Evaluation of salinity and irrigation guidelines for lucerne

By

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DECLARATION

I, Kevin Louis Fourie, declare that the master's degree research dissertation of interrelated publishable manuscripts/published articles or course work Master's degree mini-dissertation that I herewith submit for the Master's Degree qualification in Inter-disciplinary Soil Science at the University of the Free State in my independent work, and that I have not previously submitted it for a qualification at another institution of higher education.

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ABSTRACT

Evaluation of salinity and irrigation guidelines for lucerne remains important to improve current management practices under irrigation. Internationally, well-established yield response curves, set over 30 years ago, serves as a general guide for salinity management. However, more specific guidelines for lucerne production under South African conditions are needed. The aim of this study was to determine the effect of increasing irrigation and soil water salinity on the water uptake and yield of lucerne and evaluate simulations of these results, with the model SWAMP, under osmotic stress conditions.

An experiment was conducted in a non-weighing lysimeter facility. Lucerne (cv. SA Standard) was grown under controlled conditions using irrigation water with salinities that ranged from a control treatment up to 1200 mS m^{-1}. Irrigation water of the different treatments consisted of various amounts of salts to achieve the desired concentrations. The soil water balance was used to reflect on water gains and losses during the growing season. The mean daily transpiration rate as well as the seasonal transpiration of the cuttings decreased with increasing irrigation water salinity. Similarly, water table depletion and yield decreased with increasing water and soil salinity. The relationship between relative mean above-ground biomass and water salinity was curve linear, which differs from the well-established relationship reported in literature. A calculated critical level divided water and soil salinity into two management classes each with different rates of a reduction in yield. A linear decrease in the crop productivity with an increase in water salinity was obtained. The cultivar SA Standard is more salt tolerant than those used in literature.

Results from the lysimeter trail was used to validate water uptake and yield simulation under osmotic stress conditions with SWAMP. Most of the soil parameters e.g. evaporation, transpiration, root density, infiltration and redistribution of rainfall and/or irrigation water, drainage and water table uptake have been calibrated for the two soils. Data from the control treatment was used to calibrate the parameters used in simulating the transpiration requirement. Default values were used for the remaining parameters. Various indices and test statistics were aggregated into a single indicator module (I_{SWAMP} when 0 = good and when 1 = poor) with a fuzzy-logic based expert system, which represent the model's aggregated accuracy, correlation and pattern performance. SWAMP was able to reasonably simulate a yield decline due to an in increase in water salinity (I_{SWAMP} = 0.0903), which was also true for seasonal transpiration (I_{SWAMP} = 0.0305).

Weekly simulations of transpiration were not good. A high pattern value indicated the presence of some macro-patterns. This was attributed to the fact that the residuals were not evenly distributed during the growing season, which was not the case with an increase in water salinity. Hence, the crop growth algorithm for simulating the daily transpiration requirement needs to be improved.

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CHAPTER 1
INTRODUCTION

1.1 Motivation

Lucerne (*Medicago sativa* L.) has established itself as a major crop amongst forage and field crops in the world (Dovrat, 1993; Wang *et al*., 2013). In South Africa the crop is well established in six of the seven provinces. Ten present, or 150 000 ha of the total irrigated area in the country is currently under lucerne, this constitutes 90% of the South African lucerne production (Gronum *et al*., 2000). Approximately 3.7 million tons of hay are produced every year on this area (Gronum *et al*., 2000), compared to the 0.28 million tons of teff, 3 million tons of wheat and 9 million tons of maize (National Department of Agriculture, 2013).

Lucerne is a commonly used forage crop because of its lower production costs, high feed-quality (digestibility and protein content) and regular availability throughout the year. Unfortunately there is an awareness that lucerne is a luxurious water user. Lucerne uses anything from 800 to 1600 mm of water per growing season (FAO, 2012a). This puts immense pressure on a country that only receives a mean annual rainfall of 480 mm (Van Rensburg *et al*., 2012). This low and unreliable rainfall is the reason why more than 70% of fresh water in South Africa is used by irrigators to sustain food production (Department of Water Affairs and Forestry, 1996). One of the biggest problems with irrigation is the deterioration of water quality of both surface and groundwater (Backeberg *et al.*, 1996).

This problem is more relevant in semi-arid regions with low rainfall and high evaporative demand, which strongly contribute to increase in soil salinization (Viégas *et al.*, 2001). Subsequently, a combination of salts from irrigation water will end up in the soil, provided that no leaching of salts occurs. Irrigated soils require some level of leaching to control salinity in the root zone, however it is important to quantify the change in soil water content with a soil water balance, in order to maintain adequate soil-water availability to the crops. The disposal of saline drainage water is a big environmental problem that leads to degradation of water resources. Studies show that this is happening in the Vaal, Harts, Riet and Orange rivers (Du Preez *et al.,* 2000), as well as the Breede, Berg, Great Fish and Sundays rivers (Ghassemi *et al*., 1995).

Salts in soil water decrease the total soil water potential, which is comprised of matric and osmotic potentials (Hillel, 2000). Hence, salts reduce the osmotic potential of water, increasing the energy that plants use to extract moisture from soil. As a result of the osmotic gradient between the roots of the plant and the soil solution, less water is taken up, leading to stress conditions similar to that of drought (Moolman *et al.,* 1999; Van Rensburg, 2010). In addition to contributing to water stress, salt ions like Na^+ and Cl^- inherently accumulate through passive entry into the leaves and stem of the plant, causing impairment of both biochemical and photochemical processes of photosynthesis (Munns & Tester, 2008; Dinler *et al*., 2014). Plants undergo some metabolic alterations that affect activities like transpiration, respiration, protein synthesis, nucleic acid, chlorophyll as well as carbohydrate and enzyme activity (Guerrero-Rodriguez, 2006).

Dramatic differences in response to salinity are found among plant species. Various crops have a higher threshold to poor water quality compared to other crops, as documented by Maas & Hoffman (1977). This work done by Maas & Hoffman has become the standard salinity guidelines used in South Africa over the past 40 years. Some crops can produce acceptable yields at much greater salinity levels that others. This is because they vary in their ability to make the needed osmotic adjustments, like producing organic solutes like proline, betaine or sugars to be able to extract water from the soil profile (Guo *et al*., 2016).

Extensive research has been done on the effects of salt stress on vegetative growth of lucerne, including germination, seedling development, plant physiology, and shoot biomass (Castroluna *et al.,* 2014; Guo *et al.,* 2016). In addition, the effect of salinity on the nutritive value, like fibre and digestibility and chemical composition of lucerne are well documented (Guerrero-Rodriques, 2006: Eman *et al*., 2009). Various studies have also examined the effects of different strains of lucerne-*Rhizobium* (Latrach *et al*., 2014), as well as seed priming to overcome salinity stress in this crop (Sepehri *et al*., 2015).

On-farm management of lucerne and the effects of irrigation water salinity and soil water salinity remains problematic, due to fluctuations in the complex interaction of factors affecting crop water use. Simulation models are important tools to help understand the effect that plant-soil interactions have on the water balance components as well as the effects of salinity on crop growth. These models can assist in decision making because quantification of irrigation, evaporation, transpiration, drainage, runoff and change in soil water content is possible. Hence, the usage of an alternative model that does not rely on salinity thresholds and slope parameters i.e. the **S**oil, **WA**ter, **M**anagement **P**rogram (SWAMP)

It is not clear how one of the most recognised and cultivated South African cultivars (‘SA Standard’) compares to the lucerne cultivars used by Maas & Hoffman (1977) to establish the various salt tolerance guidelines set 40 years ago.

An additional concern raised by Sanden & Sheesley. (2007) is that it is unclear whether the yield decline found by Maas & Hoffman (1977), was due to sodium or chloride, or a combination of these elements. Information about the cultivars used in developing these norms are not freely available, and according Sanden & Sheesley (2007) these norms were established under tightly controlled conditions in sand tanks using a saline solution dominated by sodium and chloride.

Therefore, the effect of irrigation water salinity and soil water salinity on lucerne will be addressed in this study to determine the effect on the transpiration, biomass yield, water table depletion and the crop water productivity of lucerne.

1.2 Specific objectives

Specific objectives were:

(1) (i) to quantify the effect of EC_i on transpiration, water table depletion and yield of lucerne, (ii) to determine the relationship between EC_i and relative biomass yield, as well as EC_e and relative biomass yield, and (iii) and assess crop water productivity as influenced by irrigation water salinity.

(2) to establish how credible SWAMP will be in simulating (i) yield decline with increasing irrigation water salinity, (ii) seasonal transpiration and (iii) weekly transpiration of lucerne, grown on sandy to sandy loam water table soils in semi-arid regions, under conditions of osmotic stress.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Water stress has become a worldwide problem and is a severe threat to sustainable agriculture (Castroluna *et al*., 2014). The United Nations Food and Agricultural Organization (FAO, 2012b), projects that feeding a world population of 9.7 billion people by 2050 would require raising overall food production by some 70% between 2005/2007 and 2050. According to Haka (2010), irrigation will play a prominent role in meeting this projection made by the FAO. However, one of the biggest concerns with regards to irrigation is salinization of irrigation water and soil water especially in the arid and semi-arid regions. Irrigation water is classified according to the amount of salts dissolved in it, and the salt content generally has an adverse effect on agricultural crop performance, and can also affect soil properties (Ayers & Westcot, 1985).

Soluble salts, like Na^+, Cl^-, SO_4^{2-} and CO_3^{2-} ions, accumulate in the soil and/or soil water due to either primary salinization (natural weathering of the earth's surface or soil) or secondary salinization (human induced processes like irrigation) or a combination of the two processes. Salinity is associated with high osmotic pressure that reduces water availability and ion imbalance that can induce nutrient deficiencies or toxicity (Guerrero-Rodriques *et al*., 2011; Bertrand *et al*., 2015). Consequently, without knowledge of both soil and water salinity and correspondingly appropriate management, long-term irrigated crop productivity can decrease.

Lucerne is one of the most cultivated forage crops not only in the world (Wang *et al*., 2013) but also in South Africa (Gronum *et al*., 2000). A vast amount of research has been done on the effects of salinity on lucerne. Severe restrictions are found from as early as germination up to final harvest of the above ground biomass. Furthermore, transpiration, water uptake, and crop productivity are all negatively affected with salt stress (Castroluna *et al*., 2014; Latrach *et al*., 2014; Guo *et al*., 2016). Each lucerne cultivar differ in their reaction to salinity, and the susceptibility to salt stress is greatly affected by the different environmental factors like rainfall, temperature, evaporation, capillary rise and drainage (Emam *et al*., 2009). Evidently, direct measurements of all these physical, chemical and biological interactions is often not possible in the field. Mathematical simulation models are an important tool to understand these processes and to contribute to on-farm management.

The purpose of this literature review is: (i) To provide a brief summary on the most common used guidelines to classify irrigation water on the basis of its quality and the salinity levels; (ii) To clarify the variation in crop salt tolerance and to define the threshold response guidelines established by Maas & Hoffman (1977) 40 years ago; (iii) To understand the effect of irrigation water salinity on lucerne; (iv) To explain the factors or processes associated with the water balance like evaporation, transpiration, crop water productivity, and the change in soil water content; (v) Finally, to indicate how to quantify the effect of salinity on lucerne through mathematical modelling.

2.2 Irrigation water quality

Water quality is defined by its physical, chemical or biological characteristics, and this classification method will determine the use and suitability for different irrigation practices. All water contains dissolved salts, whether it's from primary- and/or secondary salinization. Hence, irrigation water differ depending upon type and quantity of dissolved salts it contains.

Salinity is a common widespread problem in arid or semi-arid areas found under irrigated agriculture (Bertrand *et al*., 2015). Salts and other substances accumulate in the soil as the water evaporates from the surface as well as any withdrawal of water from the soil profile by the crop. Two types of salt problems exist: those associated with total salinity and those associated with sodium, and soils maybe affected by either one or both of these hazards. In general, soil sodicity is associated with a breakdown in soil structure due to swelling and dispersion of the soil colloids. Soil sodicity, however, does not form part of this study and a detailed discussion will not be included here.

The classification of irrigation water is determined by the concentration of the dissolved salts. When salts dissolve in water, they form a number of positive (cations) and negative ions (anions). The most common ions are calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}), chloride (Cl^{-}), sulphate (SO_4^{2-}) and bicarbonate (HCO_3^{-}). There are other ions, like CO_3^{2-}, NO_3^{-} and K^{+}, that also play a role in the total charge that is carried in the various water sources (Ehlers, 2007). This charge, which is transferred through the water, can be measured as electrical conductivity (EC) and expressed in milliSiemens per meter (mS m^{-1}).

Furthermore, irrigation water salinity (EC_i) is also expressed through the total salt concentration or total dissolved solids (TDS) and is expressed as milligrams of salt per liter (mg ℓ^{-1}) of water. The current international guidelines for water salinity are depicted in Tables 2.1 and 2.2 and the South African guidelines for water salinity are depicted in Table 2.3.

Water can be divided into various classes according to its EC_i and/or TDS values (Table 2.1) and ranges over six categories from non-saline to brine. Table 2.2 shows a different classification method using only the EC_i and four distinct classes are identified with a brief recommendation with regards to the soil (United States Salinity Laboratory Staff, 1969). Table 2.3 provides the South African classes of irrigation water and the effects of TDS/EC on relative crop productivity.

Since EC_i is easier to measure, it is used to determine TDS. Accordingly, EC_i and TDS are directly proportional, and according to the Department of Water Affairs and Forestry (1996), the average conversion factor for most waters can be calculated using Equation 2.1 where TDS is expressed in mg ℓ^{-1}, EC is the electrical conductivity in mS m^{-1} and the Cf is the conversion factor.

$$\mathrm{TDS} = \mathrm{EC} \times \mathrm{Cf} \tag{2.1}$$

However, the exact value of the conversion factor depends on the concentration of the ionic components like pH and HCO_3^-. The common conversion factors range between 6.4 and 7.5 depending on the water source (Du Preez *et al.*, 2000; Hanson *et al.*, 2006).

Table 2.1 Classification of water based on the salinity (adapted from FAO, 1992)

Water classification	EC (mS m^{-1})	TDS (mg ℓ^{-1})
Non-saline water	< 70	< 500
Slightly saline	70 - 200	500 - 1 500
Medium saline	200 - 1000	1 500 - 7 000
Highly saline	1 000 - 2 500	7 000 - 15 000
Very saline	2 500 - 4 500	15 000 - 35 000
Brine	> 4 500	> 35 000

Table 2.2 Irrigation water classes (United States Salinity Laboratory Staff, 1969)

Salt content	Class	EC (mS m^{-1})	Recommendation
Low	C1	> 250	No danger of salinization
Medium	C2	250 - 750	Provision for salt leaching and salt resistant crops used
High	C3	750 - 2250	Only well drained soils, periodical leaching and salt resistant crops used
Very high	C4	< 2250	Not suitable as irrigation water, emergency measure on sandy soils only

Table 2.3 Irrigation water classes and effects of TDS/EC on relative yield (Department of Water Affairs and Forestry, 1996)

Target water quality range EC (mS m^{-1})	Recommendation
0 – 40	Salt-sensitive crops can be grown without yield decreases if irrigated with low frequency irrigation systems
40 – 90	Moderately salt-sensitive crops can be grown and a 95% relative yield can be obtained if low frequency irrigation systems is used
90 – 270	Moderately salt-sensitive crops can be grown and a 90% relative yield can be obtained if low frequency irrigation systems is used
270 - 540	Moderately salt-sensitive crops can be grown and a 80% relative yield can be obtained if a high frequency irrigation systems is used
>540	Selected crops can be grown with these water. However, sustainable crop production decreases rapidly without proper irrigation management.

The long-term EC_i average and median for South Africa’s major rivers and irrigation schemes are summarized in Table 2.4. When comparing these salinity levels to international guidelines, it is evident that the salinity levels are low, but the deterioration of irrigation water is an ongoing process.

Table 2.4 Long-term average electrical conductivity (EC_i, mS m^{-1}) and sodium adsorption ratio (SAR) values for the Vaal, Harts, Modder, Riet and Orange Rivers, and long-term electrical conductivity (EC_i, mS m^{-1}) median values for the Berg and Breede Rivers

River	Measuring points	EC_i (mS m^{-1})	SAR	Reference
Vaal	From Bloemhof dam to Vaal/Orange confluence	52 - 74	1.2 - 1.9	Du Preez *et al*. (2000)
Harts	Schweizer-Reneke downstream to Delportshoop	70 - 115	2.3 - 2.4	Du Preez *et al*. (2000)
Modder	From upstream Krugerdrift Dam downstream to confluence of Modder/Riet	48 - 63	1.16 - 1.49	Du Preez *et al*. (2000)
Riet	From upstream Jacobsdal to Riet/Modder confluence	51 - 136	1.43 - 3.17	Du Preez *et al*. (2000)
	Orange-Riet canal	21	0.4	Du Preez *et al*. (2000)
Orange	Upstream of Hopetown to the Vaal/Orange confluence	17 - 20	0.34 - 0.4	Du Preez *et al*. (2000)
	Downstream of Vaal/Orange confluence	23	0.53	Volschenk *et al*. (2005)
Berg	Paarl	10		De Clercq *et al*., 2001a
	Hermon	21		De Clercq *et al*., 2001a
	Drieheuwels	24		De Clercq *et al*., 2001a
	Misverstand	35		De Clercq *et al*., 2001a
	Jantjiesfontein	82		De Clercq *et al*., 2001a
Breede	Ceres	24		De Clercq *et al*., 2001a
	Nekkies	10		De Clercq *et al*., 2001a
	Nuy River	385		De Clercq *et al*., 2001a
	Le Chasseur	24		De Clercq *et al*., 2001a
	Kogmanskloof rivier	305		De Clercq *et al*., 2001a
	Wolvendrift	70		De Clercq *et al*., 2001a
	Drew	82		De Clercq *et al*., 2001a
	Swellendam	53		De Clercq *et al*., 2001a

2.3 Crop salt-tolerance and response curves

Crop salt tolerance is the degree to which a crop can grow and produce satisfactory yields in conditions otherwise unfavourable and limiting to crop biomass productivity (Hanson *et al*., 2006). According to Munns *et al*., (2006), plants suffering from salt stress normally show growth reduction in two phases. In the first phase (exogenous), the presence of salt in the soil solution reduces the ability of the plant to take up water through the roots, leading to slower growth, this is the osmotic or water deficit effect of salinity. The second phase (endogenous) results from accumulated salts and the toxic effects to salt inside the plant. This has rapid, transient but reversible effects on photosynthesis-involved activities (Guo *et al*., 2016).

Salinity has some adverse effects on the development of the plant and dramatic differences in response to salinity are found among plant species. For example, sugarbeet might have a reduction of 20% in dry weight, moderately tolerant species such as cotton might have a 60% reduction and some sensitive crops might have a total crop failure if exposed to saline conditions exceeding 200 mS m^{-1} (Munns, 2006).

The two main detrimental effects on crops are caused by the quality of irrigation water and the quality of the soil water. Firstly, irrigation water quality may cause foliar injury when the foliage is wetted with irrigation water with a high salt concentration. Crops' susceptibility to foliar injury depends on various factors, for example leaf characteristics such as leaf size, the rate of salt absorption through the leaf and the leaf's waxy layer (Maas, 1986). The rate of Na and Cl absorption differ between growth stages of crops and the sensitivity of various crops can be seen in Table 2.5 as grouped by Maas (1986) to serve as a guideline to prevent foliar damage.

Table 2.5 Relative susceptibility of crops to foliar injury from saline sprinkling waters (Maas, 1986)

Na^+ or Cl^{-1} concentrations causing foliar injury (mg ℓ$^{-1}$)			
< 178	178 – 355	355 – 710	> 710
Almond	Grape	**Lucerne**	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Sorghum	Sugar beet
Plum	Tomato	Maize	Sunflower

Secondly, crops are influenced by the soil water quality. Salts accumulate in the soil profile impacting the osmotic potential and evidently the total water potential of the soil (Hillel, 2000). The potential difference between the roots and soil water leads to water stress and lower yields (Moolman *et al.*, 1999; Van Rensburg, 2010). The effect of soil water salinity (EC_e) on the relative yield of various crops can be calculated by Equation 2.2 established by Maas & Hoffman (1977).

$$Y_r = 100 - b\,(EC_e - a) \qquad (2.2)$$

where Y_r = 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 (mS m^{-1})

a = Threshold value of EC_e (mS m^{-1}), starting point of yield decrease

b = Slope of the percentage yield loss due to surpassing threshold values

Salt tolerance of various crops can be calculated based on their threshold value (mS m^{-1}) and the percentage yield decline to be expected. Crops are classified according to their sensitivity to soil water salinity, and the guidelines for lucerne and some major agronomic crops cultivated under irrigation are depicted in Table 2.6.

