasonal means for the first and second season were 641 and 843 mS m^{-1} respectively. Despite the lower change in EC_e calculated for the second season, precipitated salt accumulation could be observed on the soil surface (Figure 3.5).

Table 3.6: The mean root zone (0-1200 mm) soil salinity (EC_e) at the beginning and end of the first and second season for both Clovelly and Bainsvlei soil as affected by irrigation water salinity treatments (EC_i)

EC_i (mS m^{-1})	Beginning of first season		End of first season/ Beginning of second season		End of second season	
	(EC_e, mS m^{-1})					
	Clovelly	Bainsvlei	Clovelly	Bainsvlei	Clovelly	Bainsvlei
Control	174	200	244	258	359	413
450	160	196	567	453	805	669
600	220	180	494	729	726	1080
900	182	221	846	843	1041	984
1200	186	282	1054	1574	1282	1830
Mean	184	216	641	771	843	995
Seasonal mean EC_e	200		706		919	

In this study, a single point sample per depth was taken to determine EC from a saturated paste extract as minimum disturbance to the lysimeters was crucial. Therefore, the static samples could have misrepresented changes in salinity in the root zone for the following reasons: Firstly, single point sampling does not account for the possibility of salt redistribution within the profile (Franzen & Peck, 1995). Secondly, the complex molecular scale phenomenon of salt precipitation, known to occur in the top 50 mm of the soil profile (Nachshon *et al*., 2010; Dashtian *et al*., 2018) as visible in Figure 3.5 may have been misrepresented as the first soil sample was only taken at 300 mm.

Figure 3.5: Salt precipitation indicated by white patches on the (a) Bainsvlei and (b) Clovelly soil lysimeters irrigated with water of 1200 mS m^{-1} during the second season.

3.3.3 Grain yield

The mean grain yield of barley from the Clovelly and Bainsvlei soil types over two seasons is given in Table 3.7. There was a significant decrease in grain yield with an increase in EC_i on both soil types over the two seasons. In the first season, significant differences were observed between the control and the highest EC_i treatment. However, significant differences occurred among all treatments in the second season.

The highest mean grain yield of 1.14 kg lysimeter $^{-1}$ was obtained from the control treatment on the Clovelly soil type. The lowest mean grain yield of 0.10 kg lysimeter $^{-1}$ was from the 1200 mS m^{-1} treatment. There was therefore a total of 91% difference in yield with an increase in salinity from the control treatment to the 1200 mS m^{-1} on the Clovelly soil type in the second season. On the Bainsvlei soil type, this percentage reduction was at 89% for the same period.

Table 3.7: Mean grain yield for five EC_i treatments on two soil types over two growing seasons

EC_i (mS m^{-1})	Season 1		Season 2	
	Clovelly	Bainsvlei	Clovelly	Bainsvlei
	Grain yield (kg lysimeter $^{-1}$)			
Control	0.97 a	0.93 a	1.14 a	1.01 a
450	0.85 ab	0.80 ab	0.78 b	0.73 b
600	0.56 b	0.70 b	0.65 c	0.50 c
900	0.43 b	0.60 b	0.29 d	0.37 d
1200	0.21 c	0.45 c	0.10 e	0.11 e
LSD 0.05	0.14		0.15	

Means in each column followed by different letters are significantly different according to Fisher's LSD ($P < 0.05$).

3.3.4 Grain yield and salinity relationships

The relationship between malt barley relative grain yield and the seasonal mean EC_e is given in Figure 3.6. The Maas & Hoffman (1977) function is also presented. Figure 3.7 presents the relationship between malt barley relative grain yield and seasonal mean EC_e with the Van Genuchten & Gupta (1993) sigmoidal fit.

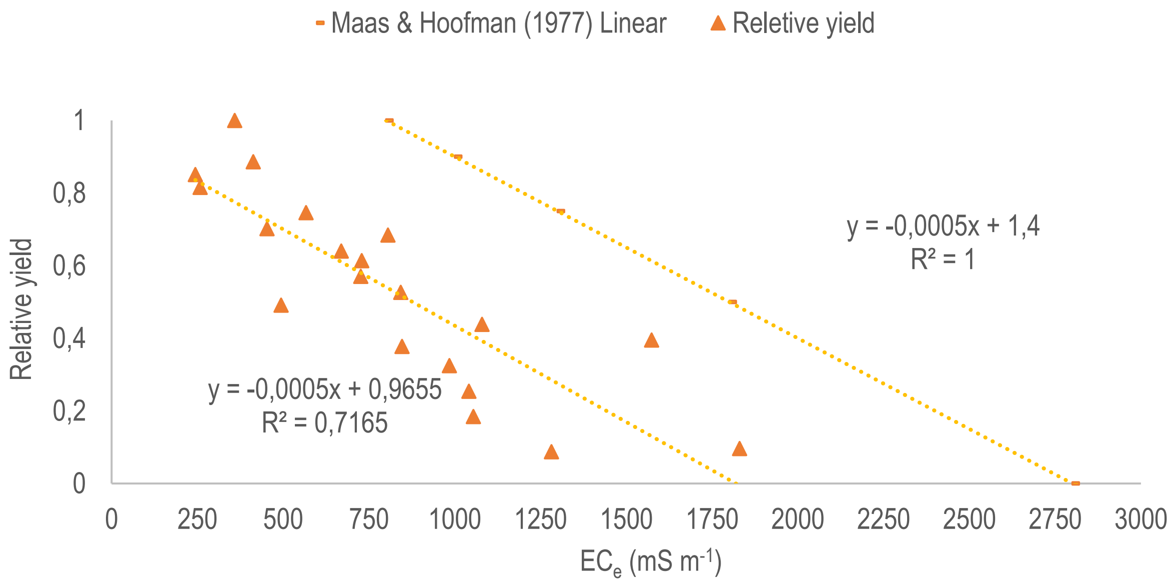

Figure 3.6: Relative barley grain yield and mean soil salinity (EC_e) relationships.

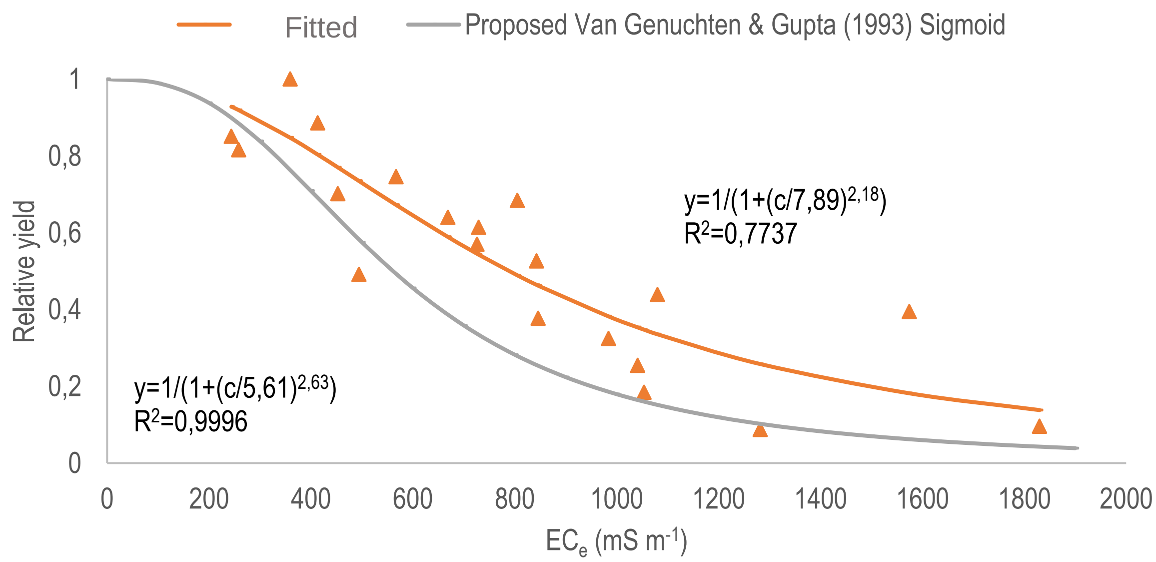

Figure 3.7: Relative barley grain yield and mean soil salinity (EC_e) relationships.

The linear regression function between relative grain yield and seasonal mean EC_e had a negative slope of 0.0005 and was typically similar to that of Maas & Hoffman (1977). However, the intercepts of the two regression lines were significantly different: $t_{19} = -6.07$ (P<0.0001). Hence, the lower R^2 value of 0.7 that was suggestive of the opportunity for a better fit model. The sigmoidal function (Eq. 3.5) provided a better fit (R^2= 0.8) to these results. For barley, Van Genuchten & Gupta (1993) proposed a c_{50} and p value of 5.61 and 2.63, respectively. The c_{50} and p value calculated for this fit were 7.89 and 2.18 respectively. The two sigmoid parameters

p_i were not significantly different from each other, $t_{39} = 1.02$ (P = 0.3140). However the c_{50} parameters were significantly different from each other, $t_{39} = -5.14$ (P<0.0001). Therefore, the two sigmoidal curves seem to have a common sigmoid parameter, but different c_{50} parameters.

3.3.5 Water productivity

Water productivity of barley for all the EC_i treatments on both soils during both seasons and the standard deviation is summarized in Figure 3.8. This shows a trend of decreasing WP with an increase in salinity. In the first season, WP decreased from 7 to 2 kg ha^{-1} mm^{-1} for the control and 1200 mS m^{-1} EC_i treatments, respectively, on the Clovelly soil types. On the Bainsvlei soil type, this decrease was from 6 to 3 kg ha^{-1} mm^{-1} for the respective EC_i treatments. Generally, WP was higher in the second season with the control treatment at 9 kg $ha^{-1}mm^{-1}$ on the Clovelly soil type and 4 kg ha^{-1} mm^{-1} for the 1200 mS m^{-1} EC_i treatments. The corresponding WP on the Bainsvlei soil type ranged from 7 to 2 kg $ha^{-1}mm^{-1}$ for the control and 1200 EC_i treatments, respectively.

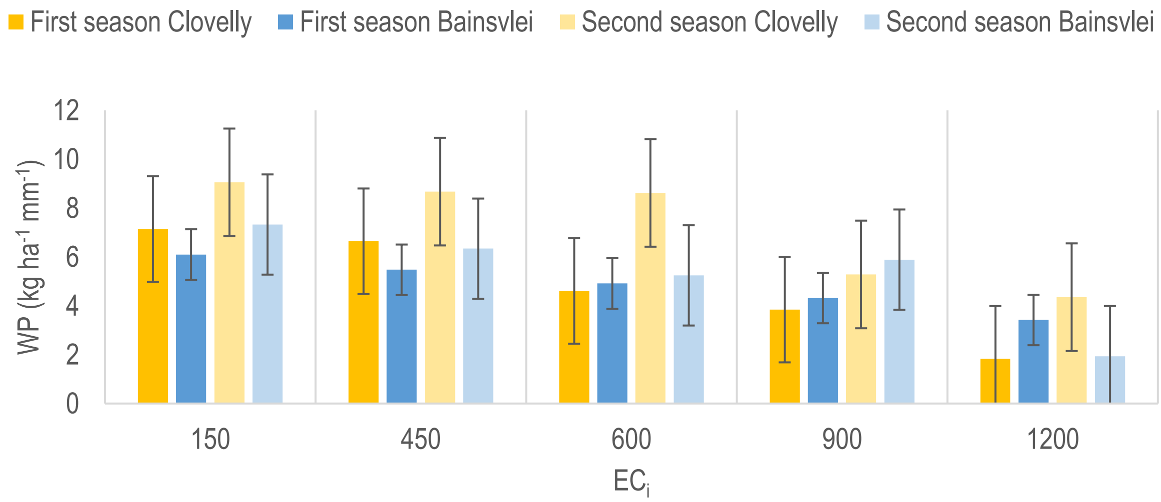

Figure 3.8: Water productivity (WP) as affected by irrigation water salinity treatments (EC_i) on both soils over the two seasons.

3.4 Discussions

This study quantified the effect of EC_i treatments on ET, groundwater table depletion (WTD) and grain yield of barley, relationships between grain yield and EC_e, and crop water productivity. Increasing irrigation water salinity from the control (150 mS m^{-1}) to 1200 mS m^{-1} caused a decline in ET, WTD, grain yield and subsequent water productivity of malt barley on the Clovelly and Bainsvlei soil types with more pronounced parameter differences in the second season.

This study succeeded in highlighting the negative effects of salinity on barley ET. Barley ET rates were reduced by the interactive effect of increasing salinity and soil type. Significantly, lower mean seasonal ET corresponded with higher EC_i treatments. Ehlers *et al*. (2007) observed similar trends of a reduction in transpiration with an increase in EC_i for maize, wheat, beans and peas. Generally, the heading and extension phases exhibited greater variation among treatments on both soils (Figure 3.4). This observation was unexpected given that barley has been shown to be more susceptible to salinity during germination and seedling establishment and less sensitive during flowering and grain filling (Pessarakli *et al*., 1991; Naseer, 2001; Yazar *et al*., 2004; Lauchli & Grattan, 2007; Dikgwathle *et al.*, 2008; Grewal, 2010), suggestive of influence of other external factors (Munns, 2002).

Encouraging crop water use from shallow ground water table is an important objective, particularly in areas that lack drainage facilities and are at risk of waterlogging and salinization. Apart from the salinization setback, shallow groundwater tables had meaningful contribution to barley water requirements. The soil type clay content played a critical part in reducing salinity effects through increased WTD. In this study, WTD for the control treatment contributed up to 63% of ET especially from the Bainsvlei soil type. Groundwater table between 600 and 1200 mm depth had up to 27% contribution to cumulative ET of barley from sandy silty loam textured soils (Hassan, 1990). For sandy loam soils groundwater table at 1000 mm depth contributed up to 63% of wheat ET (Ehlers *et al*., 2003). Higher WTD in the Bainsvlei is consisted with clayey texture of Bainsvlei soil type that favoured capillarity from the groundwater table (Ehlers *et al*., 2003).

Yield loss in saline conditions is a common outcome for many crops including barley. Progressive increase in soil salinity decreased grain yields of barley for both soil types and seasons; with a higher yield reduction in the Clovelly compared to the Bainsvlei soil type, even though the margins of loss were higher in the second season. In a study on barley, Naseer (2001) observed that irrigation water with EC of 1600 mS m^{-1} reduced grain yield by up to 46%. Irrigation water with EC levels of 300 and 600 mS m^{-1} reduced wheat grain yield by 18 and 36%, respectively (Dikgwatlhe *et al*., 2008). However, reduction in grain yield due to irrigation water salinity has been shown to be soil dependent (Ehlers *et al*., 2007). This sentiment finds support in this study because the decrease in malt barley grain yield was much higher for the Clovelly compared to the Bainsvlei soil type irrespective of the season. Differences in the soil type grain-yield responses to increasing water salinity is attributed to the soil's silt plus clay content. This physical attribute suggested that the Bainsvlei had a higher buffering capacity giving it the ability to withstand higher salinity threshold values. On the contrary, lower clay content in the Clovelly suggested higher sensitivity to small changes in EC_i hence, greater yield reduction with every unit increase in EC_i (mS m^{-1}). The Clovelly's inability to withstand increasing salinity was also observed by Ehlers *et al*. (2003) and Barnard *et al*. (2010). The latter also acknowledged the high drainage properties of the Clovelly making it easier to redistribute and drain excess salts especially in the absence of groundwater table to offset its lack of buffering capacity.

Increase in salinity has been known to reduce grain yield of barley linearly (Maas & Hoffman, 1977). However, the sigmoidal function of Van Genuchten & Gupta (1993) provided a better fit (R^2= 0.8) to the results of this study. The empirical constants, c_{50} and p describing the degree of salt tolerance of Cocktail malt barley cultivar where found to be respectively higher and lower compared to Van Genuchten & Gupta (1993). Van Genuchten & Gupta (1993) predicts a 50% decline in yield at EC_e of 561 mS m^{-1} while 50% decline in yield for the present cultivar was only reached at EC_e of 791 mS m^{-1}. This finding is more in line with the findings of Royo & Aragues (1999) who found similar c_{50} values of 795, 792 and 795 mS m^{-1} for Dacil, Reinette and RBC 188 genotypes respectively out of the 124 barley genotypes tested. The higher c_{50} value from this study is suggestive of the higher salt tolerance of this cultivar and not surprising as absolute tolerance is a complex response that varies depending on climate, soil conditions agronomic practices and type of salts (Maas & Hoffman, 1977; Genuchten & Gupta, 1993; Steppuhn & Raney, 2005). For example, the c_{50} value for Harrington barley was found to be 104 mS m^{-1} with a chloride test, but 110 mS m^{-1} with a sulphate test (Steppuhn & Raney, 2005).

Crop water productivity concept has proven useful when managing water for irrigation, especially under saline conditions. Water productivity of barley was higher in the second season especially for the Clovelly soil type. For the same season, the Bainsvlei soil type had second highest WP for all except the 1200 mS m^{-1} EC_i treatments. The first season produced average WP from both soil types in all EC_i treatments. Although higher temperatures and lower relative humidity in the first season favoured ET, the season's lower yields reduced WP, suggesting that most of the water used was channelled to evaporation instead of transpiration. Cumulative salinity reduces profile available water content over the growing season and thus affecting evaporation and transpiration differently. These two processes are affected by salinity differently and hence Dlamini *et al*. (2017) vouched for calculating WP based on T instead of ET.

3.5 Conclusions

This chapter quantified the effect of EC_i on evapotranspiration (ET), groundwater table depletion (WTD) and grain yield of barley, relationships between grain yield and EC_e, and crop water productivity (WP). Increasing irrigation water salinity from the control (150 mS m^{-1}) to 1200 mS m^{-1} caused a decline in ET, WTD, grain yield and WP of malt barley in the first and second seasons from the Clovelly and Bainsvlei soil types.

Generally, the buffering capacity of the Bainsvlei soil mitigated salinity effects to some extent in terms of ET, WTD and grain yield. Clayey textured soils are characterised by a high buffer capacity, which minimises negative effects of salinity and supports capillary rise and crop water uptake from the groundwater. ET, WTD and grain yield were inversely proportional to EC_e. The detrimental effect of saline conditions on the productive potential of groundwater table was demonstrated by the WTD that decreased to zero at irrigation water salinity above 1200 mS m^{-1}. In general, a higher maximum water use was recorded in the first season. Higher WP values in the second season reflects on unproductive water losses in the dryer and hotter first season. Users should therefore exercise caution when comparing and extrapolating WP results as it should be based on T instead of ET.

The higher salinity tolerance of the Cocktail barley cultivar was highlighted by the significantly higher c_{50} parameter observed on the sigmoidal function. Since higher EC_i treatments significantly reduced barley grain yields, it can also be expected to induce higher grain quality declines. Effects of EC_i on grain quality of malt barley will therefore be presented in the next chapter.