Table 2.6 Salt tolerance of various agronomic crops (adapted from Maas, 1986)

Common name	Botanical name	Threshold mS m^{-1}	Slope % per mS m^{-1}	Rating *
Wheat	*Triticum aestivum*	600	0.071	MT
Lucerne	***Medicago sativa***	**200**	**0.073 – 0.117**	**MS**
Maize	*Zea mays*	170	0.120	MS
Potato	*Solanum tuberosum*	170	0.120	MS
Bean	*Phaseolus vulgaris*	100	0.190	S

* S = Sensitive, MS = Medium Sensitive, MT = Medium Tolerant, T= Tolerant

Crops differ in their reaction to saline conditions and factors such as climate, agronomic management, soil conditions, and irrigation method all influence the susceptibility of crops to the saline environment (Maas, 1986). Maas & Hoffman (1977), established numerous response curves for crops as affected by increasing irrigation water salinity (EC_i), which are clearly linear (Figure 2.1). This figure indicates that lucerne can only tolerate irrigation water salinity of 130 mS m^{-1} before any yield decline is expected. If irrigated with water of 1000 mS m^{-1} total crop failure is projected. It is clear that there is a direct influence of salinity on relative yield of various crops (Maas & Hoffman, 1997).

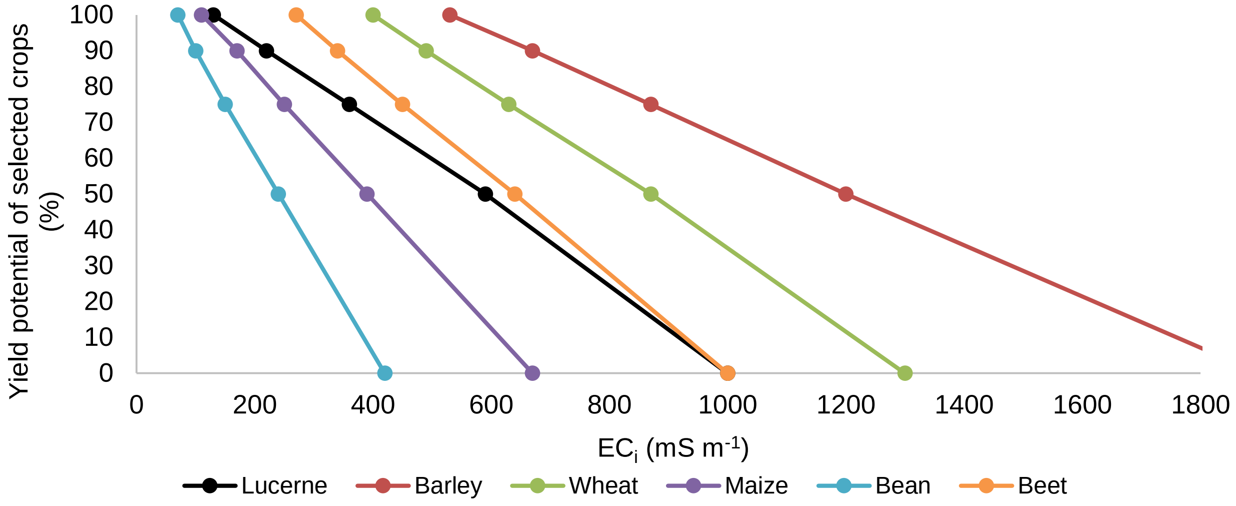

Figure 2.1 Relationship between yield potential and increasing irrigation water salinity (adapted from Ayers & Westcot, 1985).

Figure 2.2 shows the relationship between relative yield of selected crops and increasing soil salinity (EC$_e$). Accordingly, the same straight line is found with increasing EC$_e$ as was found with EC$_i$. Plants vary in their ability to tolerate different EC$_e$ levels and yield decline starts at differently salinity levels, or example, beans can only tolerate 100 mS m^{-1}, lucerne is 200 mS m^{-1} and barley can tolerate 800 mS m^{-1}.

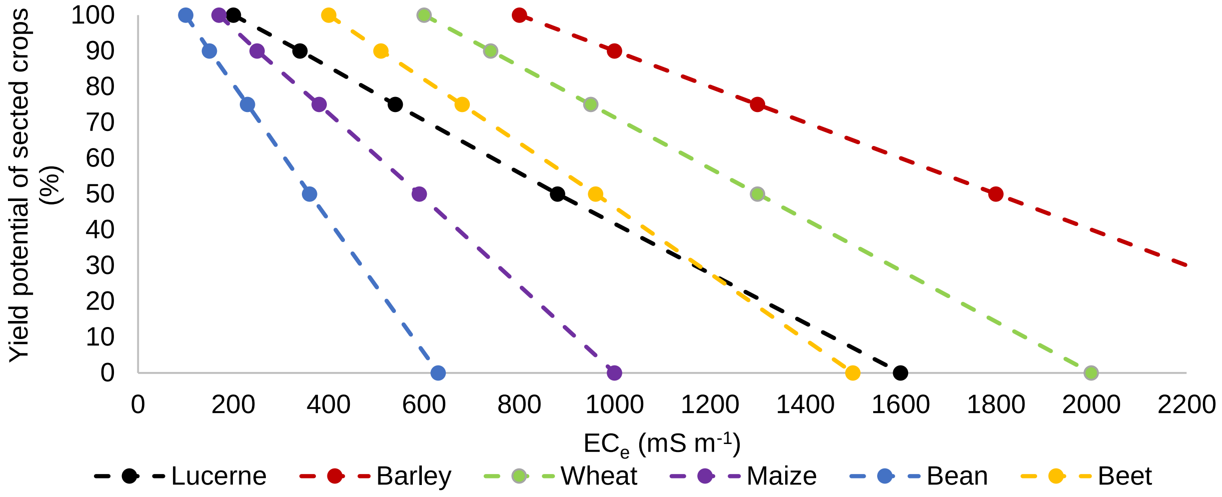

Figure 2.2 Relationship between yield potential and increasing soil salinity (adapted from Ayers & Westcot, 1985).

2.4 Effects of salinity on lucerne

Lucerne cultivars differ in their sensitivity to salinity (Eman *et al*., 2009; Castroluna *et al*., 2014). Literature indicates that cultivar differences are already evident as early as germination, through early development stages and up to harvest. According to Castroluna *et al*. (2014), salinity negatively affects seed germination of lucerne as seen in Table 2.7 where the cultivar Salina has a much higher germination percentage compared to the other cultivars tested.

Table 2.7 Average percentage of germination in controlled and stressed conditions of lucerne (Adapted from Castroluna *et al*., 2014)

	Germination in percentage (%)		
		Cultivar	
NaCl (mM)	DK166	Verdor	Salina
0	83	76	77
50	51	74	73
100	28	28	77
200	7	2	27

The difference in germination was ascribed to the variation in the seed imbibition process. This process is drastically impaired by two factors: firstly, reduced water absorption caused by osmotic conditions, and secondly, ionization through the accumulation of Na^+ and Cl^-, causing an imbalance in nutrient uptake and toxicity. On the positive side, work done by Kaya *et al.* (2006), showed that seed priming (pre-germination) can contribute to germination to reduce the adverse effects of salt stress. Sepehri *et al*. (2015) found that seed priming enhanced the mean germination rate, time and final germination percentage. Seed priming results in faster and synchronized seed germination, leading to better stand density. Successful crop production is highly correlated to the uniformity and rate of stand established in the field.

One of the major problems found in the early development stages of lucerne cultivation under salt stress is the degree to which salinity affects the legume-*Rhizobium*. Salinity affects the initiation, development and function of nodules (Saadallah *et al.*, 2001). According to Payakopong *et al*. (2006), it is not the nodular activity that is largely affected, but the infection process that is most sensitive. Hence, selecting salt-tolerant lucerne-rhizobia combinations can improve production in areas that is salt affected. Results found by Latrach *et al*. (2014), showed an improvement in salt tolerance of lucerne where two different strains were tested on two different cultivars. The plant height, shoot dry weight and nodular weight was significantly higher with the various combinations used.

In addition, the presence of salt in the rooting medium results in some physiological alterations due to chemical imbalances. Various studies reported reduced seedling growth and shoot biomass production (Castroluna *et al*., 2014; Guerrero-Rodriguez *et al*., 2011; Guo *et al*., 2016) and decreased stomatal length and breadth. Some of the changes was as a result of the osmotic gradient which reduces the water available to the plant, making the photosynthetic electron transport inactive. Hence, elevated proline accumulation, which is an important mechanism for osmotic regulation under salt stress, was found (Latrach *et al*., 2014).

The increase in osmotic potential causes leakage of Na^+ ions from the cytosol, which inactivates electron transport in both photosynthesis and respiration. The lack of water uptake due to salinity, causes limited stomatal conductance, which leads to inhibited CO_2 fixation and a decline in CO_2/O_2 ratio, and photosynthetic capacity, that leads to the reduction in plant growth (Gama *et al*., 2007; Radhouane, 2009; Xu *et al*., 2015).

2.5 Soil water balance

The water balance approach is the simplest method in the study of plant water consumption. The change in soil water content (ΔW) is an indicator to determine any productive loss (Ehlers, 2007). Soil water content is influenced by gains and losses. Gains include precipitation (P, mm) and irrigation (I, mm), while losses involve drainage beneath the root zone (D, mm), runoff (R, mm), evaporation (E, mm) from the soil surface and transpiration (T, mm) as seen in Equation 2.3.

$$\Delta W = (I + P) - (E + R + D + T) \tag{2.3}$$

The interaction between soil and water is a complicated process and the knowledge of these components can allow the effective utilization of any gains and losses during the season to secure sufficient available water to the crop. One of the most important management tasks in irrigation is to maintain soil water content between the drained upper limit (DUL) of plant-available water and the lower limit (LL) of plant-available water to ensure optimum transpiration and CO_2 assimilation (Bennie *et al.*, 1997). The water content between the two boundaries can be determined with Equation 2.4 to determine the plant available water.

$(\theta_{Dul} - \theta_{LL}) \times Z =$ Plant available water (mm) (2.4)

where θ_{DUL} = Volumetric water content at DUL
θ_{LL} = Volumetric water content at LL
Z = Rooting depth (mm)

2.6 Transpiration

Evapotranspiration (ET) is the combination of two processes where water is lost, whether it is from the soil surface by evaporation (E) or through the plant by transpiration (T) (Thornthwaite, 1984). These two processes react in relation to the leaf area of the crop. After planting, the soil surface is bare and vulnerable to evaporation where almost 100% of ET comes from E, and as the plant canopy develops E decreases and transpiration increases, until 90% of ET is from T at full canopy (FAO, 1992). According to Tyagi *et al.* (2000), the most effective way of water management is to determine the crop's evapotranspiration.

Evapotranspiration is very difficult to quantify due to all the different variables in the soil-plant-atmosphere continuum. Transpiration can be calculated using several components from the water balance equation (Equation 2.5). One of the most common ways of T calculation is the one of Lascano *et al*. (1987), where the measured E is subtracted from ET measurements. Another commonly used method of calculating T is by using the daily water balance. By manipulating the other functions, transpiration can be calculated separately because it would be the only productive loss.

$$T = P + I - \Delta W - D - R - E \qquad (2.5)$$

where T = Transpiration (T, mm)
P = Precipitation (P, mm)
I = Irrigation (mm)
ΔW = Change in soil water content (ΔW, mm over profile)
Q = Runoff (R, mm)
D = Drainage to the water table (D, mm)
E = Evaporation (E, mm)

According to Unger *et al*. (2006) various factors may influence the transpiration rate of a plant, including the environmental aspect of the soil-plant-atmospheric-component (SPAC) system where the atmospheric evaporative demand may increase or decrease the transpiration rate.

Tanner & Sinclair (1983) stated that it is a better measure to use the atmospheric water vapour pressure deficit than atmospheric evaporative demand in the calculation of the transpiration efficiency coefficient (TEC) of a crop (Equation 2.6 and 2.7).

$$Y = mT/(\text{vpd}) \tag{2.6}$$

$$m = Y/T(\text{vpd}) \tag{2.7}$$

where Y = Above ground biomass (AGB, g m^{-2})/yield
m = Crop coefficient (g kPa mm^{-1})
T = Transpiration
vpd = Vapour pressure deficit (kPa)

Irrigation water salinity has a negative effect on the transpiration of crops, and a decrease has been found by Ehlers (2007) on crops like wheat, beans, peas and maize (Table 2.8).

Table 2.8 Average cumulative evapotranspiration for different crops and irrigation water salinity treatments (Ehlers, 2007)

	Average cumulative evapotranspiration (ET, mm)			
EC_i (mS m^{-1})	Wheat	Beans	Peas	Maize
15	641	551	721,5	789
150	625	372.5	692	744
300	599	303.5	581	615
450	569,5	194.5	529.5	492
600	539,5	187	433.5	421

2.7 Salt balance

With regards to the water balance, the same main hydrological inflow and outflow factors apply in determining salt accumulation. The biggest gain of soil water is that of infiltration by rainfall or irrigation. All irrigation water contains salts and with every irrigation, salts accumulate in the irrigated root zone. With regards to losses of soil water, an increase in the salt content is firstly caused by transpiration, where salts increase in the root zone as the soil water is taken up and used by the plant. Secondly, evaporation from the soil surface results in salts that are left behind, and finally the capillary rise of water into a drier root zone from a shallow water table can also contribute to the salt load.

According to Barnard (2006), the different components that makes out the water balance, can be multiplied by its salt concentration, resulting in the salt balance of the root zone. A simple salt balance (Equation 2.8) can be obtained by adding the various inputs to and subtracting the outputs of salt to the soil water, if factors like the addition of fertilizers, precipitation, dilution and uptake by plants in the root zone are considered negligible (Beltran, 1999):

$$\Delta S = Ic_i + Gc_g - Dc_d \pm Rc_r \tag{2.8}$$

where c_i = Salt concentration of irrigation water (mg ℓ^{-1})
c_g = Salt concentration in capillary water (mg ℓ^{-1})
c_d = Salt concentration of drainage water (mg ℓ^{-1})
c_r = Salt concentration of surface flow (mg ℓ^{-1})
ΔS = Variation of salt content in the root zone (mg ℓ^{-1})

When the quantity of salt input caused by irrigation, surface flow and/or capillary water exceeds the quantity of the salt output due to leaching, the salt balance is considered as adverse and the salt content in the root zone will increase. Leaching salts from already saline or the prevention of excessive salt accumulation in irrigated soils, is essential for sustainable crop production. The timing and frequency of irrigations should only be applied when the soil salinity reaches the threshold salinity level capable of interfering with the crop yield. (Monteleone *et al*., 2004). Leaching involves applying enough excess water, without raising the water table, to translocate some of the salts out of the root zone (Barnard *et al*., 2015).

The interaction between the salt balance and leaching requirement is very important and an on-going process. In irrigated soils the optimization of this relationship can seldom be achieved and sustained without artificial drainage systems. The movement of salt in the soil is controlled by two processes as explained by Ehlers (2007). Firstly convection, the simultaneous movement of water and dissolved salts in it by mass flow through the larger water filled pores, and secondly diffusion, where salt will move from a higher salt concentration in the micro pores into mass flow to the lower salt concentration in the macro pores.

2.8 Crop water productivity

Crop water productivity (WP), also referred to as crop water use efficiency (WUE), can be defined as the relationship of biomass accumulation ratio (yield) expressed as carbon dioxide assimilation in correlation to water consumed, expressed as T and ET in the growing season (Ali & Talukder, 2008). Water productivity varies according to the different growing periods and seasons of various crops. Climatic conditions and crop canopy development are some of the most important factors in crop-water requirement determination (Tyagi *et al.*, 2000). According to Haka (2010), the water use efficiency of a crop is the way a crop can efficiently convert available water into yield. Transpiration efficiency is the ratio of above ground biomass (AGB) produced per unit of water transpired as seen in Equation 2.9 (Tanner & Sinclair, 1983).

$$TE = AGB/T \tag{2.9}$$

where TE = Transpiration efficiency (g m^{-2} mm^{-1})
AGB = Above ground biomass
T = Transpiration

2.9 Mathematical modelling to quantify the effect of salinity on lucerne

Optimization of how various plant functional traits interact with soil water systems is of paramount importance to sustain better management on the farm (Raza *et al*., 2013). Information can only be incorporated into selected mathematical models if the soil water and salt transport in irrigated soils can be quantified, as it is influenced by various external factors such as rainfall, irrigation, evaporation, transpiration, capillary rise and drainage. To understand the plant-soil interactions on water balance components and their effect on crop growth, the use of a mathematical model serves as a useful tool. Due to the difficulty to measure all these processes of the water balance in the field, i.e. evaporation, transpiration, drainage, runoff and water content change throughout the soil profile (Raza *et al*., 2013), in-field measurements are made possible with the use of lysimeters, which simulate field-like situations.

Various models are used for integrating these processes involved in water and salt movement as mentioned above, but on choosing the most applicable model to use are usually very difficult for researches. According to Wagenet (1988) and Pasioura (1996) (as cited by Singels *et al.*, 2010) generally two approaches are followed in the mathematical modelling of a system, namely the functional and mechanistic approach. The functional or empirical model is a practical model that is less intensive and is comparably less quantitative. The governing equations are solved analytically and it can be used as an estimation or prediction approach to solving problems, hence it is mostly used as management models. The mechanistic model comprehensively integrates the scientific approach and knowledge of the processes controlling soil and salt movement. The governing equations are solved numerically, hence the outputs of the model are quantitative, but if the outputs are qualitative the model only describes the nature of it (Van Rensburg *et al.*, 2012).

To quantify the data in the various models, different approaches should be used i.e. steady-state and transient-state approach. With the steady-state approach one or more of the variables within the different processes must be constant with time. With regards to quantifying the leaching fraction of salts, one of the steady-state analysis approaches requires a constant continual flow of water (Letey & Feng, 2007). However, a vast amount of shortcomings exist with this approach and according to Letey *et al.* (2011) "true" steady state conditions never exist in the field. Various steady-state models exist, i.e. Rhoades (1974), Hoffman & Van Genuchten (1983), Ayers & Westcot (1985) and Hanson *et al.* (2006).

Irrigation water guidelines developed several decades ago, were based on steady-state conditions, and in some cases these guidelines are still widely used today. As Letey *et al.* (2011) explained, these guidelines were established to develop simple relationships to estimate crop yield potential from irrigation water salinity (EC_{iw}) and various leaching fractions (LF).

As opposed to the steady-state approaches, the transient-state approach can accommodate the vast amount of variables encountered in the field, thanks to modern high-speed computer software. The chemical-physical-biological interactions in naturally occurring agricultural systems can be predicted with more accuracy. Thus, processes or changes such as accumulation and distribution of salt within a soil profile and the response of different crops to salinity, can be assessed more accurately. Letey *et al.* (2011) stated that a steady-state approach may overestimate the negative effects of saline irrigation water on crop production. Transient-state approaches in general allow for water and salt flow in irrigated water table soils.

2.9.1 Soil water flow

Understanding soil water flow, the interaction between soil, vegetation and atmospheric processes, as well as groundwater dynamics is vital to determine soil water flow. Agro-hydrological models have been an important tool for supporting decision making in the development of agricultural water management strategies. Soil-water simulation models are grouped into categories based upon the hierarchy or degree of complexity of the system modelled, in this case the soil profile (Ranatunga *et al.*, 2008). It has been shown that complex soil water models based on the numerical solution of the Richards equation (Equation 2.10) can adequately simulate transient water flow and thus soil water dynamics (De Jong & Bootsma, 1996; Scanlon *et al.*, 2002; Ranatunga *et al.*, 2008).