Chapter 4: Irrigation water salinity effects on malt barley grain quality characteristics

4.1 Introduction

Barley grain for malting is required to satisfy a series of stringent quality standards that depend on physio-chemical processes and environmental factors influencing plant growth and grain development (Coventry *et al*., 2003; Kumar *et al*., 2013). Malting is a process through which raw barley grains are converted into a product that can be used for brewing, distilling and baking purposes (Holopainen, 2015). Malting is a precursor to brewing and distilling, and takes place in six steps: grain selection, preparation and storage, steeping, germination, kilning and dressing. Of these steps, grain selection is of utmost importance because barley grain composition affects malt-processing properties such as extract yield, colour, and aroma (Halford *et al.,* 2015). Therefore different end users for selecting barley with better malt quality to meet their needs (Yesmin et al., 2014) have defined various grain quality parameters.

Although special premiums are offered for high grain quality, producers of barley grain for malting are often confronted with various challenges including among others marginal soils, extreme weather conditions and water scarcity. Effect of the latter is often coupled with poor water quality of which high salt load is the main concern, especially in semi-arid and arid areas where production of malt barley is under irrigation. Most irrigation barley producing areas in South Africa have shallow groundwater tables (Backeberg *et al.,* 1996; Le Roux *et al*., 2007). Water tables near the root zone are an attribute of soil salinization through capillary rise (Ehlers *et al*., 2003; Wang *et al*., 2015). Irrigation water of marginal quality from the Vaal, Harts, Orange and Riet Rivers has aggravated salinization of irrigated barley fields characterised with shallow water tables and poor drainage (Houk *et al*., 2006). Such fields are susceptible to waterlogging, surface runoff degradation hazards (Van Rensburg *et al*., 2012), and salt accumulation (Lambert & Karim, 2002).

Effect of limited water availability in saline soils induces a series of metabolic reactions with a suite of metabolic changes identical to those caused by water stress (Munns, 2002). The dependence of barley grain filling and development on soil-water and nutrient availability is well covered in literature (Pessarakli *et al*., 1991; Naseer, 2001; Munns, 2002; Coventry *et al*., 2003; McGoverin *et al*., 2011; Halford *et al.,* 2015; Bello *et al*., 2017). Reduced biomass is the most apparent effect of salinity stress on barley, and leads to quantitative yield losses by affecting seedling germination and establishment (Al-Seedi, 2008; Bagwasi, 2015), vegetative growth (Pessarakli *et al*., 1991; Grewal, 2010; Bagwasi, 2015) and ultimately total grain yield (Yazar *et al*., 2004; Dikgwathle *et al*., 2008).

Apart from yield reductions, salinity accelerates senescence and shortens the maturity period of crops (Munns, 2002; Begcy & Walia, 2015). Accelerated senescence alters grain quality characteristics through the translocation of nutrients in the plant. For example, the translocation of nitrogen to the reproductive plant parts tends to favour protein accumulation over starch deposition in cereal grains like wheat (Clarke *et al*., 1990; Ozturk & Aydin, 2004) and barley (Izadi *et al*., 2014; Hafez & Hassan, 2015).

Bagheri (2011) reported that salinity did not highly affect the protein content of barley. On the contrary, Izadi *et al*. (2014) found protein content to increase with an increase in salinity ranging from 6.8 to 13.4% in mealy grains and steely grains, respectively. Barley grain development and composition under saline conditions is still not fully comprehended (Thitisaksakul *et al*., 2012) and a robust investigation is required to address potential impact on barley grain composition and subsequent malt production. The objective of this chapter is therefore to quantify the effect of increasing irrigation water salinity (EC_i, mS m^{-1}) on barley grain-quality characteristics for malting.

4.2 Materials and methods

Yield and quality of barley cv. Cocktail were evaluated in a lysimeter trial over two seasons, as affected by five salinity levels of irrigation water (150, 450, 600, 900 and 1200 mS m^{-1}) on two different soil types (Bainsvlei and Clovelly) in the presence of a shallow saline groundwater table (1200 mm). Salinity of the groundwater table corresponded to irrigation water quality while leaching of salts due to over-irrigation was negligible. The lysimeter experimental layout was described in detail in Chapter 3 (Section 3.2.1). Quality characteristics of barley grains were assessed using standardised laboratory tests to gauge its potential for malting. The systematic laboratory procedures together with the apparatus and reagents used for each analysis are given below.

1000 seed weight (TSW): A seed counter was used to count 1000 seeds, which were then weighed to determine TSW in grams. No broken grains were allowed for this determination.

Viability: Grain viability was analysed with the rapid staining method. Barley grains (100 per lysimeter) that did not contain any foreign material or broken grains were placed in falcon tubes and covered with a 1% tetrazolium (Nitro-tetrazolium chloride (≈98%) TLC) solution at room temperature. Falcon tubes were maintained at 25°C for 24 hours in a water bath, after which the grains were placed on moist filter paper and examined using 10-x magnification. Examined grains were classified as:

(*X*): Completely coloured indicating healthy, living germs.

(*Y*): Grains that are damaged but intact to germinate.

Viability was calculated as:

$$\%Viability = X + Y \tag{4.1}$$

Germinative energy (GE): A count of 100 whole grains per lysimeter were placed in contact with filter paper inside closed petri dishes containing 4 ml of distilled water. The grains were placed in a dark germination cabinet at 19ºC. Germinated grains were removed at intervals of 24 hours from the onset of the test. The remaining non-germinated grains after 72 hours were counted and used to calculate GE as follows:

$$\%GE = 100 - nongerminated \tag{4.2}$$

Total nitrogen content (N) was determined with the Kjeldahl method. A homogenised sample of 1 g per lysimeter was chemically decomposed by heating with concentrated (95 to 98%) sulphuric acid to release N as ammonium sulphate through oxidation of the organic substances in the grain. The solution was distilled with 20 ml of sodium hydroxide to convert the ammonium salt to ammonia. The amount of N present was determined by back titrations with boric acid and then sodium carbonate and calculated as a percentage.

Water soluble proteins (WSP) were extracted using a protein extraction buffer set at a pH of 6.8. A ground sample of 1 g was homogenised with 10 ml of prepared protein extraction buffer (12.5 mM Tris, 2 mM EDTA, 10 mM Mercapto-ethanol, and 2 mM PMSF). The homogenised mixture was transferred to clean falcon tubes and centrifuged at 6000 rpm for five minutes at room temperature. The supernatant was transferred to clean Eppendorf vials and kept on ice until protein content could be determined. Determination was done with the Bradford method (Bradford, 1976) and absorbance read at 595 nm using a microplate reader. Protein content was calculated as mg protein g^{-1} of barley.

Crude protein (CP): Once determined, the total N content of the grain was multiplied by a factor of 6.25 to give the crude protein content (1% N is equivalent to 6.25% protein). (Dendy & Dobraszczyk, 2001; ARC, 2014).

Carbohydrates: For extraction, 1 g of ground grain (for each lysimeter) was placed in test tubes containing 10 ml of 80% ethanol, preheated to 80ºC in a water bath. To stop all enzymatic reactions, test tubes were kept at this temperature for 15 minutes. Extract was centrifuged at 6 000 rpm for five minutes at room temperature. One ml of aliquot of each replicate was placed in Eppendorf vials and evaporated in an oven at 70ºC to get rid of the alcohol. The resultant pellets were then dissolved in 1ml distilled water. At the time of analysis, the Boehringer Mannheim technique (Boehringer Mannheim, 1979) was used to determine the absorbance of maltose, sucrose and D-glucose content at 340 nm using a microplate reader.

Germination index (GI): Malting the barley grain samples was beyond the scope of the study therefore, malting potential could only be predicted and not determined. For that prediction, the Bishop's equation could not be used to calculate potential malt extract for South African cultivar, Cocktail, as the varietal constants for malt barley cultivars have not been determined (Els, 2017). The South African malt extract calculator as well as the equation proposed by Li *et al*. (2008) could also not be used as they are based on the N content of a malted sample. Francakova *et al*. (2012) proposed GI as a predictor of barley grain malting potential and high values of germination index indicate high quality and homogeneity of malt, GI was used to predict malting potential of the grain.

GI was calculated from GE removal intervals results as follows:

$$GI = 10 \times (n_{24} + n_{48} + n_{72})/(n_{24} + 2n_{48} + 3n_{72}) \quad (4.3)$$

Where:

n_{24}, n_{48}, n_{72} – number of germinated kernels at 24, 48, and 72 h.

Statistical analysis:

Treatment means and standard deviations were calculated for all results. Data was tested for normal distribution before analysis of variance. With the exception of GE and viability, residual plots were acceptable for all other variables and so a split-plot ANOVA was done. A mixed ANOVA model was fitted with soil, treatment, soil*treatment as fixed effects, and replicate and soil*replicate as random effect. The model was fitted separately for the two seasons. However, the residual plots for the variables GE and Viability suggested that a normal theory analysis would be inappropriate. Therefore, for these two variables, a non-parametric analysis was done. The two-way table of treatment versus GE, stratified by soil type, and the Mantel-Haenszel row mean score test was carried out. The variable Viability was also analysed in the same manner.

4.3 Results

Mean thousand seed weight (TSW) of barley as affected by different EC_i treatments grown on the Clovelly and Bainsvlei soil types in the first and second seasons are presented in Table 4.1. In the first season, mean TSW was affected (P<0.05) by soil type but not EC_i treatments. Despite the lack of significant differences in treatment effects, seed weight showed a general decrease with an increase in salinity (R^2 = 0.84) irrespective of the soil type. The Clovelly soil type had significantly higher mean TSW of 41.26 g compared to the 36.92 g from the Bainsvlei soil type. In the second season, significant differences (P<0.05) between the means was a result of EC_i treatment effect and not soil type. Higher TSW was associated with lower EC_i treatments, i.e. < 600 and 450 mS m^{-1} for the Clovelly and Bainsvlei soil types, respectively.