Mechanistic models such as SWAP (Ben-Asher *et al.*, 2006; Van Dam *et al.*, 2008), HYDRUS (Šimůnek *et al.*, 2008; Ramos *et al.*, 2011), ENVIRO-GRO (Pang & Letey, 1998; Feng *et al.*, 2008), UNSATCHEM (Suarez & Šimůnek, 1997; Kaledhonkar *et al.*, 2006) and SALTMED (Ragab *et al*., 2005; Montenegro *et al.*, 2010), can simulate multi-processes of soil water flow, solute and heat transport, and crop growth in great detail. Hence, because these models are suitable for more complicated conditions (Ranatunga *et al.*, 2008; Van Dam *et al.*, 2008; Xu *et al.*, 2015), they are highly valuable and are used frequently.

In contrast to complex soil water models, simple soil water models consider the soil as a reservoir (or a series of reservoirs). A fixed number of soil layers fills up or drains as a function of the water supply, whether it is rainfall or irrigation, and water loss from evapotranspiration. This is also referred to as the tipping-bucket approach, e.g. SWB (Annandale *et al.*, 1999) or SWAMP (Bennie *et al.*, 1998; Barnard *et al.*, 2015).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S \qquad (2.10)$$

where θ = Volumetric soil water content
h = Soil water pressure head
t = Time
z = Depth
K = Hydraulic conductivity
S = Sinks or sources of water

2.9.2 Plant modelling

As previously stated, transient state models, that simulate change in soil-water salinity (osmotic potential) and soil-water content (matric potential) in the crop root zone caused by irrigation and rainfall, are important tools to help quantify the changes. Only selected models, i.e. SWAP, SALTMED and SWB, make provision for a plant growth subroutine and they vary in complexity with regards to plant growth defining and plant growth limiting factors for a given set of soil and water conditions. Oster *et al.* (2012) stated that most models cannot simulate plant growth as such, but most of them rather simulate seasonal water uptake to the seasonal potential water use and then calculate relative yield as a ratio thereof.

2.9.3 Potential evaporation and transpiration

Evapotranspiration is quite a major component of the water balance and has been identified as a key factor in modelling. All components of evaporation can be effectively modelled using various equations:

a) The Penman (1948) equation, where the potential evaporation is estimated by combining the aerodynamic approach with an energy equation based on net incoming radiation.

b) The Penman-Monteith equation (Monteith, 1965) is usually adopted to estimate potential evaporation from a vegetated soil surface where the fundamental formulation is based on the use of measured net radiation.

c) The Priestley-Taylor equation (Priestley & Taylor, 1972) that allows the potential evaporation to be calculated in relations of energy fluxes without an aerodynamic component.

d) The Slatyer & McIlroy (1961) equilibrium evaporation (EEQ) equation, in which air passing over a saturated surface will gradually become saturated until an equilibrium rate of evaporation is attained. However, according to Sweers (1976) this equilibrium temperature will never be achieved due to daily cycles in meteorological conditions.

With this in mind, the most generally applied equation is the Penman-Monteith equation. A reference crop with specific characteristics, that is not short of water, are expressed as the ET combined with other crop factors to determine the potential ET (Allen *et al*., 1998). Models like the FAO-Salinity Laboratory SWS, SWB, SWAP, SALTMED, ENVIRO-GRO and HYDRUS, are all based on the Penman-Monteith equation, with the exception of some weather data parameters such as air temperature, radiation, wind speed and relative humidity.

2.9.4 Actual transpiration and root water uptake

The water transpired by plants is obtained from the soil by the plant roots. A vast number of mathematical root water uptake models exist and they all differ in concept, in complexity, and in the volume of input data required. Throughout literature there are generally two approaches in simulation of root water uptake:

- Bottom-up or microscopic models contain detailed descriptions of the plant, its root and soil systems, and the physical interaction among these components. This approach considers the converging of radial flow of soil water and water flux into a single root (Skaggs *et al*., 2006).

- Top-down or macroscopic models regard the root system as a diffuse sink term in the Richard's equation, that penetrates each depth layer of soil uniformly from the dimensionless water stress response function (Cardon & Letey, 1992).

Quite a few approaches have been used to determine various water uptake functions, using Type I and Type II formulations. Work done by Cardon & Letey (1992) showed with simulations that Type I formulations was insensitive to salinity, therefore Type II formulas are used in all transient-state models as previously stated. The Type II formula is used for both the matric and osmotic effects involved in water uptake.

2.9.5 Osmotic effect

It is important to understand that salinity can be expressed and quantified by three different parameters in numerous formulas of equations, i.e. osmotic head (π), salt concentration required for convection-dispersion equation, and electrical conductivity (EC), to determine the salinity of the water. As explained by Oster *et al.* (2012), plant response is directly related to π of the soil water in the root zone, however π cannot be measured directly but only be determined from the linear relationship of π to EC or salt concentration. Hence, the plant response to increasing salinity is therefore represented by a piece-wise linear function (Figure 2.3). This function is parameterized by four critical values of the water pressure head, $h_4<h_3<h_2<h_1$. Uptake is at the potential rate when the pressure head is $h_3 \leq h \leq h_2$, drops off linearly when $h > h_2$ or $h < h_3$, and becomes zero when $h \leq h_4$ or $h \geq h_1$.

2.9.6 Matric effects

Soil water availability varies with soil water content or soil water pressure head. As seen in Figure 2.3 the full range of pressure head is divided into three sections: 1) from saturation to field capacity; 2) from field capacity to permanent wilting point; and 3) below the wilting point.

2.9.7 Salt transport

A Large number of analytical and numerical models are available to predict flow and transport processes. These models are again based on the Richards equation (Equation 2.10) for variable saturated flow, and the Fickian based convection-dispersion equation (Equation 2.11) for solute transport.

$$\frac{\partial c\theta}{\partial t} = \frac{\partial}{\partial z}\left[\partial D\frac{\partial c}{\partial z}-q(c)\right] \qquad (2.11)$$

where c = Concentration of salt
D = Dispersion coefficient
q = Volumetric water flux

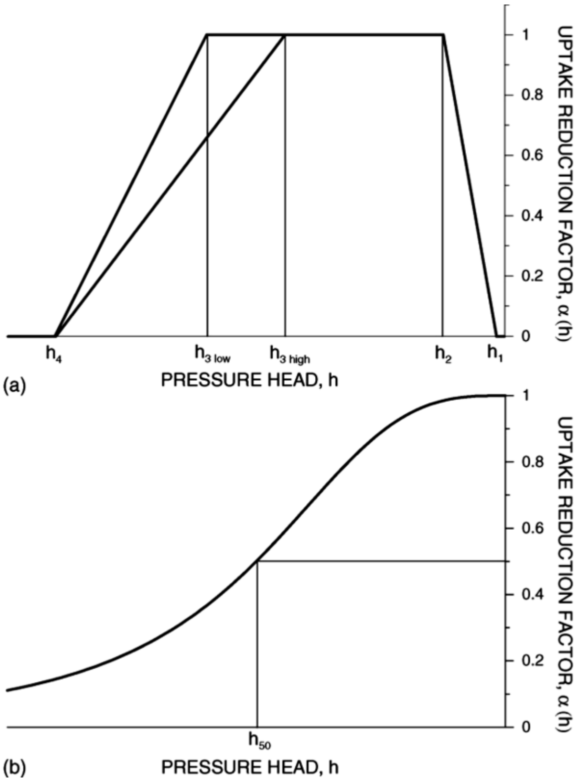

Figure 2.3 Piece-wise linear (a) and alternative S-shaped (b) water stress uptake reduction functions of Feddes *et al.* (1978) and Van Genuchten (1987) as described in Skaggs *et al.* (2006).

2.10 Conclusion

The main objectives of the literature review was to evaluate the classification guidelines of irrigation water according to the quality. From the information, it is clear that there are various ways to classify water quality. Irrigation water are classified according to the TDS or the EC of the water. Crops differ in their ability to tolerate salt stress. Crop response guidelines were established by Maas & Hoffman (1977) for lucerne, and for both EC_i and EC_e, a straight line response curve is reported.

However, these guidelines were established 40 years ago. Based on the information gathered, it’s clear that many studies have been done in the past on the effects of saline water on crops, and many factors can influence the normal growth rate and yield production of lucerne. Soil and irrigation water salinity affects lucerne through poor germination, loss of stand, reduced rate of plant growth, reduced biomass yield, and in severe cases, total crop failure. Salinity limits water uptake by lucerne, by reducing the osmotic potential and certain salts may be toxic to lucerne like Na^+ and Cl^- or may upset nutritional balances like the Na^+/K^+ ratio.

A review of modelling and all the processes involved in salinity management is given in this literature review. The most important factors with regard to the usage of simulation programs, is that is not only depends on the capability of the program, but also the analyser’s knowledge and understanding of both water flow processes and solute transport processes. The biggest advantage with the use of computer modelling is that different management scenarios can be analysed in less time and with less expense.

CHAPTER 3

EFFECT OF IRRIGATION WATER SALINITY ON TRANSPIRATION AND CROP YIELD UNDER SHALLOW SALINE GROUNDWATER CONDITIONS

3.1 Introduction

The use of land for irrigation has increased with about 300% over the past few decades (Poustini *et al.*, 2004). Worldwide, however, the future expansion of irrigation is limited, not because of a lack of suitable soils but rather good quality water resources. This is also true for South Africa where irrigation is the largest consumer of available fresh water (Department of Water Affairs and Forestry, 1996). Thus, efforts to bring additional areas under irrigation to supply the increased food demand is and will be directed towards the utilization of poor quality water. Unfortunately, the usage of poor quality water corresponds normally to low rainfall areas located in arid and semi-arid regions, which leads to salinization of soils and water resources (Sumner, 1995).

Irrigation water is classified according to the amount of solutes that dominate the water, resulting in different irrigation water qualities. These different water qualities vary in suitability for various irrigated field crops (Chhabra, 1996); because salts accumulate with every irrigation event and plants respond differently to different soil salinity levels. Various interactions like: a decrease in osmotic potential of the soil solution (osmotic stress), nutritional imbalance and specific ion effects (salt stress), or a combination of these factors, cause decreases in water uptake and yield (Ashraf, 1994; Marschner, 1995).

The salt tolerance of many field crops are well documented by Maas & Hoffman (1977), with lucerne classified as a moderately salt tolerant crop that can tolerate soil and irrigation water salinity levels of 200 and 130 m Sm^{-1}, respectively. However, since this early work by Maas & Hoffman (1977), research regarding the threshold salinity level of lucerne remains limited. This is unfortunate and can be seen as a lost opportunity for enhancing our knowledge even when salinity threshold values are applied only as a guideline, because absolute tolerance will vary depending on climate, soil conditions and agronomic practices (Skaggs *et al.*, 2006).

Hence, research where lucerne is irrigated with poor quality water under saline shallow groundwater conditions remains relevant and necessary. Especially considering that, lucerne is an apparent luxurious water user, i.e. 800 to 1600 mm per growing season (FAO, 2012a).

The objectives of this chapter are: (i) to quantify the effect of EC_i on transpiration, water table depletion and yield of lucerne, (ii) to determine the relationship between EC_i and relative biomass yield as well as EC_e and relative biomass yield and (iii) and assess crop water productivity as influenced by irrigation water salinity.

3.2 Materials and methods

3.2.1 Description of experimental site

The experiment was conducted in a non-weighing lysimeter facility (Bello *et al*., 2016), as described by Ehlers *et al*. (2003), located at Kenilworth Experimental Farm of the Department of Soil, Crop and Climate Sciences, University of the Free State near Bloemfontein (29°01'00"S, 26°08'50"E). The lysimeter facility consists of a 70 m by 35 m experimental area. In the center of this area, 30 round plastic containers (1.8 m diameter and 2 m deep) were buried with a 50 mm rim above the soil surface and arranged in two parallel rows of 15 each (Figure 3.1). Each lysimeter was equipped with two neutron probe access tubes with lengths of 1800 mm.

No interference of rain occurred because the facility is equipped with a movable rain shelter (Figure 3.1). Five 2500 ℓ reservoirs were used for mixing the different salinity classes of irrigation water. Each of the reservoirs was connected to the assigned lysimeters that was randomly allocated for the specific treatments. The reservoirs also supply the lysimeter with water in order to recharge the water table through a below-ground access chamber.

The underground chamber is 1.8 m wide, 2 m deep and 30 m long (Figure 3.2), and allows access to the inner walls of the lysimeters making it possible to regulate the height of the water table through a manometer connected at the bottom of each lysimeter.

One row of lysimeters contains a yellow sandy soil, classified as Clovelly (form) Setlagole (family), from the Sand-Vet region, and a red sandy loam soil, classified as Bainsvlei (form) Amalia (family), from the Kenilworth experimental site (Soil Classification Working Group, 1991). Particle size analysis was carried out on both soils using the pipette method of Day (1965). The mean silt-plus-clay content over a depth of 1800 mm is 8% for the Clovelly (Cv) and 18% for the Bainsvlei (Bv) soil.

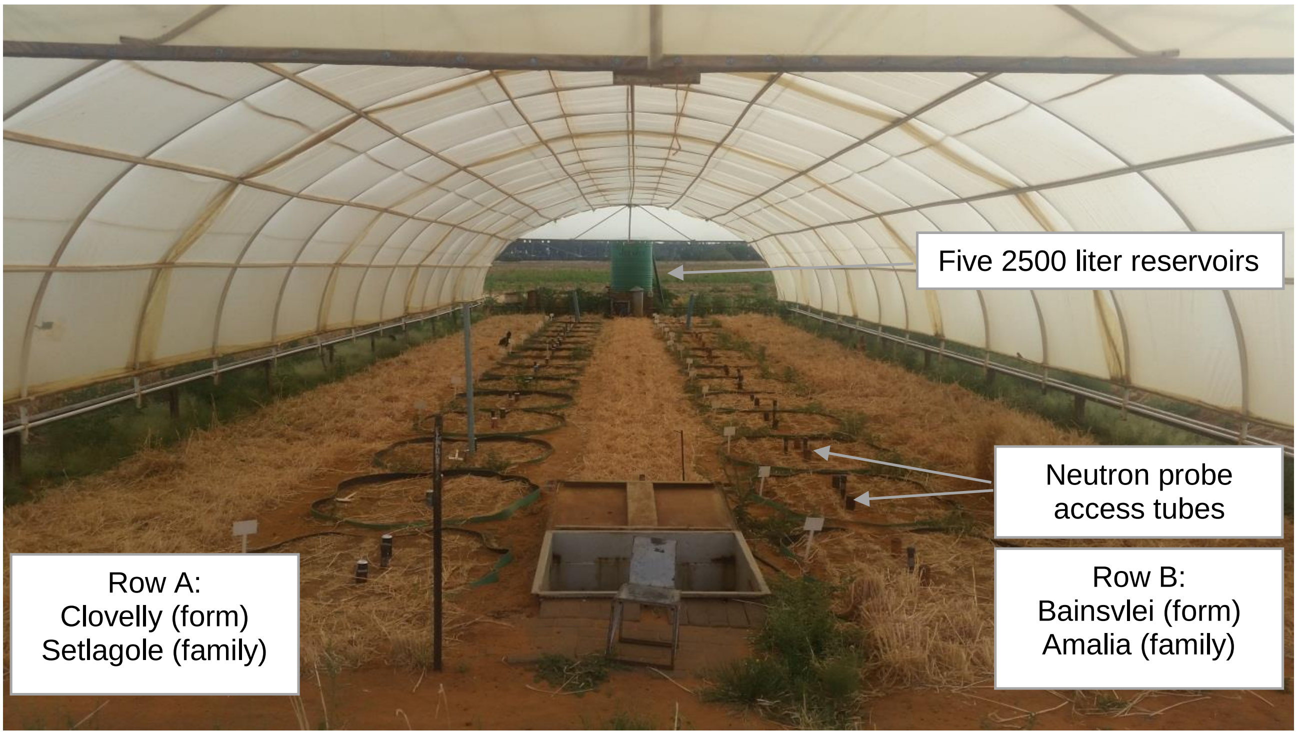

Figure 3.1 Aboveground view of the non-weighing lysimeter unit with the moveable rain shelter. Each lysimeter is equipped with two neutron probe access tubes to measure changes in soil water content over the depth of the profile.

Figure 3.2 Underground chamber with manometers connected to the bottom of each lysimeter.

The climate of the area is classified as semi-arid and is found in the mid-latitudes and affected by high elevation, i.e. the amount of moisture supplied from the ocean is very limited. Hence, the area is known for its dry-grassland climate and according to Bothma *et al*. (2012), it has an aridity index of 0.23 and a mean annual rainfall of approximately 543 mm. The area experiences hot summers from October to April, followed by cold dry winters during May to August (Figure 3.3).

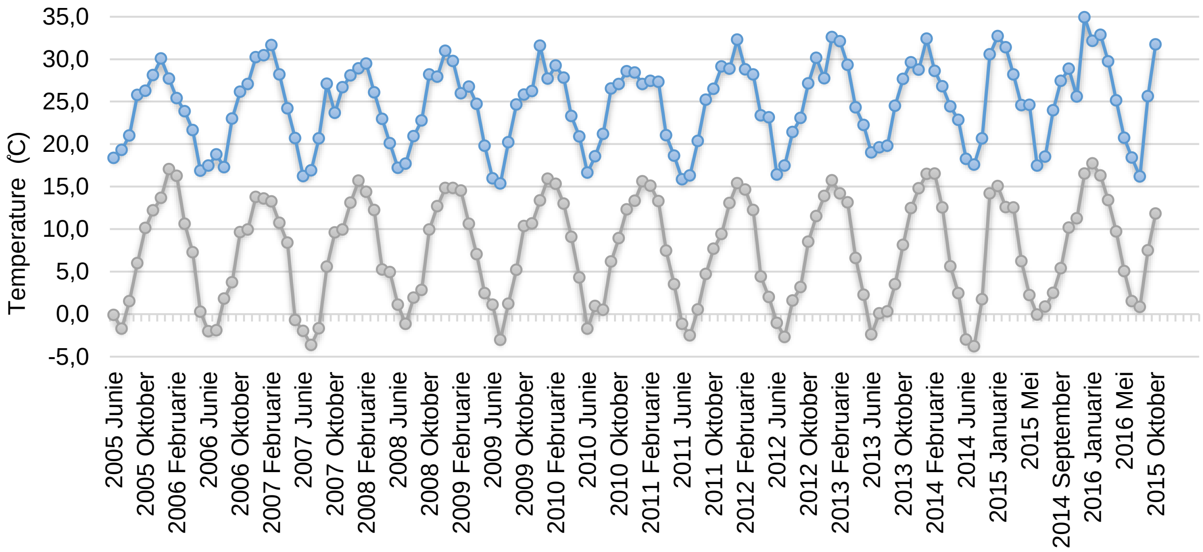

Figure 3.3 Long-term mean minimum and maximum temperatures for Bloemfontein (*https://www.**wunderground**.com*).

3.2.2 Experimental design and treatments

The experiment was laid out by allocating the treatments randomly to the different lysimeters. The treatments consisted of the two soils combined with six different irrigation water salinity levels (EC_i), i.e. a 0-15 mS m^{-1} ($EC_{i\ 0\text{-}15}$) as the control, then 150 mS m^{-1} ($EC_{i\ 150}$), 300 mS m^{-1} ($EC_{i\ 300}$), 450 mS m^{-1} ($EC_{i\ 450}$), 600 mS m^{-1} ($EC_{i\ 600}$) and 1200 mS m^{-1} (EC_i 1200). Unfortunately, the treatments could not be replicated due to limited space at the time of the experiment as it co-inside with other medium-term experiments conducted in the facility.

Irrigation water of the different treatments consisted of various amounts of salts to achieve the desired total dissolved salts (TDS, mg ℓ^{-1}) sodium adsorption ratio (SAR) and the electrical conductivity (EC_i, mS m^{-1}). The long term values of the Lower Vaal and Riet Rivers were used to determine the calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphate (SO_4^{2-}) and chloride (Cl^-) concentrations. The calcium and magnesium ratios and the sulphate and chloride ratios ranged from 1.2 to 1.6 and 1.3 to 1.4, respectively.