Table 4.1: Mean weight (g) of 1000 seeds for EC_i treatments from the Clovelly and Bainsvlei soil types in the first and second seasons

Season	EC_i (mS m^{-1})	Clovelly	Bainsvlei
First	Control	46.76 ns	38.57 ns
	450	37.18 ns	43.06 ns
	600	43.86 ns	34.41 ns
	900	42.32 ns	36.11 ns
	1200	36.13 ns	32.44 ns
	Mean	41.26 a	36.92 b
	LSD_{soil}	1.45	
Second	Control	36.36 ab	41.18 a
	450	33.33 b	40.44 a
	600	32.66 bc	33.27 b
	900	26.14 c	33.13 b
	1200	24.22 c	28.98 c
	Mean	30.54 ns	35.40 ns
	LSD_{ECi}	6.00	

Means in each column followed by different letters are significantly different according to Fisher's LSD (P < 0.05).

The effect of EC_i on grain-seed weight is further illustrated by the visual differences in the kernels from the control and 1200 mS m^{-1} treatment captured during germination tests (Figure 4.1). The former has a large, firm and plump kernel while the latter portrays a flinty kernel.

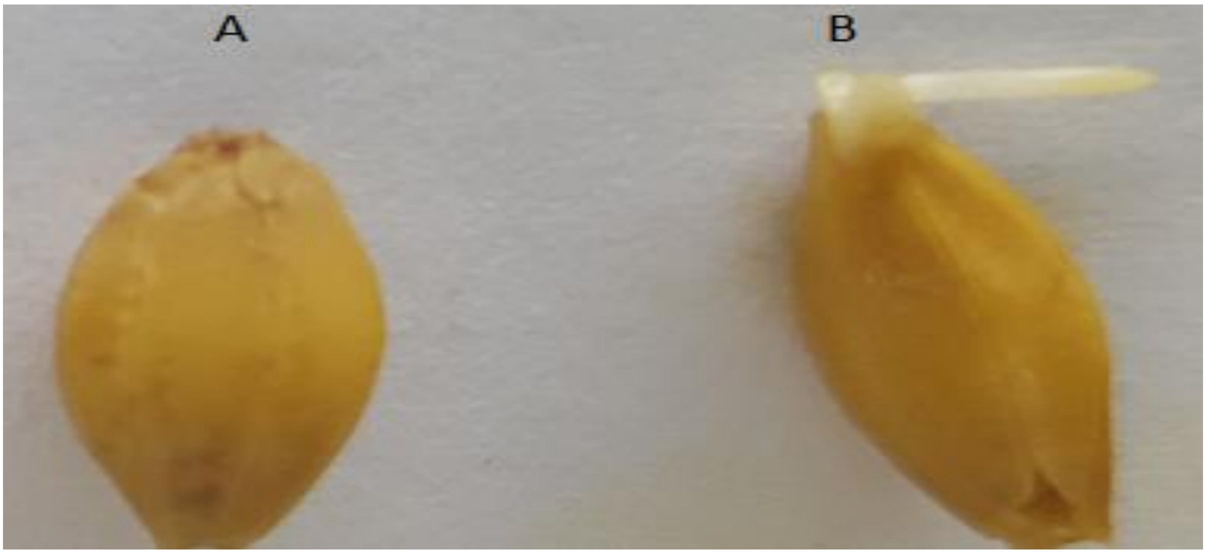

Figure 4.1: (A) Large and plump kernel from the control treatment compared to (B), a flinty kernel from the 1200 mS m^{-1} treatment during germination tests.

Grain-germination characteristics

The mean germination percentage (G%), germinative energy (GE) and grain viability, from the various EC_i treatments for the Clovelly and Bainsvlei soil types in the first and second season are presented in Figure 4.2. It is clear that the treatments did not affect grain germination characteristics significantly. The Mantel-Haenszel chi-square statistic of 4 degrees of freedom for both Viability and GE and the associated P-values of 4.97 and 1.93 were found in the first season. In the second season, the corresponding P-values were 4.42 and 5.77 for Viability and GE, respectively. However, comparing the percentage difference between the control and 1200 mS m^{-1} EC_i treatment for the three germination characteristics, the highest reduction was obtained for Viability (10%) followed by G% (9%) and GE (1%) in the second season.

The generally higher reduction in viability is depicted by the embryo staining (dark coloured) with the tetrazolium solution (Figure 4.3), which was remarkably reduced or bleached with increasing salinity.

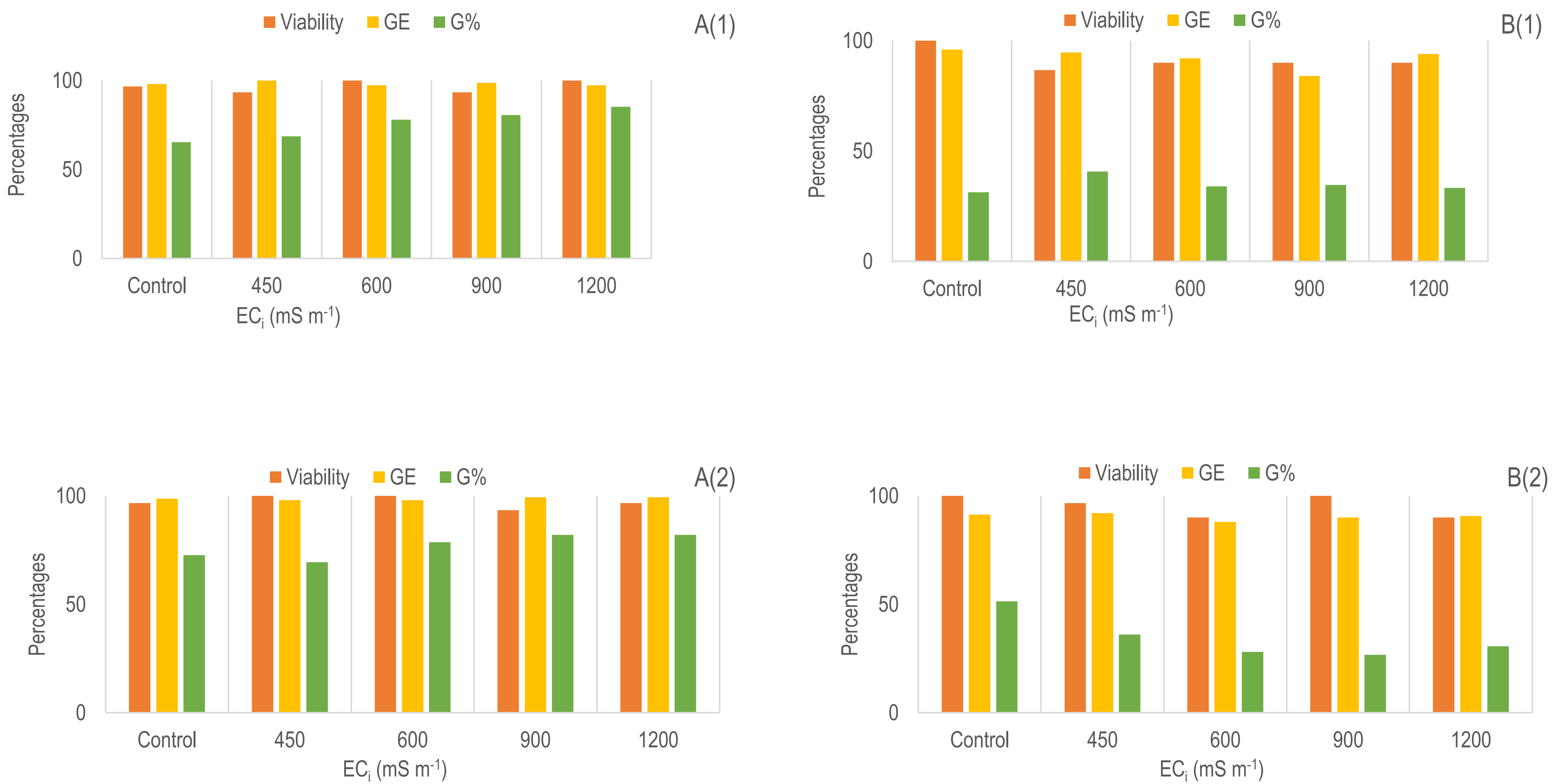

Figure 4.2: Grain viability, germinative energy (GE) and germination (G %) for the five EC$_i$ treatments on Clovelly (A) and Bainsvlei (B) soil types in the first(1) and second (2) season.

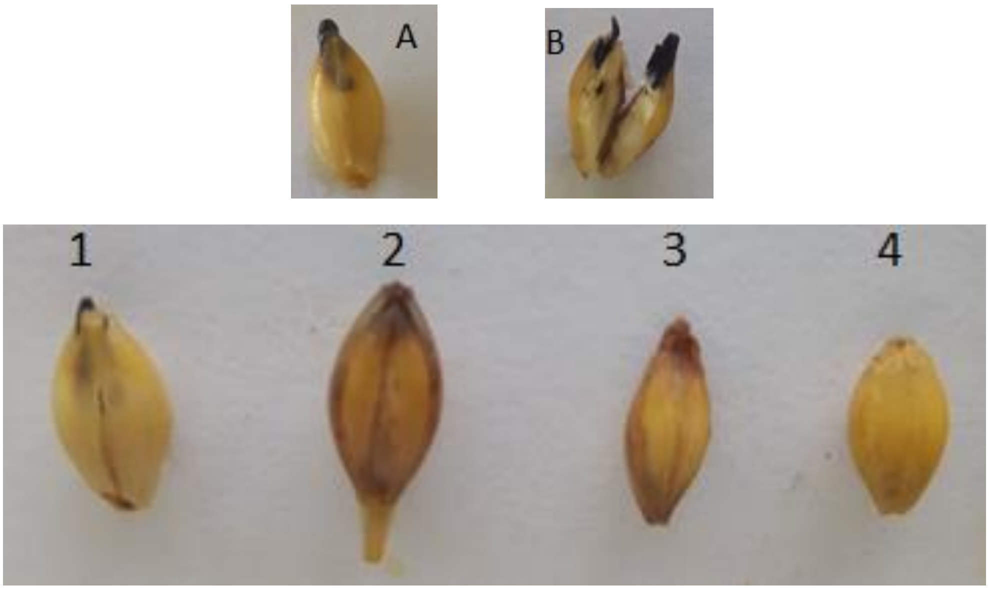

Figure 4.3: Increasing embryo bleaching with increasing salinity, illustrating reduction in grain viability from the control (A; uncut and B; cut), to (1): 450 mS m^{-1}, (2): 600 mS m^{-1}, (3): 900 mS m^{-1} and (4): 1200 mS m^{-1} treatments.

Grain proteins

Barley grains only differed significantly with regard to nitrogen (N), crude protein (CP) and water soluble protein (WSP) contents in the first season (Table 4.2).

Table 4.2: Significance levels (Pr>F) of the grain protein parameters as affected by main effects (Soil and EC_i levels) and the interaction between main effects

Season	Source	N	CP	WSP
First	Soil	0.0012 *	0.0012 *	<0.0001 *
	EC_i	0.0204 *	0.0204 *	0.1326 ns
	Soil*EC_i	0.1441 ns	0.1441 ns	0.4814 ns
Second	Soil	0.6406 ns	0.6406 ns	0.0634 ns
	EC_i	0.3362 ns	0.3362 ns	0.6363 ns
	Soil*EC_i	0.3916 ns	0.3916 ns	0.1186 ns

*Significant at the 0.05 probability level. ns for not significant.

Individual effects of the soil types and EC_i treatment levels were significant for N and CP, while only soil effects were significant for WSP. No significant differences were found in the second season and for this reason, only first season results will be displayed and discussed. Mean N, CP and WSP content of barley grains for the different EC_i treatments of the Clovelly and Bainsvlei soil types from the second season is shown in Table 4.3.

Table 4.3: Mean nitrogen (N) crude protein (CP,) and water soluble proteins (WSP) of grain for EC_i treatments from the Clovelly and Bainsvlei soil types in the first season

Season	EC_i (mS m^{-1})	N (%)		CP (%)		WSP (mg g^{-1})	
		Clovelly	Bainsvlei	Clovelly	Bainsvlei	Clovelly	Bainsvlei
First	Control	2.77 a	2.99 a	17.33 a	18.67 a	263 ns	286 ns
	450	2.51 b	2.98 a	15.70 b	18.65 a	269 ns	323 ns
	600	2.34 b	2.70 a	14.60 b	16.86 a	219 ns	293 ns
	900	2.81 a	2.73 a	17.56 a	17.04 a	257 ns	300 ns
	1200	2.71 a	3.06 a	16.94 a	19.11 a	249 ns	307 ns
	Mean	2.63 b	2.89 a	16.43 b	18.07 a	251 b	302 a
		LSD: $_{ECi}$ = 0.08 ; $_{soil}$ = 0.37		LSD: $_{ECi}$ = 2.30 ; $_{soil}$ = 0.51		LSD $_{soil}$ = 23.66	

Means in each column followed by different letters are significantly different according to Fisher's LSD ($P < 0.05$) ns for not significant.

Salinity affected mean N with the Clovelly having a significantly lower mean N of 2.63% and Bainsvlei having a mean of 2.89%. Treatment effect was only significant at a lower EC_i range (< 600 mS m^{-1}). However, in all cases the mean N content was higher than the 1.87% associated with the Cocktail malt barley cultivar. Calculated as the function of N content and conversion factor of 6.25, crude protein content was also variable among EC_i treatments and ranged from 14.6 to 17.56% and 16.86 to 19.11% for the respective Clovelly and Bainsvlei soil types. The mean water soluble protein ranged from 219 to 269 mg g^{-1} and 286 to 323 mg g^{-1} for the respective Clovelly and Bainsvlei soil types.

Grains from lower EC_i treatments had inherently large and plump kernels while from higher EC_i treatment had steely or flinty grains. Steely grains erratically acquired rootlets and shoot growth during germination tests (Figure 4.4) because of higher N content (Chandra *et al*., 1999; Beckles & Thitisaksakul, 2014).

Figure 4.4: Erratic development of shoots and roots after of steely grains obtained from the Bainsvlei soil in the second season. From left to right, 1200 mS m^{-1}, 600 mS m^{-1} and 450 mS m^{-1} during the first 24 hours of germination tests.

Grain carbohydrates

Malt barley grain mean maltose, sucrose and glucose contents showed no significant differences between treatments and soil types in the first season (Table 4.4). In the second season, soil type had a significant effect on glucose and sucrose levels. Both these carbohydrates were significantly higher in the Clovelly compared to the Bainsvlei soil type (Table 4.5).

Table 4.4: Significance levels (Pr>F) of selected grain carbohydrate parameters as affected by main effects (Soil and EC levels) and the interaction between main effects

Season	Source	Glucose	Sucrose	Maltose
First	Soil	0.5984 ns	0.7801 ns	0.2996 ns
	EC_i	0.1379 ns	0.3799 ns	0.2509 ns
	Soil*EC_i	0.6983 ns	0.7445 ns	0.6037 ns
Second	Soil	0.0269 *	0.0288 *	0.0936 ns
	EC_i	0.7421 ns	0.7518 ns	0.6446 ns
	Soil*EC_i	0.1011 ns	0.0666 ns	0.3465 ns

*Significant at the 0.05 probability level. ns for not significant.

Table 4.5: Mean glucose and sucrose (mg g^{-1}) of grains as affected by EC_i treatments on the Clovelly and Bainsvlei soil types in the second season

Carbohydrate	EC_i (mS m^{-1})	Clovelly	Bainsvlei
Glucose	Control	0.20 ns	0.14 ns
	450	0.24 ns	0.14 ns
	600	0.25 ns	0.19 ns
	900	0.15 ns	0.22 ns
	1200	0.29 ns	0.13 ns
	Mean	0.23 a	0.16 b
		LSD $_{soil}$ = 0.07	
Sucrose	Control	0.35 ns	0.26 ns
	450	0.42 ns	0.29 ns
	600	0.51 ns	0.33 ns
	900	0.31 ns	0.46 ns
	1200	0.61 ns	0.19 ns
	Mean	0.44 a	0.31 b
		LSD $_{soil}$ = 0.13	

Means in each column followed by different letters are significantly different according to Fisher's LSD ($P < 0.05$) ns for not significant.

Grain malting potential

Mean germination index (GI) for barley grain from different EC_i treatments for the Clovelly and Bainsvlei soil types in the first and second season is presented in Table 4.6. The GI was used to predict malting potential of barley grains using a scale of 1 to 10 with malting potential increasing with the scale values. Higher GI of 6 to 7 were associated with the control and 450 EC_i treatments in the first and second season. The first season had higher GI values compared to the second season for all EC_i treatments. Lower (<5.5) GI values were associated with the 900 and 1200 mS m^{-1} EC_i treatments and were variable between soil types.

Table 4.6: Mean germination index values of all EC_i treatments for both soils in the two seasons

		EC_i (mS m^{-1})				
Season	Soil	Control	450	600	900	1200
First	Clovelly	5,96	5,90	5,87	5,79	5,71
	Bainsvlei	6,77	6,11	5,84	5,89	6,02
Second	Clovelly	6,00	5.83	5,51	5,27	5,5
	Bainsvlei	5,67	5,76	5,39	5,37	5,37

4.4 Discussion

This chapter quantified the effect of EC_i treatments on 1000 seed weight, selected germination characteristics, grain proteins, and carbohydrates as well as assessed the malting potential. These grain quality characteristics were variably affected by soil type differences and EC_i treatments, however, more pronounced differences were mostly observed in the first season.

Malt barley seed weight was affected ($P<0.05$) by soil type and not EC_i treatment in the first season and in the second season it was the opposite. The buffering capacity of the Bainsvlei soil type could have been overridden by the higher salinities in the second season. For both seasons, higher seed weights were associated with the control (150 mS m^{-1}) up to 450 mS m^{-1} for the Bainsvlei and up to 600 mS m^{-1} for the Clovelly. Work by Bagheri (2011) and Ayers *et al*. (1952) proposed that salinity has minimal effect on grain weight of malt barley because of higher tolerance and acclimatisation to saline conditions. However, other authors reported that continuous water stress, whether induced by deficit irrigation (Ozturk & Aydin, 2004; Bello *et al*., 2017) or by osmotic effect (Hassan *et al*., 1970; Bagwasi, 2015; Haffez & Hassan, 2015), reduces seed weight of cereal grains. This shows that, progressively, high salinities as was the case in the second season, significantly reduces grain weight. The finding supports the work of Wardlaw *et al*. (1980) who stated that grain weight is mainly determined by the rate and duration of the grain-filling period. Therefore, any stress shortening this period will significantly reduce the final grain weight. This includes coarse textured soils with low water retention properties.