Furthermore, the sodium and calcium ratios decreased with an increase in irrigation water salinity, except for the 300 mS m^{-1} treatment where the ratio was higher (Table 3.1).

These ratios were achieved by mixing sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium sulphate ($MgSO_4$), sodium sulphate (Na_2SO_4), potassium chloride (KCl) and magnesium chloride ($MgCl_2$) in the correct quantities.

Table 3.1 The electrical conductivity (EC$_i$, mS m^{-1}), sodium adsorption ratio (SAR) and amount and combination of different salts to achieve the desired irrigation water quality treatments

	EC$_i$ (mS m^{-1})				
	150	300	450	600	1200
SAR	3	5	5	5	5
TDS (mg ℓ^{-1})	988	2003	3554	5107	11311
NaCl (mg ℓ^{-1})	360	790	1140	1415	2335
$CaCl_2$ (mg ℓ^{-1})	100	235	500	825	2270
$MgSO_4$ (mg ℓ^{-1})	297	620	1190	1740	4040
Na_2SO_4 (mg ℓ^{-1})	0	50	20	45	35
KCL (mg ℓ^{-1})	105	187	533	750	1450
$MgCl_2$ (mg ℓ^{-1})	45	40	90	250	1100
Ca:Mg (mg ℓ^{-1})	1:1.31	1:1.31	1:1.32	1:1.31	1:1.31
SO_4:Cl (mg ℓ^{-1})	1:1.33	1:1.32	1:1.33	1:1.32	1:1.33
Na:Ca (mg ℓ^{-1})	2.568:1	3.13:1	2.28:1	1.80:1	1.11:1

Soils in the lysimeters were equilibrated according to the EC$_i$ treatments by irrigating until the leachate was close to the desired EC$_i$ treatment. This was to ensure that the excess salts, which might have accumulated during the previous cutting period are removed before the start of the nest cutting cycle. This procedure was repeated after every cutting and took between 1 and two weeks, thus starting at the same EC$_i$ as the previous cutting. The water table was established at a depth of 1.2 m from the soil surface, and maintained at 1.2 m by recharging the soil with water of corresponding salinity (Figure 3.2).

3.2.3 Agronomical practices

The lucerne used in this experiment was established in 2008 by Haka (2010). Before planting, a 4:2:1 (28) fertilizer mixture was manually broadcast at a rate of 600 kg ha^{-1} together with 2000 kg ha^{-1} super-phosphate, where after the soil was tilled to a depth of 200 mm using a spade. Fertilizer application amounted to 96 kg N ha^{-1}, 258 kg P ha^{-1} and 24 kg K ha^{-1}. Lucerne (cv. SA Standard) was planted manually at a rate of 20 kg ha^{-1} with a row width of 300 mm.

This cultivar was also planted in a similar manner adjacent to the lysimeter unit on a 20 x 20 m area. After planting, the soil surface was covered with a 50 mm thick gravel mulch to restrict evaporation to a minimum. All agronomical practices were managed with the objective of creating optimal conditions for crop growth.

The cultivar (SA Standard) that was planted is widely used throughout the central parts of South Africa. However, despite the fact that SA Standard has a lower tolerance to high salinity levels compared to the more up-to-date cultivars like AgSalfa 10, SA Standard was already established, therefore used for the purpose of this study.

3.2.4 Measurements and calculations

3.2.4.1 Cuttings

Above-ground biomass yield was determined when 10% of the lucerne flowered. Plants were harvested in an area of 2.5 m^{-2} per lysimeter by cutting it manually at their base. The season consisted out of five cuttings (CT) for lucerne, CT 1 (16 March 2010 to 22 April 2010 - growing period of 37 days), CT 2 (01 June to 16 August 2010 - 76 days), CT 3 (1 September to 27 September 2010 - 26 days), CT 4 (11 October to 15 November 2010 - 35 days) and CT 5 (16 March to 11 May 2011 - 49 days). Before weighing the plant material, it was dried until it reaches a constant weight using a ventilated oven at 50^{o}C.

3.2.4.2 Soil water balance

The soil water balance as express in section 2.5 was used to reflect on water gains and losses during the experimental period.

Soil water content: The change in soil water content (ΔW, mm over the profile) was measured using the Campbell Pacific Neutron 503 Hydroprobe neutron soil water meter (NWM) every Monday, Wednesday and Friday at 0.3 m depth intervals to a depth of 1.8 m.

Irrigation: The crop was irrigated (I, mm) manually using 20-liter plastic containers connected to dripper lines (Figure 3.4). A total of 60 drippers per lysimeter, with a discharge rate of 4 ℓ h^{-1}, were used to ensure a uniform water distribution at the surface. Lucerne was irrigated once a week with surface drip; each lysimeter received 40 liters per week. Sub-irrigation (IRs) were applied almost daily through the manometer tube to keep the water table depth at a constant depth of 1200 mm.

Precipitation: Rainfall (P, mm) was zero during the duration of the experiment. This was possible by moving the moveable rain-shelter over the experimental site every time it started to rain.

Evaporation: Soil water evaporation (E, mm) was assumed zero because the surface area was covered with a thick gravel mulch as described earlier. Dlamini *et al*. (2016) proved that the soil water evaporation under the same mulching conditions were low compared to a bare mulch treatment.

Runoff: This parameter (R, mm) was taken as zero, because the lysimeters had a 50 mm rim. The surface storage capacity created this was sufficient to control the hydraulic head during irrigations over the duration of the experiment.

Deep drainage: This parameter (D, mm) was controlled during the season. There was no overflow from the sub-irrigation equipment and hence deep drainage was measured to be zero.

Transpiration: Water that evaporates from the plant surface was seen as transpiration (T, mm) (Haka, 2010). Given above boundary conditions, transpiration was calculated using Equation 3.1.

$$T = (-\Delta W) + I \tag{3.1}$$

where T = Transpiration (mm)
I = Irrigation (mm) - surface and sub = surface

Figure 3.4 Surface driplines connected to the 20 L reservoirs for controlling the amount of irrigation of the different EC_i treatments.

3.2.4.3 Salt balance

The salt balance of the profile was express through Equation 3.2 (Ehlers, 2007). Accordingly, drainage and percolation of water below the root zone was zero (managed through the manometers on each lysimeter), thus these parameters were taken as zero. In order to simplify the calculations, the uptake of salts by lucerne from the root-zone was assumed to be negligible. Salt additions through rain was also zero; managed by movable rain-shelter. Hence, the salts applied via irrigation and water table depletion accumulated in the root-zone above 1200 mm. From this boundary conditions the salt content was calculated and then converted to electrical conductivity of the root zone, EC_e.

$$\Delta S_{soil} = S_R + S_I + S_{wtu} - S_D \qquad (3.2)$$

where S_R = Amount of salt applied by rainwater (kg ha^{-1})
S_i = Amount of salt applied by irrigation water (kg ha^{-1})
S_{WTU} = Amount of salt applied by upward flow from the water table (kg ha^{-1})
S_D = Amount of salt lost from deep percolation and drainage (kg ha^{-1})

Therefore, to determine EC_e at the end of each cutting (S_{end}) all the incoming salt in the period preceding each cutting were added, i.e. irrigation water (S_i), the upward flow from the water table (S_{WTU}) as well as the soil water salinity at the beginning of each cutting (S_{start}) as seen in Equation 3.3.

$$S_{end} = S_i + S_{wtu} + S_{start} \tag{3.3}$$

3.2.4.4 Crop water productivity

For every cutting period the crop water productivity (CWP_{AGB}, g m^{-2} mm^{-1}) of lucerne were calculated with Equation 3.4. The above ground biomass (AGB, g m^{-2}) per cutting were divided by cumulative seasonal transpiration (T, mm).

$$CWP_{AGB} = AGB/T \tag{3.4}$$

3.2.4.5 Statistical analysis

Data was analysed in excel, with various statistical functions to determine average and standard deviations, and the analysis tool Pak to determine any correlations, descriptive statistics and t-test. The critical points between the relative mean biomass yield and both EC_i and EC_e were determined as described by Cate and Nelson (1971).

The relationship between the relative yield and both EC_i and EC_e were partitioned and the partitioning occurred when the R^2 reaches the maximum. The steps followed were: The first step was to pool all the data for all the cuttings together before arranging them in order per relative yield versus EC_i or EC_e. The data of relative yield versus EC_i or EC_e were arranged in the form of the smallest to the highest based on the EC_i and EC_e values. EC_i and EC_e were on X axis while relative yield was on Y-axis. These sets were thereby divided into 2, plotted on the same graph and trend lines were added to these plots with their R^2 and equations. This is followed by interactive process to obtain a series of R^2 by increasing number of samples for each set each time until a critical point was reached, where R^2 of one of the trend lines for each set was at the maximum and the other was at the lowest close, to the horizontal level.

3.3 Results and discussion

3.3.1 Transpiration

The mean daily transpiration (T, mm), as affected by the EC_i treatments, is presented in Figure 3.5 for the five cuttings. The total cumulative transpiration for the individual treatments over all the cuttings, of the two soils are presented in Appendix 1.

Accordingly, the results show a general decrease in the daily transpiration with an increase in the salinity of the irrigation water. This trend is confirmed with the mean transpiration rate of the cuttings that decreased from 5.3 mm day^{-1} in the control treatment to 3.6 mm day^{-1} in the 1200 mS m^{-1} EC$_i$ treatment. The mean coefficient of variation for the control treatment was 8% for the cuttings, compared to the 14% found in the 1200 mS m^{-1} EC$_i$ treatment. Further proof of the negative influence of salinity on transpiration can be seen in the mean cumulative transpiration (T, mm) of the cuttings reported in Table 3.2. Here the values decreased from 254 mm for the control EC$_i$ treatment to 183 mm measured in the 1200 mS m^{-1} EC$_i$ treatment.

Ehlers (2007) observed similar trends of a reduction in transpiration with a rise in irrigation water salinity in field crops, like maize, wheat, beans and peas. Ehlers *et al*. (2003) attributed the phenomenon to the osmotic effect that reduces the availability of soil water to crops. The authors explain that under increasing saline conditions, crop roots are in competition with salts for water. The higher the absolute osmotic potential of the soil water, the greater the portion of water retained by dissolved salts in the soil solution and hence the greater the amount that becomes unavailable for crop uptake. The higher sodium to calcium ratio for the 300 mS m^{-1} treatment might have a specific ionic effect on the transpiration and yield. However, ion uptake was not measured in the plant and the lower transpiration or yield cannot fully be explained by this phenomenon. The actual or measured EC of the irrigation water was within 5 units from the target value and hence the osmotic effect. Barnard *et al*. (2015) recently illustrated this principle in a simulation study. They showed how salt built-up reduces the profile available water content over the growing season of wheat and maize.

Another finding of the study is that there is a large difference in the transpiration within each cutting as well as between the different cuttings. This variation was mainly attributed towards the duration and prevailing weather conditions during the cycles. Considering the duration period of the cuttings, the results shows that the transpiration period varies from 35 to 76 days between cuttings. Hence, it is obvious that the longer the duration of the cutting cycle the higher the cumulative transpiration.

Regarding the effect of the weather, it is a general fact that the higher the potential evaporation (ET$_0$), the higher the transpiration under irrigation conditions (Brown *et al.*, 2005; Tesfuhuney *et al*., 2013; Tesfuhuney *et al*., 2015; van Rensburg *et al*., 2013). In this case, the potential evaporation rate varies from 2.5 mm to 5.4 mm day^{-1} over the cycles (Table 3.2).

Table 3.2 Mean cumulative transpiration (T, mm), for each cutting and EC_i treatments over all the cuttings

EC_i (mS m^{-1})	Cutting 1 T (mm)	Cutting 2 T (mm)	Cutting 3 T (mm)	Cutting 4 T (mm)	Cutting 5 T (mm)
Growing Season Length (Days)	37	76	26	35	49
15*	169.9	227.8	167	248.5	254
150	202.5	253.5	166.1	275.2	271.3
300	171.8	228	160.3	225.5	231.1
450	157.8	231.2	166.1	192.5	247.8
600	135	186.3	150.3	190	232.8
1200	110.4	170.1	124	145	183
Mean ET_0 rate (mm day^{-1})	3.21	2.5	4.9	5.4	2.9

*Control

3.3.2 Water table depletion

Mean daily water table depletion (WTD, mm) as affected by irrigation water salinity for the five cuttings are depicted in Figure 3.6, while the seasonal water table depletion is summarized in Table 3.3. The total cumulative water table depletion for the individual treatments over all the cuttings, of the two soils are also presented in Appendix 1.

These results, as in the case of transpiration, show a general trend that suggests a decline in the water table depletion with increasing irrigation water salinity treatments. For example, the average WTD for the control was 95 and it decreased to 55 mm towards the 1200 mS m^{-1} treatment. Ayars *et al.* (2009) confirmed that less water would be taken up from shallow groundwater with increasing groundwater salinity EC_e, due to the moderately salt sensitivity of lucerne.

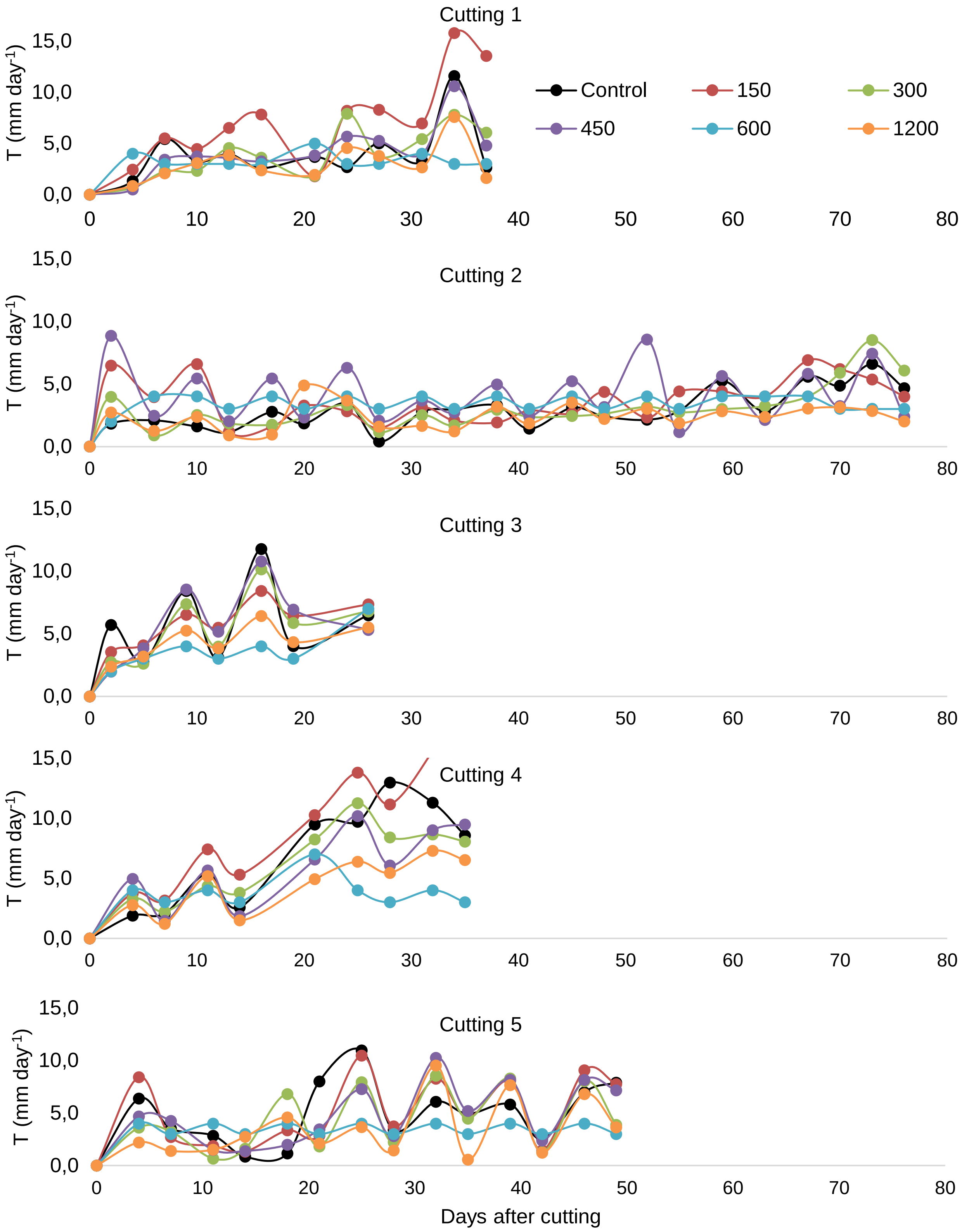

Figure 3.5 Mean lucerne daily transpiration (T, mm day^{-1}) for all the treatments over the five cuttings of both the soils.

Another feature of the daily water table depletion is the cyclic nature found in all the cuttings. This is attributed to the soil water availability during the depletion periods induced by the irrigation practice. Accordingly, the depletion rate is at its lowest during and just after irrigation and then increases over the length of the period towards the next irrigation. During irrigation and just after irrigation the unsaturated zone experience a higher water potential, compared to the saturated zone as was found by Haka (2010). Hence, better water uptake from the unsaturated zone compared to the saturated zone. However, as the length of the drying cycle between irrigations proceeds, the matrix suction decreases with desorption of the unsaturated zone.

The desorption process induces an increases in the concentration of the dissolved salts which results in an increase in the osmotic head, making water less available to the roots (Hillel, 2004). In addition, lucerne has a well proliferate root system (Doorenbos & Kassam, 1979) that can thoroughly explore the soil water from unsaturated zone. Thus, lucerne has a larger potential for *in situ* use of ground water compared to field crops such as wheat and maize (Ayars *et al.*, 2009).

Concerning the contribution of the water table as a source of total transpiration, the results in Table 3.3 indicated that, the total contribution from the water table decrease with an increase in EC_i treatments. The average loss in the contribution towards total transpiration was quantified by regressing the water table contribution (%) with the EC_i treatments; $y = -0.0095x + 50.118$, $R^2 = 0.5$. In addition, the mean water table contribution of the control treatment amounted to 44% of the total transpiration. This finding is consistent with the measurements of Haka (2010) who reported a contribution of 44%. Overall, the impact of salinity on water table contribution was also confirmed by Ayars *et al.* (2009), stating that lucerne will use significant quantities of water from shallow groundwater even when the groundwater salinity is in excess of the Maas and Hoffman threshold salinity.

Table 3.3 Mean cumulative transpiration (T, mm), water table depletion (WTD) and the percentage contribution of the water table as a source of total transpiration for each cutting and EC_i treatments over all the cuttings

EC_i	Cutting 1			Cutting 2			Cutting 3			Cutting 4			Cutting 5		
(mS m^{-1})	T (mm)	WTD (mm)	% of T	T (mm)	WTD (mm)	% of T	T (mm)	WTD (mm)	% of T	T (mm)	WTD (mm)	% of T	T (mm)	WTD (mm)	% of T
15*	169,6	64,7	38,2	227,8	33,5	14,7	167,0	84,1	50,3	248,5	95,7	38,5	254,0	194,6	76,6
150	202,5	119,0	58,8	253,5	69,0	27,2	166,1	64,1	38,6	275,2	135,0	49,0	271,3	208,3	76,8
300	171,8	68,9	40,1	228,0	35,5	15,6	160,3	94,6	59,0	225,5	151,0	67,0	231,1	169,0	73,1
450	157,8	73,9	46,9	231,2	75,0	32,4	166,1	98,5	59,3	192,5	75,9	39,4	247,8	178,9	72,2
600	135,0	63,9	47,3	186,3	45,4	24,3	150,3	69,9	46,5	190,0	92,7	48,8	232,8	108,2	46,5
1200	110,4	40,4	36,6	170,1	43,5	25,6	124,0	43,3	34,9	145,0	49,3	34,0	183,0	97,3	53,2

* Control

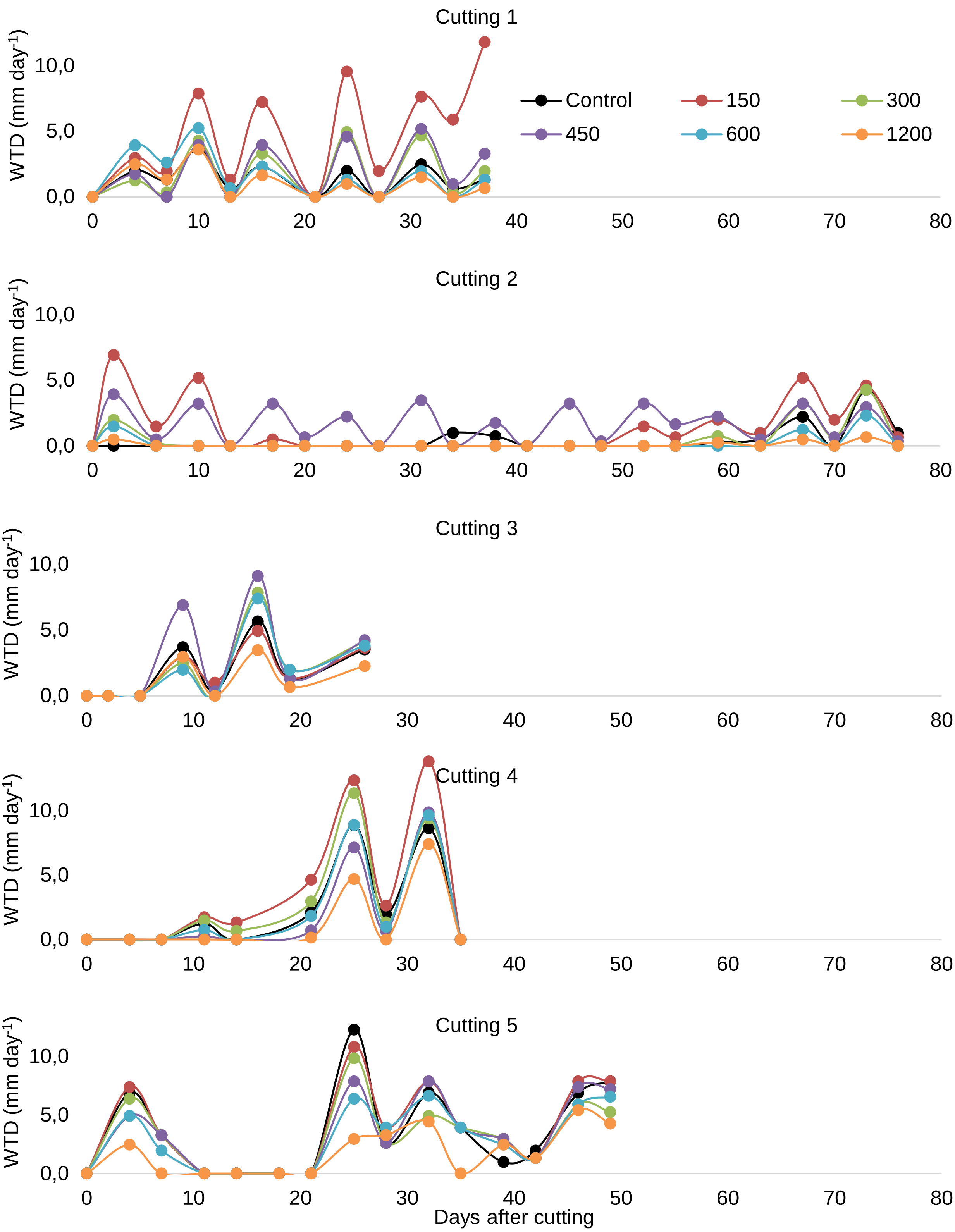

Figure 3.6 Mean daily water table depletion (WTD, mm) of both soils for all the treatments of the five cuttings.

3.3.3 Crop yield

The results of the mean biomass yield (BM) and the standard deviation for the EC_i treatments for the five cuttings are depicted in Figure 3.7. The total above-ground biomass yield for the individual treatments, of the two soils are presented in Appendix 2. From these results, two main findings were derived.

Firstly, there is a general trend that biomass decreased with increasing water salinity (EC_i) over all the cuttings. This is consistent with the findings of Guerrero-Rodrigues (2011) where biomass production of lucerne decreased with increasing salinity concentrations. Guo *et al*. (2016) found that shoot biomass production showed dramatic decline after salt stress. Comparing these results with work done by Ehlers (2007) on other crops, wheat, beans, peas and maize, all resulted in the same decreasing trend in biomass yield with increasing water salinity was observed.

Secondly, with respect to the sequence of cuttings, there is an increase in biomass from cutting 1 to 3 within all the salinity treatments. However, irrigation water with EC_i of 300 mS m^{-1} and higher caused the increase in relative yield to level-out later in the growing season (Cutting 4 and 5), compared to that of the higher irrigation water quality treatments ($EC_{i\ 15}$ and $EC_{i\ 150}$). The steady increase in the yield over the season for the high quality irrigation water treatments is in line with observations made by Coruh *et al.* (2008). They found that measured above-ground biomass increased during a range of stand ages. The highest yield was found in year 3 after planting, thus confirming the yield increase over time as measured here.

3.3.4 Crop yield and salinity relationships

3.3.4.1 Relative above ground biomass yield and EC_i

The results of the polynomial functions that describe the relationship between the relative mean above-ground biomass and EC_i for the cuttings are summarized in Table 3.4. However, the two-tail test (Tabel 3.5) reveled no significant difference between the trend lines of the different cuttings for the EC_i. Hence, the data of the cuttings were grouped and presented as a polynomial function in Figure 3.8.

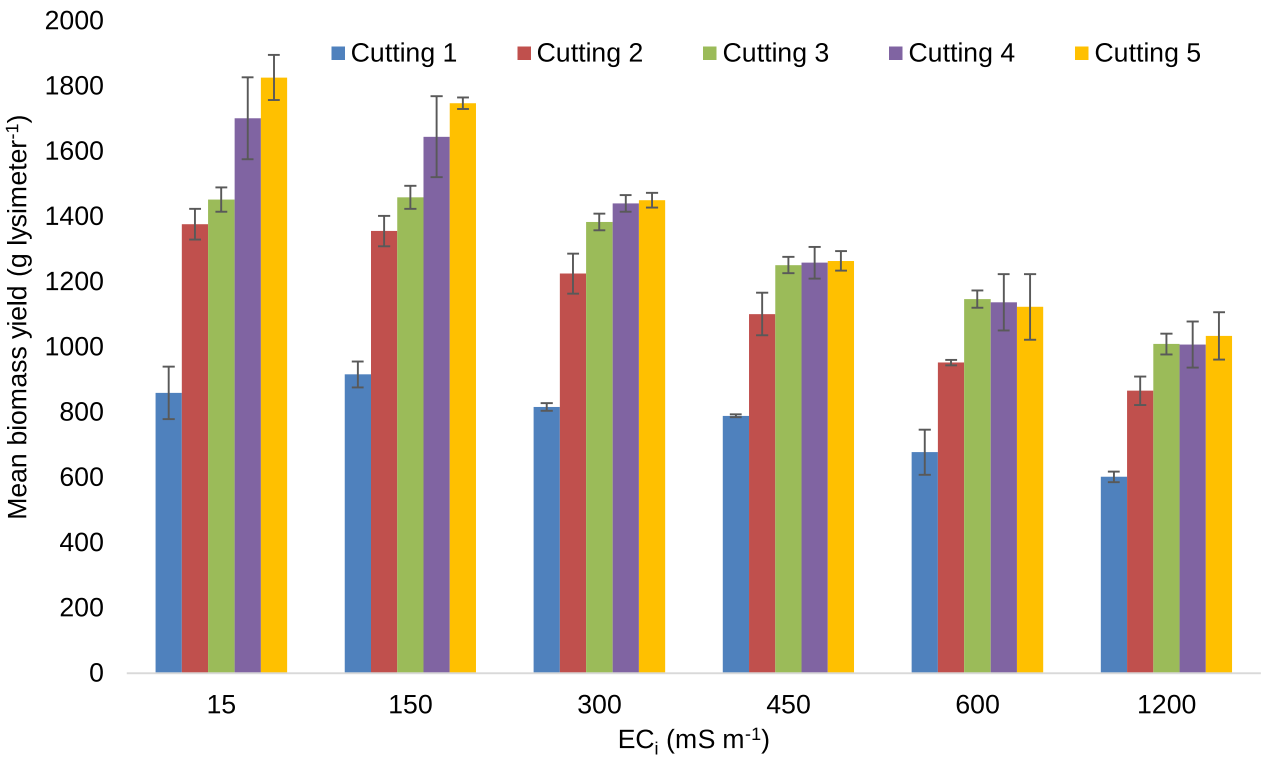

Figure 3.7 The mean biomass yield of the five cuttings as affected by irrigation water salinity treatments (EC_i).

The polynomial function indicated that the relationship between relative mean above-ground biomass and EC_i is curve linear. This relationship differs from the linear relationship reported by Maas & Hoffman (1977) as depicted in Figure 3.8. According to the authors' response curve, lucerne yield will decline at a constant rate of 0.11% per unit mS m^{-1} with increasing EC_i, while the results of the cultivar SA Standard, showed two linear response sections over the curve. The sections were separated using the critical level procedure as described in Section 3.2.4.4. The critical level is 686 mS m^{-1}. The first response class, which stretches from 130 to the critical level, represents a yield loss of 0.06% per unit increase in mS m^{-1}. Hence, for this salinity range it seems that the cultivar SA Standard is more salt tolerant than those used by Maas & Hoffman. (1977).

The second section on the curve linear function represents irrigation water salinity class above the critical level up to 1200 mS m^{-1}. This linear function estimates a constant yield loss of 0.009% per unit mS m^{-1} over the mentioned range of salinity conditions. Comparing to the Maas & Hoffman (1977) function the reduction in biomass is considerably lower for the cultivar SA Standard.

Considering the salinity threshold value, the results of this experiment confirmed the value of 130 mS m^{-1} estimated by Maas & Hoffman (1977). Hence, it is clear that the research provides new information for the SA Standard, regarding management of irrigation water salinity for lucerne. Three irrigation water salinity classes were identified: Firstly, to manage for full potential the EC_i should be below 130 mS m^{-1}. Secondly, for irrigation water above the threshold to the critical level, the user must accept a constant yield loss of 0.06% per unit mS m^{-1}. Lastly, salinity levels between the critical level and 1200 mS m^{-1} a constant yield loss of 0.009 % per unit, mS m^{-1} is predicted.

Table 3.4 Statistical coefficients for the polynomial functions that describes the relationship between relative mean biomass yield and EC_i

	Equation	Coefficient of determination
Cutting 1	$y = 4E\text{-}07x^2 - 0.0008x + 1{,}1829$	$R^2 = 0.9724$
Cutting 2	$y = 7E\text{-}07x^2 - 0.0013x + 1{,}1226$	$R^2 = 0.9974$
Cutting 3	$y = 5E\text{-}07x^2 - 0.0011x + 1{,}1145$	$R^2 = 0.9997$
Cutting 4	$y = 5E\text{-}07x^2 - 0.001x + 1{,}1317$	$R^2 = 0.9901$
Cutting 5	$y = 3E\text{-}07x^2 - 0.0007x + 1{,}1143$	$R^2 = 0.9886$

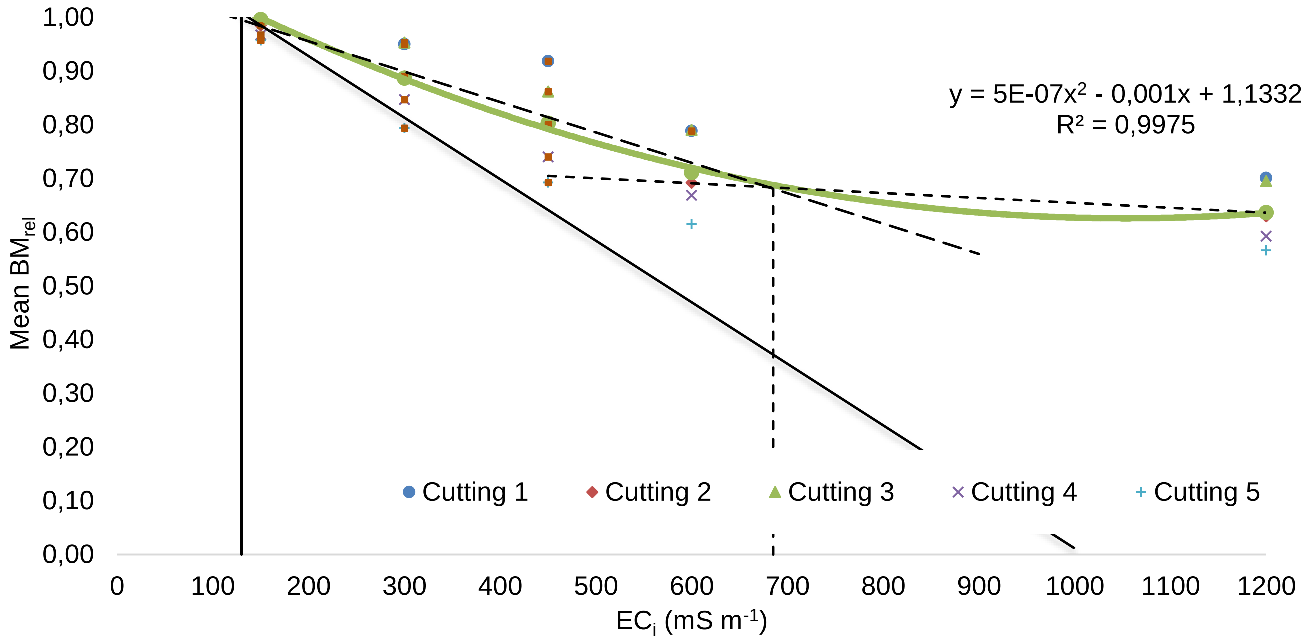

Figure 3.8 The relationship between the mean relative biomass yield (BM_{rel}) and irrigation water salinity treatments (EC_i, mS m^{-1}) of lucerne compared to the Maas & Hoffman. (1977) reported response.

Table 3.5 T- test results, comparing the different combinations of relative mean biomass yield and the EC_i relationships for the cuttings

	df	p values
C1 vs C2	8	0,372728
C1 vs C3	8	0,221199
C1 vs C4	8	0,784171
C1 vs C5	8	0,128925
C2 vs C3	8	0,489409
C2 vs C4	8	0,705409
C2 vs C5	8	0,456738
C3 vs C4	8	0,28974
C3 vs C5	8	0,165662
C4 vs C5	8	0,702089

3.3.4.2 Relative above ground biomass yield and EC_e

Table 3.6 summarizes the polynomial functions of the cuttings that describe the relationship between the relative mean above-ground biomass and soil water salinity (EC_e, mS m^{-1}). The results on the T-test performed on the polynomial functions of the cuttings are listed in Table 3.7 for the cuttings.

Based on this results it is clear that there were no significant differences between the polynomial functions for the different cuttings. Hence, data were grouped, regressed and then plotted to represents the relative biomass - EC_i response curve for Lucerne (SA Standard). As reference, the response function of Maas & Hoffman (1977) was also depicted in Figure 3.9.

As in the case with the relative yield - EC_i response curve, the relative yield - EC_e relationship made it possible to determine the critical EC_e level on the curve, namely 865 mS m^{-1}. Hence, it splits the curve into two distinct EC_e classes, namely salt built-up that represents EC_e conditions between 200 and 865 mS m^{-1}, and conditions above the critical level towards 1489 mS m^{-1}. The linear function that represents salinity conditions over the first class suggests a similar loss in biomass per unit increase in salinity of the soils as promoted by the Maas and Hoffman (1977) response function; 0.05% per mS m^{-1}. However, the response function that represents salinity conditions above the critical level of 1489 mS m^{-1} provides new information on salinity management of lucerne.

The results show here that the loss in biomass yield due to salts that built-up in the soil is not as drastic as suggested by the Mass and Hoffman function; the biomass loss in this study was found to be 0.05 mS m^{-1} compared to the 0.07% by the Maas and Hoffman reference. Hence, it is clear that lucerne (SA Standard) is considerably more tolerant to salinity conditions than that was previously promoted in crop-salinity guidelines (Ayers & Westcot. 1994), because the guideline for lucerne is based on the Maas and Hoffman response function that was determined in a sand culture with NaCl as main constituents of the irrigation water (Sanden & Sheesley. 2007). However, the results of this study confirms the soil salinity threshold of 200 mS m^{-1} as a norm to avoid the start of yield loss due to salt built-up in the soils.

Table 3.6 Statistical coefficients for the polynomial functions that describes the relationship between the relative mean biomass yield and EC_e

	Equation	Coefficient of determination
Cutting 1	$y = 3E\text{-}07x^2 - 0.0007x + 1{,}1898$	$R^2 = 0.9707$
Cutting 2	$y = 3E\text{-}07x^2 - 0.0008x + 1{,}1367$	$R^2 = 0.9841$
Cutting 3	$y = 4E\text{-}07x^2 - 0.0009x + 1{,}1289$	$R^2 = 0.9974$
Cutting 4	$y = 4E\text{-}07x^2 - 0.0009x + 1{,}1289$	$R^2 = 0.9974$
Cutting 5	$y = 4E\text{-}07x^2 - 0{,}001x + 1{,}1351$	$R^2 = 0.9973$

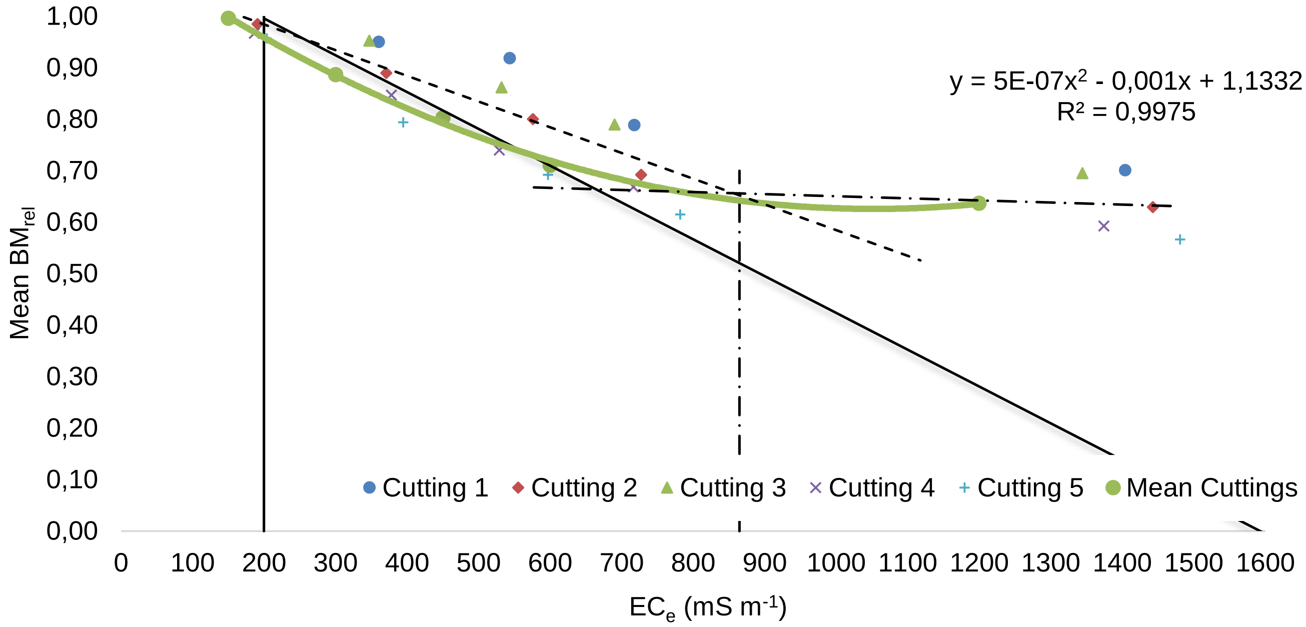

Figure 3.9 The relationship between the mean relative biomass yield (BM_{rel}) and soil water salinity (EC_e, mS m^{-1}) of lucerne compared to the Maas & Hoffman. (1977) reported response.