One of the key qualities of malting barley is its ability to germinate rapidly and homogeneously. According to the minimum standards for homogeneity in barley during malting, viability, germinative energy and germination percentage must not fall below 98, 95 and 97%, respectively (ARC, 2017). However, these minimum requirements were increasingly unsatisfied with increased salinity with germinative energy percentage failing in all EC_i treatments including the control. Frankakova *et al.* (2012) also noted that testing of the barley samples in the first weeks after the harvest showed low values for germinative energy and germination index due to persisting dormancy. Although the reason was not highlighted, several research findings also indicated lower germination percentage of barley seeds even for the control treatment. Al-Seedi (2008) found 90% for the control treatment of distilled water, El-Dardiry (2008) recorded 77% for the control treatment of 50 mS m^{-1}, while Yousofinia *et al*. (2012) observed between 80 and 90% for four barley cultivars when the control treatment was 0 Mm NaCl. Adjel *et al*. (2013) also found a lower germination percentage of 86% for the control treatment of 0 mM of NaCl. Kumar *et al*. (2013) stated dormancy as a factor that interferes with the rapid and homogeneous germination of malt barley grains. Many hypotheses have been proposed to explain the mechanism of seed dormancy, including the hormone balance theory, the metabolic deficiency theory and the changes in grain respiration. However, because of its complexity, the fundamental basis of the induction, maintenance and termination of dormancy is poorly understood (Woonton *et al*., 2005; Rodriuez *et al*., 2015; Shu *et al*., 2015).

Barley with extensively high or low N content cannot produce malt of the required quality for brewing purposes. The mean N contents were higher than 1.87% associated with the Cocktail malt barley cultivar used in this study while crude protein was higher than the maximum allowable limit, i.e. between 9% and 11.5% (ARC, 2017). Results of the first season that showed a general increase in N with an increase in salinity are in accordance with Izadi *et al*. (2014). However, the second season N results supported Bagheri (2011) who reported that increases in salinity did not highly affect the protein content of barley. With significant differences observed only at a lower EC_i range (< 600 mS m^{-1}), findings from this study are in accordance with Agastian *et al.* (2000) who reported that soluble protein increases at low salinity and decreases at high salinity in mulberry. Nonetheless, what is known is that, reduced biomass in stressed plants is often the result of reduced photosynthetic carbon assimilation and the concentration of all other elements tends to be increased, leading to higher crude protein and mineral concentrations (Ashraf, 2004). Though high protein content presents difficulties with homogeneity during malting, *AB-InBev* will still buy grain with such low quality and rather have it malted differently. This is done to honour the contract entered into with barley producers. However, such grain still fetches a lower premium (Els, 2017).

Malt extract quality is influenced by the starch content of the grain and it is of great economic importance as it indicates the cultivar’s potential for beer yield. In the second season, soil type had a significant effect on glucose and sucrose levels. Both these sugars were significantly higher in the Clovelly compared to the Bainsvlei soil type, a result that could be attributed to the Clovelly’s porous texture, which did not support capillary rise of dissolved salts or accumulation in the root zone. Increased salinity was observed to increase soluble saccharides in the shoots of barley (Bagheri, 2011). On the contrary, in this experiment, sucrose levels generally increased with a decrease in the clay content of the soil. This is not surprising given that, sugar changes do not follow a static model and vary with the genotype and the stress factor (Rosa *et al*., 2009). A consequence of enhanced amino acid remobilization under stress conditions is that, protein synthesis is less affected and in contrast, synthesis of carbohydrates in seeds is affected as it depends primarily on concurrent carbon fixation during grain filling. Hence, nutrients translocation processes favours protein accumulation over starch deposition (Clarke *et al*., 1990; Ozturk & Aydin, 2004; Izadi *et al*., 2014; Hafez & Hassan, 2015).

The barley malting potential decreased with salinity and this result was expected because of the negative effects salinity has on plant water uptake and physiological development. In this study, malting potential was nearly similar ranging from five to seven for both soil types and seasons suggesting that the nutritional composition of the malting barley grains were similar. However, the general decline in germination index with increase in salinity was fairly represented in this study since malting potential from the control was approximately seven and variably decreased to about five in the 1200 mS m^{-1} EC_i treatment. Malt extract is influenced by the starch content of the grain. It is therefore of a great economic importance as it indicates the cultivar's potential for beer yield (Fox *et al*., 2003).

4.5 Conclusions

The objective of this chapter was to quantify the effect of increasing irrigation water salinity (EC_i, mS m^{-1}) on barley grain-quality characteristics of the Cocktail cultivar grown for two seasons on the Clovelly and Bainsvlei soil types. Mean of 1000 seed weight was variably affected by soil type and EC_i (150 to 1200 mS m^{-1}) treatments and decreased with increased salinity above 600 mS m^{-1} in particular. Salinity played no major role in the germination characteristics of malt barley and rather these characteristics were primarily influenced by the inherent property of grains, particularly dormancy.

In all salinity treatments, the mean N content was higher than the 1.87% associated with the Cocktail malt barley. Crude protein was variable and decreased by 2% with increase in salinity particularly for the Bainsvlei soil type in the second season suggesting cumulative salt built up favoured higher N content and crude protein. For carbohydrates apart from maltose that remained stable, glucose and sucrose was affected ($P<0.05$) by increased salinity in the first season. Effect of limited water availability due to salinity shortened the maturity period resulting in accelerated senescence that altered carbohydrate translocation processes.

Overall, grain quality characteristics were mostly affected by salt accumulation as was reflected by lower (<5.5) germination index values associated with the 900 and 1200 mS m^{-1} EC_i treatments. Peculiar however was the interchange in performance of the two soils between the two seasons. For Clovelly and Bainsvlei higher grain quality was associated with respective EC_i of under 600 and 450 mS m^{-1} in the first season and in the second it was the opposite. This result was indicative of the course textured Clovelly ability to redistribute salts under lower (EC_e of 706 mS m^{-1}) salinity, but for higher salinity (EC_e of 919 mS m^{-1}) the

Bainsvlei buffering capacity was able to minimise the impact of increasing salinity. The study therefore concludes that exclusive saline irrigation with no provision for leaching variably affects grain quality characteristics associated with malting and that, biochemical responses to salinity is a complicated subject that is influenced by the soil-plant-atmosphere continuum.

Chapter 5: General conclusions and recommendations

5.1 General conclusions

Irrigation water quality is an important factor in irrigated grain crop production and affected processing minimum grain-quality characteristics especially malting barley grain quality. In arid and semi-arid areas, regional and provincial river basins and dams are a primal water source for irrigation schemes and due to the vastness of their catchments contain substantial levels of dissolved salts. South Africa has about 6% (94050 ha) of irrigation schemes affected by salts and waterlogging and has limited local malt barley production to about 65%. Improving production up to 90% requires comprehensive knowledge and understanding of the factors influencing malting barley grain production and quality, irrigation water salinity in particular. Hence, this dissertation had two objectives to investigate concerning malting barley: (I) the effect of increasing irrigation water salinity (EC_i) on water use and grain yield and, (II) the effect of increasing irrigation water salinity (EC_i) grain quality characteristics. The study was conducted under field-lysimeters conditions, keeping the shallow groundwater table constant by daily sub-irrigation. Five different water qualities were irrigated manually on the surface of the Clovelly and Bainsvlei soils. In this chapter, the study's main conclusions and recommendations are presented.

Based on the first objective addressed in Chapter 3, crop water use in terms of evapotranspiration and groundwater table depletion as well as grain yield was found to decrease with increasing irrigation water salinity. Despite the increased contribution of groundwater table depletion to evapotranspiration on the Bainsvlei soil form in particular, groundwater table depletion decreased to zero at irrigation water salinity above 1200 mS m^{-1} and was indicative of the detrimental effect of saline conditions on the productive potential of groundwater table. In the first and second season, soil salinity profiles under different irrigation water salinity regimes dependent on initial soil salinity status suggesting that seasonal soil salinity management was essential especially under shallow water table conditions. Nevertheless, in both seasons, irrespective of soil types, the effect of salinity was comparatively lower on the Bainsvlei compared to the Clovelly soil form due to the buffering capacity (higher cation exchange capacity) associated with the higher clay content. Declining grain yields with irrigation water salinity showed that even though crop cultivars of high salt tolerance and soils of high buffering capacity is used, saline conditions induce abiotic and biotic stresses to crop growth and yields.

To this effect, this relationship between soil salinity and grain yield of barley was more sigmoidal than linear as had been generally accepted through the use of the Maas & Hoffman (1977) threshold values. The Cocktail barley cultivar used in this study showed more tolerance to salinity than barley generally is as highlighted by the lower c_{50} parameters observed on the sigmoidal function. Water productivity results echoed by Dlamini *et al*. (2017) showed that it is imperative to use transpiration and not evapotranspiration to assess crop water productivity.

With a mean EC_i of 52.22 mS m^{-1}, increases of up to 6.82 mS m^{-1} per annum were projected for a 50-year period at Vaalharts irrigation scheme (Du Preez *et al*., 2000). This implies a steady decrease of irrigation water quality over time (Herold & Bailey, 1996; Du Preez *et al*., 2000 Darko *et al*., 2016). Therefore, in 32 years' time, EC would have reached the 400 mS m^{-1} range and henceforth the demonstrated effects of decreasing irrigation water quality felt.

With respect to the second objective addressed in Chapter 4, 1000 seed weight decreased linearly and was affected ($P < 0.05$) by increasing water salinity and showed that salinity was detrimental to the grain mass of barley. However, irrigation water salinity had no effect on germination characteristics (germination percentage, germinative energy and viability) of malt barley. Furthermore, lower germination performances were generally influenced by the high grain dormancy that is characteristic of the barley crop. This pointed to the fact that seed treatment to break dormancy before malting was essential. A germination index lower than 5.5 showed that the accumulative salinity, especially for the 900 and 1200 mS m^{-1} EC_i treatments, affected the malting potential of malt barley. Mean grain nitrogen content for all treatments was above the cultivar's inherent mean of 1.87% and was suggestive of the altered translocation mechanisms resulting from accelerated senescence.

Although responsible factors were not identified, possibility of a downgrade to feed barley was listed as a key risk for producers in the Northern Cape production areas (Demana, 2015). Results of this study offers irrigation water quality as a possible factor for the downgraded barley and associated profit loss in these regions.