Table 3.7 T-test results, comparing the different combinations of relative mean biomass yield and the EC_e relationships for the cuttings

	df	p values
C1 vs C2	8	0,372728
C1 vs C3	8	0,784171
C1 vs C4	8	0,221199
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C2 vs C3	8	0,489409
C2 vs C4	8	0,705409
C2 vs C5	8	0,456738
C3 vs C4	8	0,28974
C3 vs C5	8	0,165662
C4 vs C5	8	0,702089

3.3.5 Crop water productivity

Crop water productivity (CWP_{AGB}, g m^{-2} mm^{-1}) for each cutting of all the EC_i treatments is summarized in Table 3.8. Regression of the crop water productivity against the corresponding EC_i values reveal a strong polynomial relationship; $y = 9E\text{-}07x^2 - 0.0013x + 2.6553$; $R^2 = 0.9$. There was also a strong linear relationship observed between crop water productivity and EC_i values from the control up to 600 mS m^{-1}; $y = -0.0007x + 2.6$, $R^2 = 0.87$. This relationship shows a linear decrease in the crop productivity with an increase in EC_i. There was no difference in the crop water productivity between 600 and 1200 mS m^{-1} treatments. This suggests that the crop is more tolerant than generally reported in literature. However, Sanden & Sheesley (2007) explains the supressing effect as result of a reduction in stomatal conductance in CO_2. They found that when plant water potential exceeds the threshold for lucerne, all the stomata shut down, and growth stops.

However, the mean crop water productivity over the five cuttings and all the treatments were 2.424 g m^{-2} mm^{-1}, while that of the control varies between 2 and 3.4. The control's value is consistent with those reported by Haka (2010) which stretches from 2.32 and 3.51 g m^{-2} mm^{-1}. Singh *et al.* (2007) reported slightly lower values that range between 0.9 and 2.5 g m^{-2} mm^{-1}. The difference can be attributed to differences in weather conditions, soil water regime, season, location, seasonal evapotranspiration, growth cycle and the different cultivar of lucerne studied (Gramshaw, 1994; Singh *et al*., 2007).

Table 3.8 Crop water productivity (CWP_{AGB}, g m^{-2} mm^{-1}) as affected by irrigation water salinity for the cuttings

EC_i (mS m^{-1})	Cutting 1 CWP_{AGB} (g m^{-2} mm^{-1})	Cutting 2 CWP_{AGB} (g m^{-2} mm^{-1})	Cutting 3 CWP_{AGB} (g m^{-2} mm^{-1})	Cutting 4 CWP_{AGB} (g m^{-2} mm^{-1})	Cutting 5 CWP_{AGB} (g m^{-2} mm^{-1})
15*	2	2.4	3.4	2.7	2.8
150	1.8	2.1	3.5	2.3	2.5
300	1.9	2.1	3.4	2.5	2.5
450	2	1.9	3	2.6	2
600	2	2	3	2.4	1.9
1200	2.1	2	3.2	2.7	2.2

*Control

3.4 Conclusions

The salinity experiment with lucerne (SA Standard) as test crop was conducted in the non-weighing lysimeter facility of the Department of Soil Crop and Climate Sciences, University of the Free State, Bloemfontein. Concerning the first objective of quantifying the effect of irrigation water salinity on transpiration, the results and findings confirm the general trend that both the daily transpiration and seasonal transpiration decline with increasing irrigation water salinity. This salinity trend was also evident in both the daily and seasonal water table depletion results, as well as the above ground-biomass yield. Concerning the contribution of the water table as a source of total transpiration, it was clear from the control treatment that the water table contributed 44% of the total transpiration. Again, the increasing irrigation water salinity resulted in a decrease in the contribution of the water table toward transpiration.

With respect to the second objective, the study provides new information regarding management of irrigation water salinity for lucerne. Hence, it was clear that the EC_i-above ground biomass response curve was different compared to the well-established Maas & Hoffman function. The response curve in the study suggest a critical level at 685 mS m^{-1}, which divides irrigation water salinity into two management classes, *viz.* between 130 and 685 mS m^{-1}, and between 685 and 1200 mS m^{-1}. Accordingly, the function predicts a constant yield loss of 0.06% and 0.009% mS m^{-1} for the two classes, respectively, compared to the constant yield decline of 0.11% from 130 to 1200 mS m^{-1}. Concerning the relationship between EC_e

and relative biomass, similar management classes was defined, viz. between 200 and 865 mS m^{-1} and between 865 and 1489 mS m^{-1}. From these relationships and the fact that the crop productivity did not differ from 600 up to 1200 mS m^{-1}, it can be concluded that lucerne (SA Standard) is more tolerant to irrigation water salinity than reported in literature by Maas and Hoffman (1997).

CHAPTER 4

SIMULATING MACROSCOPIC WATER UPTAKE OF LUCERNE UNDER OSMOTIC STRESS: SWAMP

4.1 Introduction

Soil and water are two precious resources that need to be utilized efficiently to ensure sustainable food production. Irrigation has contributed significantly to increased crop production. Unfortunately, irrigation has also lead to increased degradation of agricultural lands due to soil salinization caused by poor water and salt management (Le Roux *et al*., 2007). Crop production on agricultural lands with saline irrigation water requires adoption of various management options. These options require determination of water and salt movement through the soil profile and prediction of crop response to irrigation water salinity, as influenced by various soil, plant and climatic conditions (Rasouli *et al*., 2013).

Several soil, plant and climatic factors have a direct influence on the dynamic process of root water uptake i.e. soil water pressure head, soil hydraulic conductivity, osmotic head (soil salinity), evaporative demand, rooting depth, root density distribution and plant properties (Homaee *et al*., 2002a,b). Mathematical simulation models are an important tool to understand all these soil-plant interactions. Many studies regarding the effect of increasing soil salinity on root water uptake and yield were done under steady state conditions (Maas & Hoffman, 1977; Mass, 1986, 1990 & Maas & Grattan, 1999 Homaee *et al*, 2002a). According to Corwin *et al*. (2007) steady-state conditions do not exist under most field conditions, and emphasized the need to make use of transient-state modeling (Letey & Feng, 2007; Letey *et al*., 2011).

Transient-state mathematical models allow for complex processes in a continuous changing crop root zone, for example water and salt flow in irrigated water table soils and the corresponding response of different crops to matric and osmotic stress. Issues like: fluctuating irrigation water salinity, amount of water applied, upward salinization from shallow groundwater and variation in rainfall have an effect on these integrated processes (Homaee *et al*., 2002a,b; Corwin *et al*., 2007; Letey & Feng, 2007; Oster *et al*., 2012).

Several popular transient-state models exist like: EVIRO-GRO (Feng *et al*., 2003), SWAP (Van Dam *et al*., 2008), HYDRUS (Šimunek *et al*., 2008), SALTMED (Ragab *et al*., 2005) and SWAMP (Bennie *et al*., 1998; Barnard *et al*., 2015). The **S**oil **WA**ter **M**anagement **P**rogram (SWAMP) does not rely on salinity threshold and slope parameters. In general these parameters are used by most models in the piecewise linear or smooth S-shaped reduction functions to simulate water uptake under decreasing osmotic potentials (Barnard *et al*., 2015). SWAMP was originally developed to support *in situ* field observations of water management for rain-fed cropping systems in central South-Africa (Bennie & Hensley, 2001; Hensley *et al*., 2011). In 2003 some adaptations were made to allow for simulations of water table uptake through capillary rise (Ehlers *et al*., 2003). One major limitation of SWAMP is the fact that it was developed primarily for rain-fed cropping systems. Barnard *et al*. (2013) showed however that it can also be used successfully in irrigated cropping systems to support *in situ* field observations of water management. In 2015 SWAMP was adapted to include the effect of osmotic stress on water uptake and yield (Barnard et al., 2015). This was possible with limited adaptation to the soil layer water supply rate algorithm, which was originally used to simulate transpiration or water uptake from a rooted soil layer due to matric stress.

Hence, SWAMP simulates matric and osmotic stress of field crops grown on sandy to sandy loam soils with shallow water tables in semi-arid regions reasonably accurate. Additionally, it was also found with an independent study that the soil layer water supply rate algorithm outperformed various other models in simulating water uptake of sugarcane and soil induced crop water stress (Singels *et al*., 2010). The objective of this chapter is to establish how credible SWAMP will be in simulating (i) yield decline with increasing irrigation water salinity, (ii) seasonal transpiration and (iii) weekly transpiration of lucerne, grown on sandy to sandy loam water table soils in semi-arid regions, under conditions of osmotic stress.

4.2 Methodology

4.2.1 Model description

4.2.1.1 Infiltration

The amount of water received, with every rainfall under rain-fed (dryland) conditions, or water received in combination with rain and irrigation or irrigation only under irrigated conditions, needs to infiltrate the soil. If the rainfall or irrigation rate do not exceed the infiltability of the soil, and there is no water running out of the land, the runoff are assumed negligible. The model cannot simulate infiltration. Thus, the model infiltrates rainfall and/or irrigation as a single event on a daily basis.

4.2.1.2 Redistribution

Water are redistributed through the soil profile with the net effect of convection. The infiltrated water will flow into the first layer (k = 1), until the drained upper limit (DUL, mm) is reached, where after water flows into the next lower layer (k > 1). This redistribution according to the cascading principle (tipping-bucket) will continue on a daily basis until the water that flows into a specific soil layer is less than needed to refill that specific layer.

Each soil layer has a different DUL value. To differentiate between the soil layers, the DUL of the root zone (DUL_{rz}, mm) needs to be weighed according to the layer thickness (z, mm) and the silt-plus-clay (SC, %) content of each layer. To determine the DUL_{rz}, the model uses a drainage curve, i.e. Equation 4.1 (Ratliff et al., 1983). Where W_{soil} is the water content of the soil (mm) during the drainage period, a is the slope (mm d^{-1}), b the intercept (mm) and DS the number of days after the soil has been saturated. This concept do not make provision for bare soils or soils that has an established crop on it. Therefore the drainage curve equation was adapted to be applicable for either a bare (Equation 4.2) or cropped (Equation 4.3) soil, where E is soil evaporation (0.1 mm d^{-1}) and T_R the maximum simulated daily transpiration requirement during the growing season.

$$W_{soil} = - a \ln DS + b \qquad (4.1)$$

$$DUL_{rz(Bare)} = b - a \ln \left(\frac{a}{E_{(d)}}\right) \qquad (4.2)$$

$$DUL_{rz(Crop)} = b - a \ln \left(\frac{a}{T_{R(d)}}\right) \qquad (4.3)$$

4.2.1.3 Drainage

The drainage rate (DR, mm) for a specific day (d) is calculated with Equation 4.4, where W_S (mm) is the simulated water content of the soil profile during the specific day, RI (mm) the rainfall-plus-irrigation during a specific day and i one day more than DS for W_s plus RI (Equation 4.5). When rainfall-plus-irrigation is more than the DR during a specific day excess water will remain in the soil profile for the next day.

$$DR_{(d)} = (W_{S(d)} + RI_{(d)}) - (-a \times \ln i + b) \qquad (4.4)$$

$$i = \text{Exp}\left(((W_{s(d)} + RI_{(d)}) - b) / -a\right) + 1 \qquad (4.5)$$

4.2.1.4 Evaporation

To simulate cumulative evaporation from a bare (E_{Bare}, mm) soil surface, Equation 4.6 is used, where t is the amount of days between every rainfall and/or irrigation event and C an empirical parameter (Equation 4.7). If the soil surface is covered with a crop (E_{crop}, mm), E_{Bare} is reduced with a factor equal to one minus the fractional shading (FB).

Bennie *et al*. (1998) found that the parameter C are best determined by desorptiwity (Equation 4.8), where Θ_a is the air dry volumetric soil water content (mm mm^{-1}), z the thickness of the evaporative soil layer, and Θ the simulated volumetric soil water content on a specific day (mm mm^{-1}).

$$E_{Bare} = C(t)^{0.5} \text{ where } E_{Bare(d)} = E_{Bare} - E_{Bare(d-1)} \tag{4.6}$$

$$E_{Crop} = E_{bare}\,(1 - FB_{(d)}) \text{ where } E_{Crop(d)} = E_{Crop} - E_{Crop(d-1)} \tag{4.7}$$

$$C_{(d)} = 0.087\,(z_{(k=1)})\,(\Theta_{(k=1)(d)} - \Theta_{a(k=1)}) + 1.36 \tag{4.8}$$

4.2.1.5 Potential transpiration or transpiration requirement

The rate of transpiration is influenced by the evaporative demand of the atmosphere surrounding the leaf, humidity, temperature, wind and occurring sunlight. If the soil water supply is non-limiting, the transpiration requirement and rate will be determined by climatic conditions and plant characteristics. To achieve maximum biomass production (Y_m, kg ha^{-1}), the necessary potential transpiration (T_P, mm), is calculated with Equation 4.9 (De Wit, 1958, according to Hanks & Rasmussen, 1982), where ET_o is the mean atmospheric evaporative demand, expressed as reference evapotranspiration of a clipped cool-season grass, and m a crop specific parameter.

$$T_P = ET_o \left(\frac{Y_m}{m}\right) \tag{4.9}$$

To obtain a specific input target yield, a particular seasonal transpiration is required (T_R) and can be calculated with Equation 4.10, where Y_a is the total biomass production (Y_a, kg ha^{-1}) for that specific yield (Stewart *et al*., 1977).

The seasonal T_R is distributed throughout the growing season with Equation 4.10 using a generated growth curve equation for calculating the relative daily T_R ($T_{R\,Rel}$), where DAP is the number of days after planting. The growing season is divided is three distinctive growth periods i.e. vegetative, reproductive development and physiological maturity represented by B', C' and D' (DAP). At the end of growth phase A' and D' the relative daily crop water requirement is represented by a' and d', respectively, and Q the area under the relative daily T_R line.

$$T_R = T_P - \left[T_P \left(1- \frac{Y_a}{Y_m}\right)\right] \qquad (4.10)$$

$$T_{R(d)} = T_{R(Rel)(d)} \left(\frac{T_R}{Q}\right) \qquad (4.11)$$

$$T_{R(Rel)(d)} = \left(\frac{a'}{A'}\right) \text{(DAP) when DAP} \leq A'$$

$$T_{R(Rel)(d)} = a' + \left(\frac{1-a'}{B'-A'}\right) \text{(DAP – A') when A'} < \text{DAP} \leq B'$$

$$T_{R(Rel)(d)} = 1 \text{ when B'} < \text{DAP} \leq C'$$

$$T_{R(Rel)(d)} = 1 - \left[\left(\frac{1-d'}{D'-C'}\right) \text{ (DAP-C')}\right] \text{when C'} < \text{DAP} \leq D'$$

4.2.1.6 Root density

Roots are simulated with SWAMP by increasing the depth of root growth and length. The total length per unit surface area ($L_{(d)}$, , mm mm^{-2}) during the growing season is determined with a root growth rate parameter for each specific crop. The distribution of roots among the soil layers, i.e. the rooting density (Lv, mm roots mm^{-3} soil) is determined with Equation 4.12, where $f_{(d)}$ is the daily root distribution coefficient (Gerwitz and Page, 1974).

$$Lv_{(k)(d)} \quad \frac{L_{(d)}\left[\left(1\text{-Exp}\left(-f_{(d)} k\, z_{(k)}\right)\right) - \left(1\text{-Exp}\left(-f_{(d)}(k-1) z_{(k-1)}\right)\right)\right]}{z_{(k)}} \qquad (4.12)$$

4.2.1.7 Actual transpiration

SWAMP uses the approach by Philip (1966) to simulate actual transpiration, i.e. a dynamic physical continuum with a demand and supply component. The daily-simulated E and T_R represent the demand component and Equation 4.13 the supply component (profile water supply rate). The supply of water from the root zone (PWSR, mm d^{-1}) must be sufficient to supply crop water requirements and hence prevent any matric stress. The water supply component of a specific soil layer is calculated by an algorithm developed by Bennie *et al*. (1988) and depends on the rooting density, matric and osmotic potential and critical leaf water potential.

$$\mathrm{PWSR}_{(d)} = \sum_{k=1}^{n} \mathrm{LWSR}_{(k)(d)} \tag{4.13}$$

The water supply rate of a rooted soil layer (LWSR, mm d^{-1}) are determined with Equation 4.14 (Bennie *et al.*, 1988) where, ψ_m is the matric potential (-kPa), F_{sr} the soil root conductance coefficient (mm^2 d^{-1} kPa^{-1}), ψ_p the critical leaf water potential where plant stress sets in (-kPa) and Θ_o the volumetric soil water content (mm mm^{-1}) where $\psi_m = \psi_p$.

$$\mathrm{LWSR}_{(k)(d)}=F_{sr}\ln\left(\frac{\Theta_{(k)(d)}}{\Theta_{(k)(d)}}\right)\left(\Pi Lv_{(k)}\right)^{0.5}\left|\psi_{m(k)(d)}-\psi_p\right| z_{(k)} \tag{4.14}$$

By using a retention curve (Equation 4.15), the daily ψ_m of each soil layer are determined from the daily simulation of Θ, where Θ_{1500} is the volumetric soil water content of the specific soil layer at 1500 kPa, Θ_{10} the volumetric soil water content of the specific layer at 10 kPa and c equal to Equation 4.16.

$$\psi_m=1500\left(\frac{\Theta_{1500(k)}}{\Theta_{(k)(d)}}\right)^{c_{(k)}} \tag{4.15}$$

$$c_{(k)}=\frac{-5.0056}{\ln\frac{\Theta_{1500(k)}}{\Theta_{10(k)}}} \tag{4.16}$$

If adequate water is supplied by the soil, the water potential difference between the root xylem and soil solution is high. Hence, the supply is more than the demand. However, when the demand is equal or more than the PWSR for a specific day the actual transpiration for the crop will be equal to the PWSR, i.e. soil induced water stress. The water uptake from a specific rooted soil layer is determined with Equation 4.17.

$$T_{A(k)(d)}=\left(T_{R(d)}\right)\left(\frac{\mathrm{LWSR}_{(k)(d)}}{\mathrm{PWSR}_{(d)}}\right) \tag{4.17}$$

4.2.1.8 Water table uptake

The approach of Malik *et al*. (1989) is used in SWAMP for simulating water table uptake (WTU, mm), i.e. relating the maximum upward flux (q_m, mm d^{-1}) from a water table to a specific height above the water table. q_m is determined for each layer within the capillary zone (CZ), where K_s is the saturated hydraulic conductivity (mm d^{-1}), y an empirical parameter describing the decline in hydraulic conductivity above the water table and Z_f the height between the middle of the layer and the water table surface (Equation 4.18).

$$q_{m(k=CZ)} = (K_s)(Exp^y)(Z_f) \tag{4.18}$$

4.2.1.9 Salt addition

Rainfall and irrigation water contains salts which are added to the soil together with salts from the water table through capillary rise. To calculate the amount of salts applied, the volume of water applied is multiplied by the corresponding electrical conductivity (EC) and a parameter the convert EC to salt content (kg salt ha^{-1} mm^{-1} water).

4.2.1.10 Salt leaching

Leaching and redistribution of salts through miscible displacement are calculated as a function of percolation with leaching curves developed by Barnard *et al*. (2010).

4.2.1.11 Osmotic potential

Osmotic potential (ψ_0) is calculated with Equation 4.19, which shows that a decrease in volumetric soil water content (Θ, mm mm^{-1}), subsequently, will lead to salt concentrating and resulting in a decrease in osmotic potential. Hence, the effect of osmotic stress is simulated at actual Θ and not at saturation (Θ_s), where c_2 is a parameter used to convert EC (mS m^{-1}) to total dissolved salts (TDS, mg ℓ^{-1}) and c_3 to convert TDS to ψ_0.

$$\psi_{0(k)(d)} = \left[\frac{(EC_{e(k)(d)}(c_2)(c_3)}{\Theta_{(k)(d)}}\right]\Theta_{s(k)} \tag{4.19}$$

4.2.1.12 Seed yield

Equation 4.10 is used to determine the expected seed yield given the specific matric and osmotic stress conditions during the growing season. In the equation the seasonal transpiration requirement is replaced with the actual transpiration. Hence, the actual biomass is simulated, which is multiplied with the harvest index to obtain an expected seed yield.