5.2 Recommendations for future research

The study investigated grain yield and quality characteristics of malt barley that are required for malting purposes as affected by salinity. The results indicated that saline conditions reduces water use and grain yield with ultimately inferior quality under semi-controlled conditions, therefore, the following recommendations can be made:

- Although the results of this experiment could be applicable to irrigated fields located in semi-arid and arid regions with water tables, of sand to sandy loam soils, they could be verified by repeating under more controlled and on-farm field conditions.
- It would be beneficial to explore management of irrigated cumulative seasonal soil salinity under shallow groundwater tables with and without provision for drainage and leaching, especially during fallow periods.
- Further research is needed to explore interactive effects of salinity and other abiotic stresses on grain quality and influence of cultivar variations. Furthermore, the financial impact on grain processors should also be addressed.
- A more suitable model describing the relationship between grain yield and soil salinity for specific crops should be identified and used for salinity related studies to avoid the assumption of a linear relationship. Additionally, salinity threshold values also need to be determined for South African cultivars to assist in management of irrigation with marginal quality water.
- Knowledge of barley response to salinity especially in terms of dormancy, would improve management practices in fields, increase our understanding of salt tolerance mechanisms of this cereal grain, and hence improve its irrigated production.
- In South Africa there is no equation linking grain quality characteristics directly to malt quality like the Bishop Equation or the Equation developed by Blazewicz *et al*. (2007). It would be worthwhile to invest in developing such an equation for South African malt barley cultivars to be used as a prediction tool for producers, processors and researchers.

The results of this study are applicable to irrigated fields in arid and semi-arid regions with shallow groundwater tables, of sand to sandy loam soils. Therefore, care should be taken when interpreting and extrapolating these findings.

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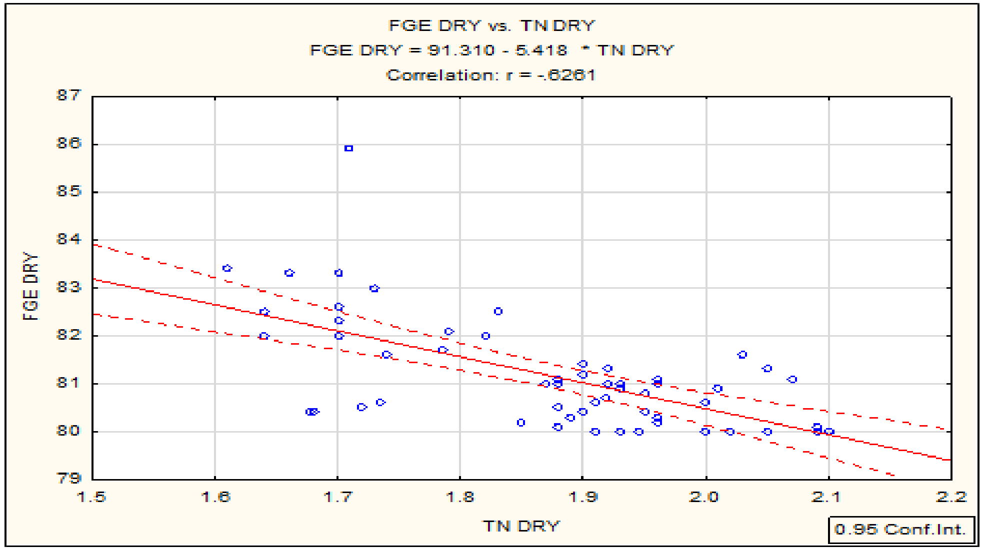
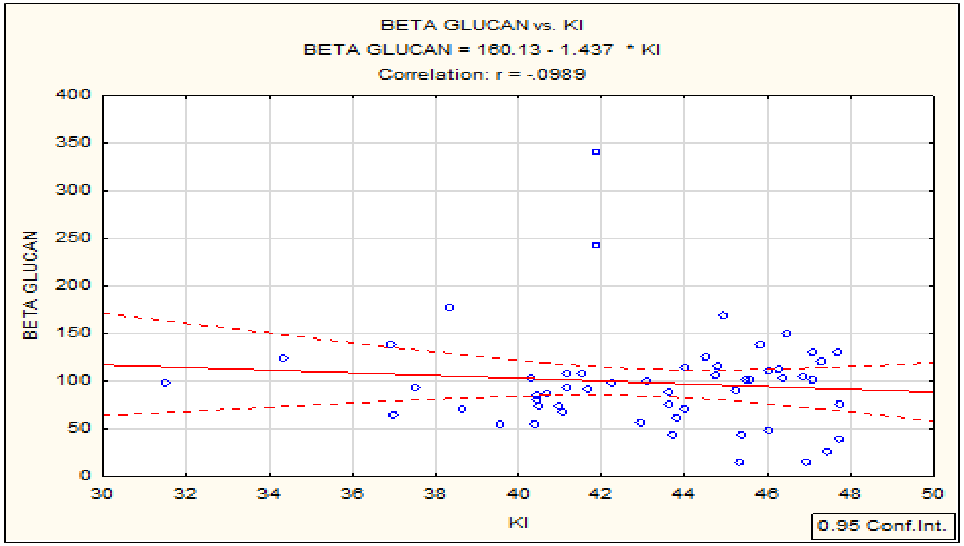
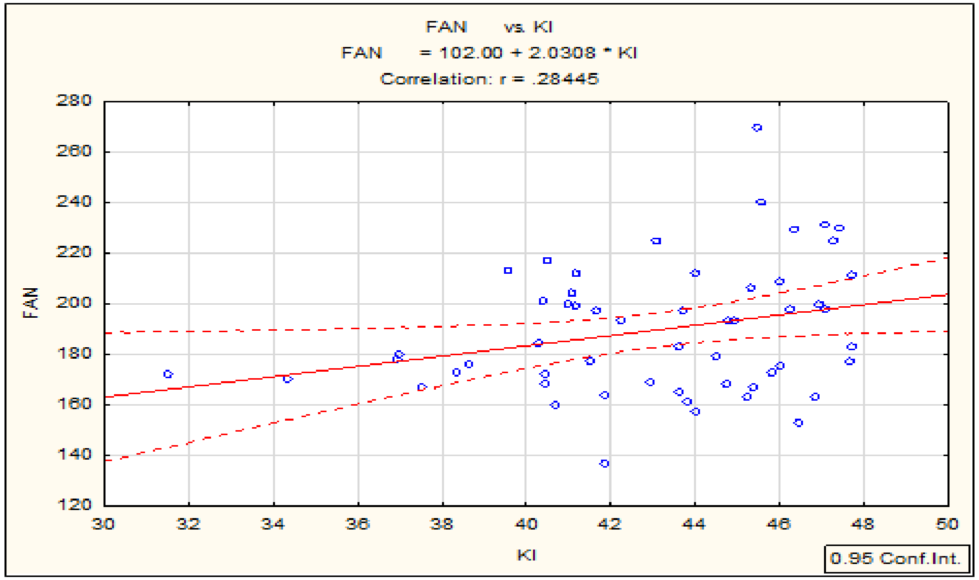
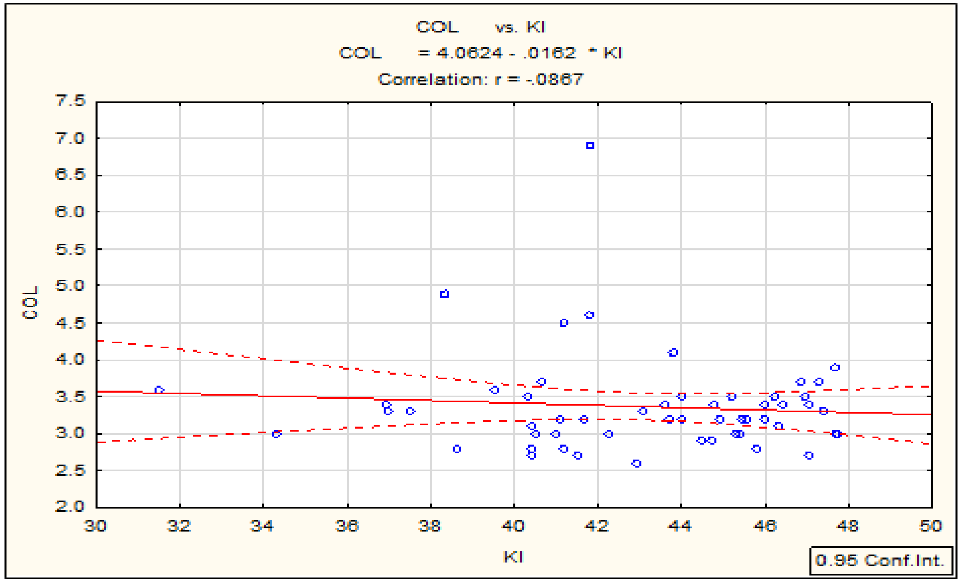
Appendices

Appendix 2.1: South African malt extract calculator based on the total soluble nitrogen (TSN) of malted barley.