4.2.2 Model inputs and parameters

The climate, soil, crop and water inputs (initial and boundary conditions or information that does not require calibration) for the five cuttings are listed in Table 4.1. The yield and harvest index for the five cuttings of the control treatment for lucerne grown on both soils were used as the target yield for all the simulations of the different treatments. Constant input variables that are not listed in Table 4.1, are, the thickness of soil layer k ($z_{(k)}$, 300 mm), silt-plus-clay content of soil layer k ($SC_{(k)}$, 9 % for the Clovelly and 10 % for the Bainslvlei), electric conductivity of layer k at the start of each cutting ($EC_{c(k)}$, 15 mS m^{-1}), depth of water table (Z_{WT},

Table 4.1 Inputs which include simulation length and initial and boundary conditions required by the model SWAMP for the five cuttings of the control treatment for lucerne

Input	Abbreviation and unit	CT1	CT 2	CT 3	CT 4	CT 5
Mean atmospheric evaporative demand over growing season	ET$_{o,}$ (mm d^{-1})[*]	3.21	2.45	4.9	5.4	2.9
Planting date	PD	16/03/10	01/06/10	01/09/10	11/10/10	16/03/11
Growing season length	GSL (days)	37	76	26	35	49
Target or actual yield	TY (kg ha^{-1})	3599	5061	5644	6045	6529
Volumetric soil water content of layer *k* at the start of the season	Θ_k (mm m^{-1})	0.054[Cv]	0.048[Cv]	0.043[Cv]	0.047[Cv]	0.057[Cv]
		0.055[Bv]	0.053[Bv]	0.053[Bv]	0.062[Bv]	0.047[Bv]
Irrigation amount and distribution during season	I (mm)	110	173	63	79	110

[*] Expressed as reference evapotranspiration of a clipped cool-season grass. [**]Expressed as a saturation extract.

[Cv] = Clovelly soil

[Bv] = Bainsvlei soil

1200 mm), mean electrical conductivity of water table during the season (EC_{WT}, 15 mS m^{-1}) and the mean electrical conductivity of irrigation water during the season (EC_i, 15 mS m^{-1}).

Each lysimeter had seven distinct soil layers (z, mm), six soil layers each 300 mm thick and the seventh soil layer 200 mm thick (Table 4.2). The soil layers' particle size distribution (%) was measured and the silt-plus-clay (SC) content entered in conjunction with the initial volumetric soil water content (ϴ, mm mm^{-1}) (Table 4.3).

Each lysimeter was leached with the target EC_i after each cutting, hence, the EC_e at the start of each cutting was set equal to the EC_i treatment. The water table was kept constant at a depth of 1200 mm, with the EC's the same as the irrigation water EC_i treatment. Measured weekly irrigations during the growing season of lucerne for cutting 1 (CT1), cutting 2 (CT2), cutting 3 (CT3), cutting 4 (CT4) and cutting 5 (CT5) amounted to a total of 110, 172, 63, 79 and 110 mm on both soils, respectively. The movable rain shelter made it possible to ignore any rain.

Table 4.2 Particle size distribution (%) of both soils for the different depths in the lysimeters

Soil	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	25.6	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

Table 4.3 Inputs used in SWAMP to simulate the effect of osmotic stress on water uptake and yield of lucerne

		Clovelly	Bainsvlei
	Treatment (mS m^{-1})	$\Theta_{\text{start 0-200 mm}}$ (mm mm^{-1})	$\Theta_{\text{start 0-200 mm}}$ (mm mm^{-1})
CT1	15*	0.157	0.296
	150	0.147	0.279
	300	0.168	0.249
	450	0.176	0.260
	600	0.173	0.240
	1200	0.178	0.244
CT2	15*	0.193	0.283
	150	0.172	0.292
	300	0.178	0.277
	450	0.183	0.296
	600	0.183	0.284
	1200	0.188	0.278
CT3	15*	0.194	0.280
	150	0.191	0.307
	300	0.198	0.280
	450	0.190	0.282
	600	0.194	0.291
	1200	0.201	0.279
CT4	15*	0.191	0.280
	150	0.190	0.296
	300	0.189	0.272
	450	0.198	0.302
	600	0.185	0.297
	1200	0.199	0.288
CT5	15*	0.133	0.211
	150	0.144	0.221
	300	0.156	0.227
	450	0.148	0.232
	600	0.153	0.238
	1200	0.167	0.245

* Control

The measured model parameters (information that requires calibration) and equations used to determine default (unmeasured) parameters are presented in Table 4.4. Most of these parameters have been calibrated for the two soils. Data from the control treatment was used to calibrate the parameters used in simulating the transpiration requirement.

Table 4.4 Measured model parameters and equations used to calculate the un-measured parameters (defaults) that were required to simulate the effect of osmotic stress on water uptake and yield of lucerne

Redistribution	Cv: $a = 28.94$ mm d^{-1}; $b = 476.86$ mm Bv: a = 18.73 mm d^{-1}; $b = 535.54$ mm	Measured (Barnard *et al*., 2010)
Evaporation	$z_{(k=1)}=\text{Exp}\left[3.4244\left(SC_{(k=1)}\right)^2+5.7193\right]$ $\Theta_{a(k=1)}=0.0012\left(SC_{(k=1)}\right)+0.006$ $FB_{(d)}=\left(\frac{FB_m}{100}\right)\left(T_{R(Rel)(d)}\right)$ $FB_m=(FB_1)(TY)+FB_2$ when $TY \leq FB_3$ $FB_m=1$ when $TY > FB_3$	FB_m = maximum fractional cover. FB_1 and FB_2 = default parameters for each crop, which describes the linear relationship between yield and FB_m (FB_1 = for lucerne) (FB_2 = for lucerne) FB_3 = seed yield where FB_m is below 1. (FB_3 = kg/ha^{-1} for lucerne)
Transpiration requirement	$Y_m = 6500$ m = 98.68 A' = 5 B' =32 C' =35 a' =01 d' =0.9	Measured
Root density	$L_{(d)} = L_m T_{R(Rel)(d)} \left(\frac{FB_m}{1}\right)$ $F_{(d)} = \frac{2.303}{(0.7)(RPR)(d)}$	L_m = default root length index (mm mm^{-2}) (L_m = for lucerne) RPR = default root penetration rate for the specific crop (mm d^{-1}). (RPR = for lucerne)
Actual transpiration	$\Theta_{10(k)}=0.0345\left(SC_{(k)}\right)^{0.611}$ $\Theta_{1500(k)}=0.00385\left(SC_{(k)}\right)+0.013$ $\psi_P=1500$ for lucerne $F_{sr}=0.000044$ for Cv :0.000068 for Bv	Default values Determined with an interaction subroutine as described in Barnard *et al*. (2015). (mm^{-2} d^{-1} kPa^{-1}) $SC_{k=CZ}$ = silt-plus-clay (%) of layer k in capillary zone (CZ)
Water table uptake	$K_s = 2925.8\ \text{Exp}^{-0.1218(SC_{k=CZ})}$ $y = 0.0003\ (SC_{k=CZ}) - 0.011$	

4.2.3 Model evaluation

SWAMP was evaluated with the same procedure used by Barnard *et al*. (2013, 2015). This makes it possible to compare their water uptake simulations with SWAMP (field crops) to water uptake simualtions done here (lucerne). The model outputs for the different treatments were analyzed and compared against measurements. Various indices and test statistics were used to quantify the models response, i.e. model residuals, the correlations between estimates and measurements, and if any patterns occur between the residuals over external variables. Hence, numerous statistics were considered in one collected measure to have a complete understanding of the model response (Bellocchi *et al*., 2002).

The fuzzy-logic based approach where various statistical indices and tests are aggregated into tree modules, i.e. accuracy, correlation and pattern, and then into a single indicator module, I_{SWAMP}, as proposed by Bellocchi *et al*. (2002) were used. The statistical indices and test used in the accuracy module includes relative median absolute error (RMdAE, Equation 4.20), relative modeling efficiency (REF, Equation 4.21) and Kolmogorov-Smirnov (KS) test. Spearman's rank correlation coefficient (r_s) (Donatelli *et al*., 2004b) was used for the correlation module and for the pattern module, independent variables, such as growing season length ($PI_{v\ GSL}$), days after cutting ($PI_{v\ DAC}$), and irrigation water salinity ($PI_{v\ ECi}$) against the pattern of residuals. To determine $PI_{v\ GSL}$, $PI_{v\ DAC}$ and, $PI_{v\ ECi}$, the residuals were divided into five groups, i.e. five treatments and five cuttings, followed by calculating the pair-wise differences between the average residuals of the groups (Donatelli *et al*., 2004b). A range-based variable pattern index (PI_v) was used for all the independent variables, GSL, DAC and EC_i, because it allows groups with different lengths.

$$\text{RMdAE} = \text{median}_{i=1,\ldots,n}|Ms_i - Sm_i|\frac{100}{\bar{O}} \qquad (4.20)$$

$$\text{REF} = \text{median}_{i=1,\ldots,n}\left(\frac{\text{median}_{i=1,\ldots,n}|Ms_i - \bar{O}| - \text{median}_{i=1,\ldots,n}|Ms_i - Sm_i|}{\text{median}_{i=1,\ldots,n}|Ms_i - \bar{O}|}\right) \qquad (4.21)$$

where RMdAE = median percentage error in simulations by SWAMP

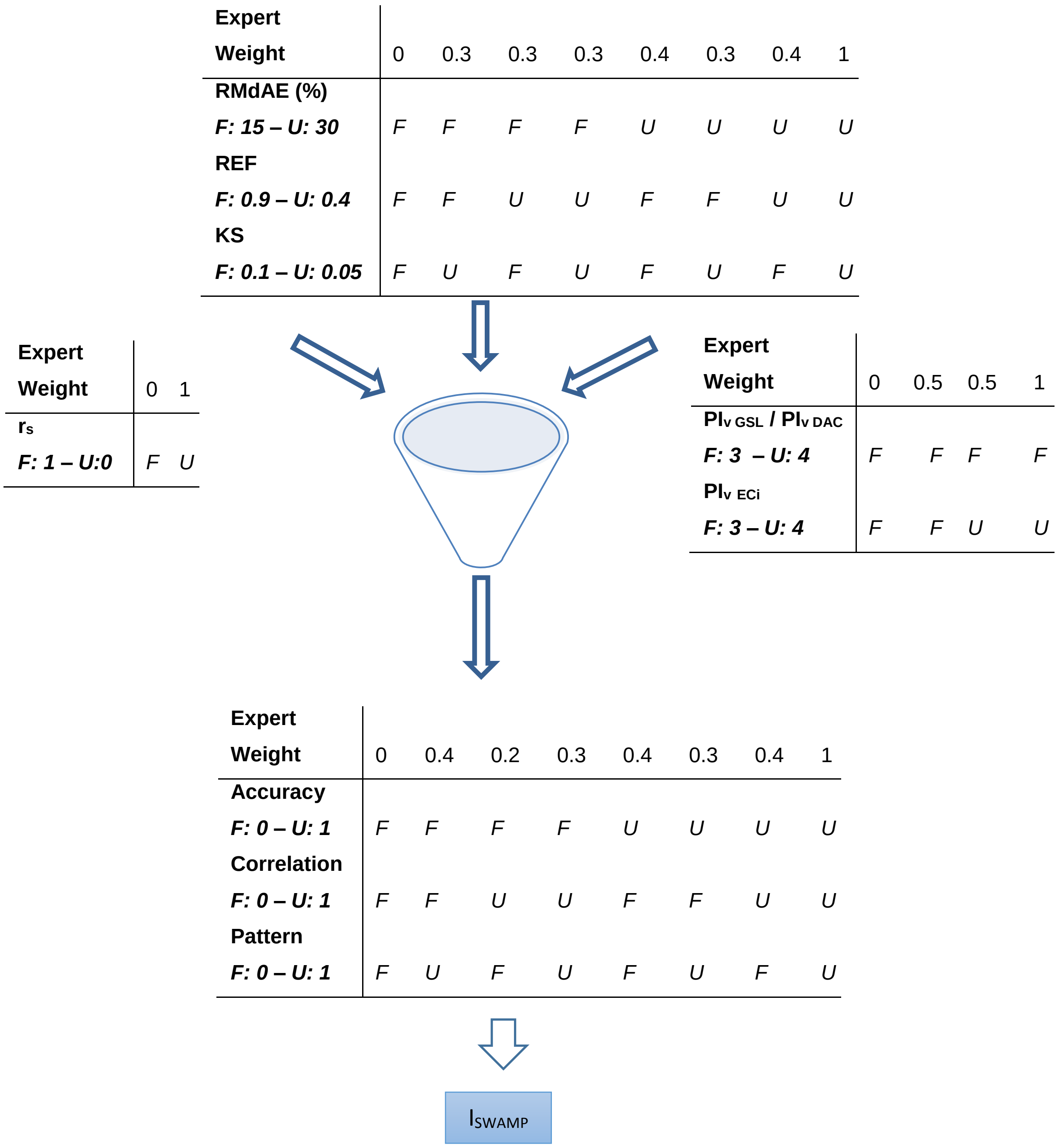
REF = simulated values compared to the median value of the measurements

i = the ith measured (Ms) and simulated (Sm) value

n = number of data pairs

$\bar{O}$ = mean of the measurements

r_s = measure of association between measurements and simulations



Expert Weight	0	0.3	0.3	0.3	0.4	0.3	0.4	1
RMdAE (%) ***F: 15 – U: 30***	*F*	*F*	*F*	*F*	*U*	*U*	*U*	*U*
REF ***F: 0.9 – U: 0.4***	*F*	*F*	*U*	*U*	*F*	*F*	*U*	*U*
KS ***F: 0.1 – U: 0.05***	*F*	*U*	*F*	*U*	*F*	*U*	*F*	*U*

Expert Weight	0	1
r_s ***F: 1 – U:0***	*F*	*U*

Expert Weight	0	0.5	0.5	1
PI$_{v\ GSL}$ / PI$_{v\ DAC}$ ***F: 3 – U: 4***	*F*	*F*	*F*	*F*
PI$_{v\ ECi}$ ***F: 3 – U: 4***	*F*	*F*	*U*	*U*

Expert Weight	0	0.4	0.2	0.3	0.4	0.3	0.4	1
Accuracy ***F: 0 – U: 1***	*F*	*F*	*F*	*F*	*U*	*U*	*U*	*U*
Correlation ***F: 0 – U: 1***	*F*	*F*	*U*	*U*	*F*	*F*	*U*	*U*
Pattern ***F: 0 – U: 1***	*F*	*U*	*F*	*U*	*F*	*U*	*F*	*U*

Figure 4.1. The statistical indices (RMdAE = relative median absolute error, REF = relative modeling efficiency, r_s = Spearman's rank correlation coefficient, PI$_{v\ GSL}$ = range-based fixed pattern of residuals by growing season length, PI$_{v\ DAC}$ = days after cutting PI$_{v\ ECi}$ = range-based fixed pattern of residuals by EC$_i$) and test (KS = Kolomogorov-Smirnov), three modules (accuracy, correlation and pattern) and indicator (I_{SWAMP} = single module indicator) used to evaluate SWAMP along with the decision criteria and their systematic aggregation (F = favorable, U = unfavorable), as adapted from Barnard *et al*. (2015).

These statistical indices and tests were used because the data did not represent populations with normal distributions (Donatelli *et al*., 2004b). Figure 4.1 shows the various expert weights that were used to aggregate the different statistics into the three modules and I_{SWAMP}. Concurrently, three classes were defined to determine when the index is favorable (*F*), or unfavorable (*U*). These three modules were then aggregated into a single indictor module. A value, that ranged between 0 (best model performance) and 1 (poor model performance), was calculated, with the classes together with the corresponding decision criteria and expert weights to evaluate the models performance (Bellocchi *et al*., 2002). The data analysis software IRENE (Integrated Resources for Evaluating Numerical Estimates, Fila *et al*., 2003), was used as well as the Statistics/Data Analysis software STATA 11.0 to determine KS and r_s (StataCrop, 2009).

4.3 Results and discussion

Figure 4.2 a and b presents a comparison between measured and simulated yield (t ha^{-1}) as well as seasonal transpiration (mm) for both soils of all the EC_i treatments, respectively. The statistical indices and tests that were used to evaluate simulations of yield and seasonal and weekly transpiration are shown in Table 4.5. The weekly simulated and measured transpiration for each cutting under no osmotic stress conditions (control treatment) are presented in Figure 4.3, while Figure 4.4 shows weekly values under osmotic stress conditions (treatment 5).

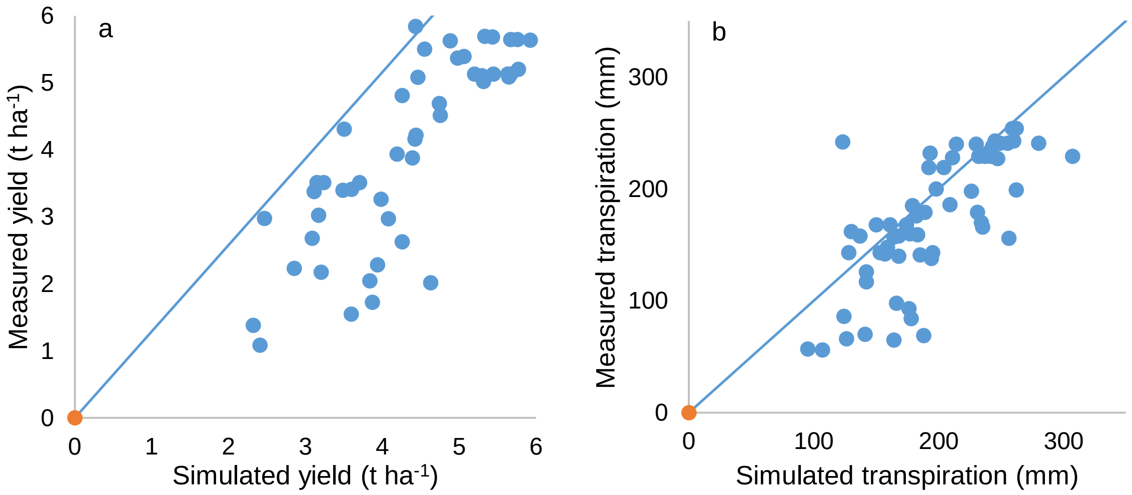


Figure 4.2 Relationship between (a) measured and simulated yield (t ha^{-1}) and (b) measured and simulated transpiration (mm) of all the cuttings for the two soils with increasing irrigation water salinity (EC_i, mS m^{-1}).

SWAMP was able to reasonably simulate a decline in yield, i.e. from 6 to 2 t ha^{-1}, due to an increase in EC$_i$ during the different cutting periods. As seen in Figure 4.2, the mean simulated yield for the different cuttings of the control treatment amounted to 5.477 t ha^{-1} compared to a measured value of 5.671 t ha^{-1}, while for treatment 5 the mean simulated and measured yields amounted to 2.986 t ha^{-1} and 3.615 t ha^{-1}, respectively. The degree with which seasonal yield simulations correlated with measurements was high with a value of 0.0423 for the correlation module. As seen in Table 4.5, the accuracy with which SWAMP simulated a decline in yield due to decreasing water quality was higher than 85%. There was no macro-pattern observed in simulating yield for the various growing season lengths and with an increase in osmotic stress, i.e. the residuals were evenly distributed (over simulation = under simulation) with an increase in growing season length and EC$_i$ (pattern module = 0.2819).

There was a good comparison between mean simulated (182 mm) and measured (195 mm) seasonal transpiration for the different cutting periods under no osmotic stress conditions and where osmotic stress occurred (simulated = 85 mm and measured = 126 mm). According to the correlation module, the extent with which the seasonal transpiration correlated with the measurements was high (correlation < 0.11). The accuracy with which SWAMP simulated seasonal transpiration was good with a value of 0.15. The low value of 0.000 for the pattern module indicate the absence of macro-patterns (Table 4.5). Hence, the residuals were evenly distributed with an increase in growing season length and EC$_i$.

From Figure 4.3 and 4.4 it is evident that weekly simulations of transpiration per cutting for both the control treatment and under osmotic stress conditions were not good. The mean simulated weekly transpiration during the different cutting periods amounted to 4.6 mm and measurements 5.4 mm for the control treatment, while under osmotic stress conditions the simulated value amounted to 2 mm and measurements 3.5 mm. The correlation module, however, for weekly transpiration had a higher value of 0.416 compared to 0.1075 for seasonal transpiration. The accuracy with which SWAMP simulated weekly transpiration was poor with a value of 1. Furthermore, the pattern module had an elevated value of 0.4995, which indicate the presence of some macro-patterns, i.e. the residuals were not evenly distributed during the growing season. The elevated pattern index is mostly due to the higher $PI_{V\ DAC}$ as supposed to $PI_{V\ ECi}$. Hence, the residuals were evenly distributed with an increase in EC$_i$.

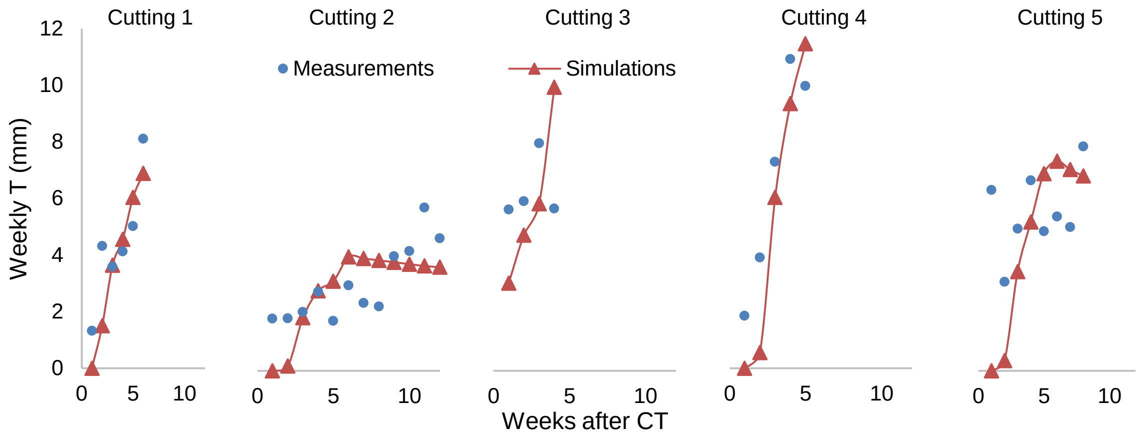


Figure 4.3 Simulated and measured mean weekly transpiration (T) for matric (ψ_m) potential under the control treatment of both soils over the five cuttings.

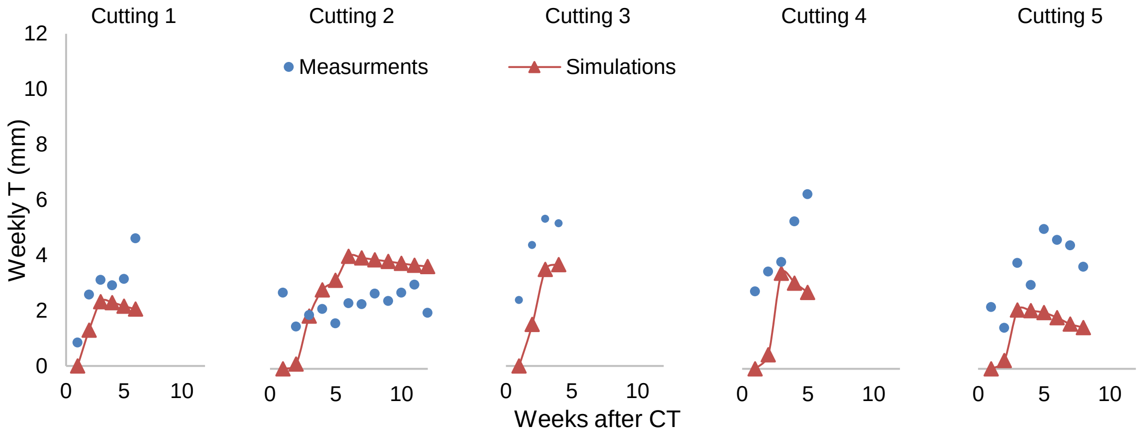


Figure 4.4 Simulated and measured mean weekly transpiration (T) for osmotic (ψ_o) potential of treatment five (osmotic stress) of both soils over the five cuttings.

The model did not simulate weekly transpiration of lucerne under osmotic stress as good as it did with crops like peas and maize (Barnard *et al*., 2015). Evidently, a higher accuracy and correlation was found with simulating weekly transpiration of peas and maize as appose to lucerne. The aggregated accuracy, correlation and pattern performance (I_{SWAMP}) for weekly transpiration for peas and maize was more that 75%, compared to the 51% (I_{SWAMP}) for weekly transpiration of lucerne.

Table 4.5 Statistical indices and test that were used to evaluate the simulations of yield, seasonal- and weekly transpiration of lucerne by SWAMP

Simulation	Yield	Seasonal T	Weekly T
RMdAE	8.601	10.525	77.5
REF	0.4765	0.1010	0.1378
KS (*p*-value)	0.304	0.2000	0.20665
r_s	0.8546	0.7682	0.54485
$PI_{v\ ECi}$	3.533	2.846	1.9555
$PI_{v\ GSL}$* $PI_{v\ DAC}$ **	2.762*	2.975*	2.9325 **
Accuracy	0.1430	0.1500	1
Correlation	0.0423	0.1075	0.41605
Pattern	0.2819	0.0000	0.4995
I_{SWAMP}	0.0903	0.0305	0.49035

The structure in weekly transpiration residuals during the growing season ($PI_{V\ DAC}$) was not because of adaptations to the layer water supply algorithm, but rather the fitting of daily transpiration over the growing season length. An average crop specific factor (m) was used in SWAMP to relate the transpiration requirement over all the cuttings to the maximum biomass yield. Lucerne production differ to normal cash crops like maize and peas because of the long growth period, hence, a m value for each growth phase (Haka, 2010; Barnard *et al*., 2013), or each cutting might improve the daily transpiration simulations during the growing season. Adaptation to the growth curve equation and determination of relevant parameters specifically for lucerne might also improve daily simulations of transpiration. The growth equation was designed for field crops like maize, wheat and peas.

The following might improve daily simulations of transpiration with an increase in EC_i (osmotic stress) although the soil layer water supply algorithm showed no structure. The simulated daily volumetric soil water content (θ, mm mm^{-1}), critical leaf water potential where plant water stress sets in (ψ_p, kPa) and volumetric soil water content where $\psi_m + \psi_o = \psi_p$ (Θ_p), is used in the algorithm. Barnard *et al*. (2015), suggested that to enhance the water supply rate algorithm, water and salt flow simulations between the different soil layers, should be done with Richards and the convection-dispersion equations, rather that the cascading approach currently used.

SWAMP does not make use of Type I formulations (Cardon and Letey, 1992) to simulate actual water flow from the soil, to and through the plant root. Instead the total potential gradient from a rooted soil layer are used to determine the water supply to meet crop water requirements. SWAMP does not require salinity thresholds and slope parameters for the piecewise linear or S-shaped reduction functions to simulate seasonal yield, transpiration and weekly transpiration for lucerne under osmotic stress conditions.

4.4 Conclusions

Concerning the first objective of this chapter, to establish how credible SWAMP will be in simulating yield decline, under conditions of osmotic stress. The results and findings established confidence in the outputs, and SWAMP was able to reasonably simulate yield decline. The variation between simulated and measured yield, for the control treatment, amounted to 5.477 compared to 5.671 t ha^{-1} and for treatment 5, it was 2.986 compared to 3.615 t ha^{-1} respectively. Hence, SWAMP was able to simulate a decline in yield due to decreasing water quality with accuracy higher than 85%. Regarding to the second objective, this high accuracy (< 85%) was also the case where the mean simulated and measured seasonal transpiration was correlated. It was concluded that SWAMP was able to simulate a yield decline and seasonal transpiration, over all the cuttings with all the treatments on both soils under osmotic stress well, i.e. the aggregated accuracy, correlation and pattern performance of the model (I_{SWAMP}) was over 90% for the yield and 96% seasonal transpiration simulations.

In relation to the last objective, the model did not simulate weekly transpiration under osmotic stress very good. The model (I_{SWAMP}) performed only up to 53 % for the weekly transpiration, hence, calibrating the necessary parameters of the layer water supply rate algorithm could lead to higher performance of the model. To improve the structure found in weekly transpiration residuals during the growth season ($PI_{V\ DAC}$) can be improved if a specific crop factor (m) was used in SWAMP and not an average, to relate the transpiration requirement over all the cuttings to the maximum biomass yield.

CHAPTER 5
SUMMARY AND RECOMMENDATIONS

5.1 Summary

The main objectives of this study was to determine, firstly, the effect of irrigation water salinity on lucerne production, with the specific focus on transpiration, biomass yield, water table depletion and the crop water productivity. The relationship between EC_i and relative biomass yield, as well as EC_e and relative biomass yield were compared to the well-established response guidelines of Maas and Hoffman (1977). Secondly, the credibility of SWAMP in simulating yield, and seasonal and weekly transpiration was evaluated.

Concerning the first main objective, Chapter 3 was divided into specific objectives to (i) quantify the effect of EC_i on transpiration, water table depletion and yield of lucerne, (ii) determine the relationship between EC_i and relative biomass yield as well as EC_e and relative biomass yield and (iii) assess crop water productivity as influenced by irrigation water salinity. In order to achieve these objectives an experiment was conducted in a non-weighing lysimeter facility of the Department of Soil, Crop and Climate Sciences, University of the Free State.

Lucerne (cv. SA Standard) was treated with six different irrigation water salinity levels (EC_i), i.e. control, 150, 300, 450, 600 and 1200 mS m^{-1}. Irrigation water of the different treatments consisted of various amounts of salts to achieve the desired TDS, SAR and EC_i values. Any excess salts, which might have accumulated during the previous cutting period were removed before the start of the nest cutting cycle. The season consisted of five cuttings, and each cutting was done at 10% flowering. Plant material was dried and weighed to determine the total above ground biomass. The soil water balance was used to reflect on water gains and losses during the experimental period.

With respect to the first specific objective, the mean transpiration rate of the cuttings decreased from 5.3 for the control treatment to 3.6 mm day^{-1} for the 1200 mS m^{-1} treatment. These results were confirmed with a decrease in the seasonal transpiration. The cumulative transpiration declined from 254 mm for the control to 183 mm for the 1200 mS m^{-1}. In addition to transpiration, increasing EC_i resulted in a general trend that suggested a decline in water table depletion as well as yield. In relation to the contribution of the water table as a source of total transpiration, it was clear that increasing irrigation water salinity resulted in a decrease in the contribution of the water table toward transpiration.

The second specific objective resulted in new information regarding management of irrigation water salinity for lucerne. The relationship between relative mean above-ground biomass and EC_i was curve linear, which differs from the linear relationship reported by Maas & Hoffman (1977). The response curve in the study suggest a critical level at 685 mS m^{-1}, which divides irrigation water salinity into two management classes, *viz.* between 130 and 685 mS m^{-1}, and between 685 and 1200 mS m^{-1}. The first response class, which stretches from 130 to the critical level, represents a yield loss of 0.06% per unit increase in mS m^{-1}. The second section on the curve linear function represents irrigation water salinity class above the critical level up to 1200 mS m^{-1}, which represents a constant yield loss of 0.009% per unit mS m^{-1}. Hence, for both the salinity ranges it seems that the cultivar SA Standard is more salt tolerant than those used by Maas & Hoffman (1977). Similar management classes were obtained for the EC_e and relative biomass relationship; between 200 and 865 mS m^{-1} and between 865 and 1489 mS m^{-1}.

In relation to the final specific objective, a strong linear relationship was observed between crop water productivity and EC_i values from the control up to 600 mS m^{-1}; $y = -0.0007x + 2.6$, $R^2 = 0.87$. This relationship showed a linear decrease in the crop productivity with an increase in EC_i. There was no difference in the crop water productivity between 600 and 1200 mS m^{-1} treatments. This suggests that the crop is more tolerant than generally reported in literature.

Concerning the second main objective, Chapter 4 was also divided into more specific objectives in order to establish how credible SWAMP will be in simulating: (i) yield decline with increasing irrigation water salinity, (ii) seasonal transpiration and (iii) weekly transpiration. Most of the parameters have been calibrated for the two soils.

Data from the control treatment was used to calibrate the parameters used in simulating the transpiration requirement. Default values were used for the remaining parameters, which was determent with equations developed by Bennie et al. (1998). Various indices and test statistics were used to quantify the models response, i.e. model residuals, the correlations between estimates and measurements, and if any patterns occur between the residuals over external variables. These tests and statistics were aggregated into a single indicator module (I_{SWAMP}) with a fuzzy-logic based expert system, which represent the model's aggregated accuracy, correlation and pattern performance.

With respect to the first specific objective, SWAMP was able to reasonably simulate a decline in yield due to an increase in EC_i. . The degree with which seasonal yield simulations correlate with measurements was high with a value of 0.0423 for the correlation module. The accuracy with which SWAMP simulated a decline in yield due to decreasing water quality was higher than 85%. The residuals were evenly distributed (over simulation = under simulation) with an increase in growing season length and EC_i (pattern module = 0.2819).

The second specific objective proved that there was a good comparison between mean simulated and measured seasonal transpiration under no osmotic stress conditions and where osmotic stress occurred. According to the correlation module, the extent with which the seasonal transpiration correlate with the measurements was high (correlation < 0.11). The accuracy with which SWAMP simulated seasonal transpiration was good with a value of 0.15. A low value for the pattern module indicated the absence of macro-patterns

Relating to the final specific objective, the weekly simulations of transpiration for both the control treatment and under osmotic stress conditions were not good. The correlation module for weekly transpiration had a higher value of 0.416 compared to 0.1075 for seasonal transpiration. The accuracy with which SWAMP simulated weekly transpiration was poor with a value of 1. Furthermore, the pattern module had an elevated value of 0.4995, which indicate the presence of some macro-patterns, i.e. the residuals were not evenly distributed during the growing season. According to I_{SWAMP} yield decline (I_{SWAMP} = 90%) and seasonal transpiration (I_{SWAMP} = 96%) of lucerne grown on sand to sandy loam water table soils were simulated well.

5.2 Recommendations

The well-established response curves of Maas & Hoffman (1977), serves as a general guide for farming practises worldwide and has been used for over 40 years. However, guidelines should be more specific for each farming area. Hence, this study was conducted in order to provide scientific sound information with regard to salinity and lucerne production in South Africa. The research findings are applicable to irrigated fields located in semi-arid regions with water tables, of sand to sandy loam soils. Hence, care should be taken when interpreting the recommendations provided below, under different farming conditions.

5.2.1 Farming condition 1

Under ideal irrigation farming practices with high quality irrigation water and well drained soils with no restrictions in the root zone and low soil water salinity, lucerne (cv. SA Standard), has a relative yield potential of 100%. This high yield potential will continue even when the irrigation water starts to deteriorate but only up to a point. In other words, to manage for full yield potential the irrigation water salinity should be below 130 mS m^{-1}. Secondary salt built up, in the root zone, as result of irrigation practices will occur, fortunately, lucerne will tolerate soil salinization of up to 200 mS m^{-1}. These threshold values serves as a starting point were farmers can expect some yield decline. To put it in perspective, a normal production season can produce on average 6 – 8 cuttings of 3 t ha^{-1} each, resulting in an average of 21 t/ha per season, provided that the irrigation water and soil water salinity is below their respective threshold values.

5.2.2 Farming condition 2

If the irrigation water salinity is above 130 mS m^{-1}, and the soil water salinity is above 200 mS m^{-1}, irrigators could expect a constant yield decrease of 0.006% per unit mS m^{-1} up to a critical point of 685 mS m^{-1}. For example, if the irrigation water salinity is 400 mS m^{-1} a yield decline of 2.4% can be predicted. This means that if a farmer irrigate lucerne with irrigation water of 400 mS m^{-1}, the average yield of 21 t ha^{-1}, will decrease with 500g ha^{-1}. This is almost nothing compared to the 9.24 t ha^{-1} yield loss predicted by Maas & Hoffman (1977). The yield will continue to constantly decrease up to the critical point of 685 mS m^{-1}. It is only at this point where the decline in yield will slow down and very little losses can be expected with increasing irrigation water salinity.

5.2.3 Farming condition 3

This is worst case scenario. If the irrigation water salinity is above the critical point of 685 mS m^{-1} and the soil water salinity is above 865 mS m^{-1}, yield will only decrease at a rate of 0.009% per unit mS m^{-1} even up to the high salinity level of 1200 mS m^{-1}. This means that if the irrigated field is highly salt affected and salt has built up beyond the critical point, the farmer will still obtain a yield of 7.9 t ha^{-1}. This differs enormously from the total yield loss predicted by Maas and Hoffman (1977).

In conclusion, lucerne cultivar SA Standard, can be used as an alternative crop in faming conditions of high salinity and still obtain substantial yields for a constant cash flow.

5.2.4 Modelling

The model did not simulate weekly transpiration under osmotic stress very good (I_{SWAMP} = *53%*). This is mainly because of the structure found in weekly transpiration residuals during the growing season ($PI_{V\ DAC}$). Weekly transpiration simulations with SWAMP can be improved when a specific crop factor (m) is used and not an average, to relate the transpiration requirement over all the cuttings to the biomass yield.

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Appendix 1 The total cumulative transpiration (T) and water table depletion (WTD) for the individual lysimeters for the different EC_i treatments on the two different soils

		Cutting 1		Cutting 2		Cutting 3		Cutting 4		Cutting 5	
Soil	EC_i (mS m^{-1})	WTD	T (mm)	WTD	T (mm)	WTD	T (mm)	WTD	T (mm)	WTD	T (mm)
A	15*	104	189	33	211	109	157	109	221	212	259
	150	190	213	84	247	109	195	146	243	208	262
	300	47	183	30	226	99	153	99	184	173	232
	450	91	185	148	258	98	168	91	193	165	234
	600	63	142	24	199	73	142	97	182	91	256
	1200	0	95	14	164	14	107	26	124	104	188
B	15*	25	150	33	245	59	177	83	242	177	249
	150	48	174	54	260	20	141	124	307	208	280
	300	91	161	41	231	90	168	203	237	165	230
	450	57	130	2	204	99	164	61	192	193	262
	600	65	128	67	179	67	159	89	198	126	209
	1200	81	126	73	176	73	141	73	166	90	178

*Control

Appendix 2 The total biomass yield, stems and leaves data for the individual lysimeters for the different ECi treatments on the two different soils (g lysimeter^{-1})

		Cutting 1			Cutting 2			Cutting 3			Cutting 4			Cutting 5		
Soil	EC$_i$ (mS m^{-1})	BM	Stems	Leaves	BM	Stems	Leaves	BM	Stems	Leaves	BM	Stems	Leaves	BM	Stems	Leaves
A	15*	916	567	401	1288	721	622	1436	825	629	1538	922	624	1661	1015	684
	150	888	547	346	1268	720	600	1386	813	626	1508	914	566	1549	950	578
	300	807	516	340	1207	714	555	1324	803	586	1357	833	503	1382	863	545
	450	786	477	327	1067	600	518	1354	765	545	1158	656	472	1129	620	522
	600	726	393	302	1013	576	485	1210	674	519	1126	653	452	1118	582	512
	1200	614	380	261	916	508	467	1178	604	474	977	555	417	985	572	496
B	15*	802	500	348	1465	819	674	1468	809	692	1864	968	910	1991	1022	969
	150	944	481	395	1443	745	627	1433	844	684	1781	908	829	1946	1003	943
	300	824	429	376	1243	681	602	1443	790	656	1523	859	638	1318	769	649
	450	792	385	362	1136	643	561	1348	790	587	1359	806	528	1399	822	564
	600	628	381	264	891	433	450	1084	672	463	1148	622	447	1128	635	487
	1200	590	319	216	816	405	462	1002	655	440	1039	588	408	1083	554	430

*Control