Appendix 3.1: Long term mean minimum (Tx) and maximum (Tn) temperature, relative evapotranspiration (ETo) as well as minimum (RHx) and maximum (RHn) relative humidity for 16 years

Year	Month	Tx	Tn	ET_0	RHx	RHn
2000	6	19,19	0,69	2,05	83,16	26,61
2001	6	18,48	2,39	1,99	89,47	33,82
2002	6	16,83	-0,15	1,93	92,57	32,11
2003	6	17,55	-2,00	2,17	85,93	23,83
2005	6	19,60	1,76	2,85	81,82	24,86
2006	6	18,71	-0,66	2,36	89,96	25,38
2007	6	17,06	0,44	2,02	90,48	31,21
2008	6	19,04	1,96	2,13	90,12	27,96
2009	6	18,31	2,55	1,41	90,20	34,20
2010	6	19,33	-0,86	2,07	86,88	23,11
2011	6	17,64	-0,39	1,88	91,32	28,26
2012	6	18,27	1,74	2,01	81,53	29,21
2013	6	20,42	-1,05	2,55	74,30	17,70
2014	6	19,70	-1,03	2,20	77,96	20,23
2015	6	19,04	1,07	2,26	85,94	26,82
2016	6	19,64	2,60	2,21	86,32	28,44
	mean	**18,68**	**0,57**	**2,13**	**86,12**	**27,11**
2000	7	17,44	-1,36	2,15	80,93	21,82
2001	7	16,47	-0,40	2,11	89,55	29,10
2002	7	17,38	-2,35	2,37	86,89	22,65
2003	7	23,90	2,50	2,49	50,30	14,00
2005	7	20,43	0,15	2,66	76,62	19,15
2006	7	19,94	0,43	2,88	80,05	23,50
2007	7	18,25	-1,22	2,49	78,83	20,69
2008	7	19,70	-0,22	2,56	80,15	20,83
2009	7	18,06	-1,85	2,08	81,12	21,46
2010	7	20,73	1,62	2,22	78,62	21,57
2011	7	18,48	-2,02	1,99	87,87	21,10
2012	7	19,23	-1,01	2,51	81,38	19,27

2013	7	21,29	1,50	2,62	74,04	21,61
2014	7	18,96	-1,86	2,30	74,14	19,22
2015	7	19,54	2,18	2,45	78,72	24,08
2016	7	18,31	0,83	4,19	79,43	24,76
	mean	**19,26**	**-0,19**	**2,50**	**78,67**	**21,55**
2000	8	22,33	1,73	3,23	62,82	14,96
2001	8	19,74	0,04	2,96	77,71	20,92
2002	8	20,60	3,81	2,66	85,29	29,19
2003	8	19,38	-0,09	3,13	74,93	19,50
2005	8	22,51	3,14	3,89	71,15	19,15
2006	8	18,50	3,07	3,38	88,86	32,08
2007	8	22,39	0,79	3,78	67,73	16,89
2008	8	23,26	3,65	3,48	65,25	16,18
2009	8	22,25	2,49	3,09	68,27	17,53
2010	8	23,06	1,44	3,19	73,66	15,09
2011	8	22,12	1,68	3,25	81,03	17,57
2012	8	23,37	3,77	3,67	64,67	16,68
2013	8	21,24	1,05	3,38	70,39	15,20
2014	8	21,92	3,96	3,01	70,27	18,82
2015	8	25,57	4,11	3,58	60,09	12,49
2016	8	22,59	3,20	5,24	76,06	16,78
	mean	**21,93**	**2,37**	**3,43**	**72,39**	**18,69**
2000	9	22,75	5,15	3,90	72,56	22,77
2001	9	21,77	4,90	3,51	85,07	26,66
2002	9	24,00	6,18	3,78	84,37	23,57
2003	9	24,70	5,17	4,18	73,83	18,94
2004	9	23,89	4,80	3,39	77,09	20,02
2005	9	27,18	7,31	4,83	60,36	13,68
2006	9	24,50	5,48	4,64	79,13	17,75
2007	9	28,86	7,63	5,12	59,92	16,01
2008	9	25,54	3,84	4,80	60,35	10,92
2009	9	27,24	6,18	4,57	59,29	12,50
2010	9	28,58	6,92	4,35	63,34	13,24

2011	9	26,90	5,29	5,01	67,45	12,82
2012	9	24,59	4,52	4,40	70,21	15,29
2013	9	26,00	4,58	4,78	49,02	9,85
2014	9	28,90	7,18	4,50	53,39	10,58
2015	9	27,35	8,25	4,53	70,92	17,97
2016	9	26,43	6,91	7,13	64,23	14,99
	mean	**25,83**	**5,95**	**4,60**	**67,37**	**15,92**
2000	10	27,60	11,71	4,73	79,79	20,07
2001	10	26,97	11,03	4,45	82,78	25,36
2002	10	28,32	9,49	5,14	74,52	16,58
2003	10	29,80	12,85	5,39	94,40	23,30
2004	10	27,22	9,24	5,04	83,38	20,40
2005	10	27,32	10,81	5,50	75,76	20,89
2006	10	28,03	11,01	5,22	84,51	22,66
2007	10	25,63	10,64	4,51	93,20	30,50
2008	10	31,01	11,01	5,92	68,21	12,67
2009	10	27,74	11,33	4,64	86,94	24,82
2010	10	29,13	9,61	5,02	72,91	14,37
2011	10	28,40	8,34	5,60	65,67	12,73
2012	10	28,50	10,11	5,52	71,80	17,00
2013	10	28,97	9,08	5,67	64,39	13,25
2014	10	30,56	10,56	5,39	68,06	12,39
2015	10	33,01	12,74	5,94	64,18	10,64
2016	10	29,98	9,81	7,87	60,39	12,43
	mean	**28,72**	**10,48**	**5,43**	**75,69**	**18,12**
2000	11	27,01	10,50	5,27	85,29	22,98
2001	11	25,07	12,57	4,07	91,68	41,35
2002	11	28,60	10,13	5,78	78,62	16,37
2003	11	29,02	11,54	5,62	83,00	15,12
2004	11	32,48	14,43	6,30	75,14	14,83
2005	11	29,42	12,50	6,29	81,58	19,47
2006	11	28,19	12,24	5,66	87,35	26,23
2007	11	28,99	10,86	6,01	85,29	21,73

2008	11	30,83	13,61	6,06	83,59	21,10
2009	11	28,73	11,73	5,46	83,78	24,22
2010	11	30,62	12,88	5,41	84,90	22,16
2011	11	30,90	10,02	6,88	68,68	12,12
2012	11	31,81	13,01	6,34	73,36	14,96
2013	11	30,82	12,52	6,62	71,84	16,76
2014	11	27,07	12,78	4,75	81,96	25,71
2015	11	31,32	11,23	6,92	60,76	10,85
2016	11	32,04	14,96	6,27	77,80	17,94
	mean	**29,58**	**12,31**	**5,90**	**79,33**	**20,06**
2000	12	30,17	14,43	5,94	85,04	23,01
2001	12	27,14	13,15	5,18	93,59	33,76
2002	12	29,26	14,04	5,15	87,93	29,65
2003	12	28,86	13,47	6,72	90,70	24,13
2004	12	31,29	15,30	6,02	88,45	22,88
2005	12	31,10	13,96	7,05	75,87	15,21
2006	12	31,26	14,56	6,32	82,61	22,99
2007	12	30,19	14,00	5,54	90,69	28,52
2008	12	34,08	15,86	6,38	77,85	16,00
2009	12	34,28	14,57	6,82	83,97	15,18
2010	12	30,75	13,71	5,35	87,19	25,23
2011	12	30,63	13,94	5,95	86,76	22,33
2012	12	28,98	14,20	5,11	89,86	31,93
2013	12	29,89	14,56	5,87	84,57	26,05
2014	12	31,31	16,70	5,19	77,40	23,63
2015	12	36,26	16,70	7,53	63,34	10,08
2016	12	34,52	16,60	7,78	73,64	16,25
	mean	**31,17**	**14,71**	**6,12**	**83,40**	**22,74**
	Long term seasonal mean	**25,02**	**6,60**	**4,30**	**77,57**	**20,60**

Appendix 3.2: Mean daily ET for the Clovelly and Bainsvlei soil types during the first and second season as affected by EC_i treatments

			Clovelly					Bainsvlei				
Season	DAP	ETo (mm)	Control	450	600	900	1200	Control	450	600	900	1200
First	0		0	0	0	0	0	0	0	0	0	0
	15	3	0	0	0	0	0	0	0	0	0	0
	22	2	2	1	0	1	6	2	3	1	3	1
	29	3	3	3	3	4	2	4	3	3	3	2
	36	3	3	3	3	0	1	3	4	1	3	1
	60	3	2	1	2	0	2	2	1	1	2	2
	64	4	5	3	3	2	3	7	7	3	2	5
	71	5	3	3	2	3	3	4	4	3	3	4
	78	6	3	6	4	3	5	5	5	3	2	3
	85	6	6	5	6	7	6	9	9	10	7	7
	92	6	6	8	4	6	6	7	8	6	5	5
	99	6	5	8	7	7	5	8	7	4	4	10
	113	6	11	8	5	6	5	6	4	8	10	9
	120	7	9	6	11	13	8	17	15	15	13	7
	127	8	3	7	11	6	4	7	8	12	8	7
		Mean	4,07	4,13	4,07	3,87	3,73	5,4	5,2	4,67	4,33	4,2
Second	0		0	0	0	0	0	0	0	0	0	0
	54	6	0	0	0	0	0	0	0	0	0	0
	61	7	4	2	1	1	1	4	3	3	1	3
	68	6	7	5	6	4	4	7	5	4	5	4
	75	8	9	1	5	5	4	7	4	5	6	4
	84	8	4	7	3	1	2	6	7	5	2	2
	89	9	9	3	4	5	3	8	5	3	3	3
	97	8	6	4	4	4	4	7	7	6	5	4
	105	6	7	5	5	2	2	8	5	6	3	2
	112	8	10	10	5	2	2	9	8	7	3	2
	119	6	8	5	4	2	2	8	9	5	2	2
	126	5	5	1	3	2	2	7	3	4	2	2
	133	7	1	5	1	2	2	4	5	3	2	2
		Mean	5,14	3,94	3,75	2,66	2,38	5,83	4,95	4,51	3,09	2,75