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Experimental and Modeling Assessment of the Effects of Saline Water Irrigation With Nitrogen Fertilization on Tomato Growth and Yield

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Experimental and Modeling Assessment of the Effects of Saline Water Irrigation With Nitrogen Fertilization on Tomato Growth and Yield

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Environmental Sciences

by

Hasnain Farooq

June 2019

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بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

In the name of Allah, the Most Gracious and the Most Merciful

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Dedication

This humble effort is dedicated to

The Holy Prophet Mohammad صلى الله عليه وعلى آله وسلم

The torch bearer of divine wisdom and knowledge for the whole Humanity.

ABSTRACT OF THE DISSERTATION

Experimental and Modeling Assessment of the Effects of Saline Water Irrigation With Nitrogen Fertilization on Tomato Growth and Yield

by

Hasnain Farooq

Doctor of Philosophy, Graduate Program in Environmental Sciences
University of California, Riverside, June 2019
Dr. Laosheng Wu, Chairperson

Tomato has the utmost economic importance in the world's food crops. The foremost challenge in the world of agriculture is to sustain the continuously growing global population, and it is becoming more and more difficult due to climatic change, as this imposes further abiotic stress. In irrigated cropland, salinity stress is the leading factor that causes reduction in crop quantity and quality. Nitrogen is one of the most limiting nutrient in crop production systems, especially for the high nitrogen demanding crops like tomato. Evaluation of the effects of irrigation water quality and fertilization on soil salinity and crop yield is necessary to plan, manage and implement the irrigation and fertilization schemes under different soil and climatic conditions. Different analytical and numerical models have been developed to predict water flow and solute transport in the vadose zone. Model predictions can be very helpful in decision making to plan and manage different irrigation and fertilization schemes.

A greenhouse pot experiment was performed to evaluate the interactive effect of irrigation water salinity and nitrogen application rates on tomato growth, yield, and fruit

quality. The data collected from this experiment were used to calibrate and validate the HYDRUS-1D model. The model simulates water flow, solute and heat transport in vadose zone soil. The HYDRUS-1D positively simulated drainage flux, soil water storage, root zone salinity, as well as yield reductions due to salinity stress based on root water uptake. After successful calibration and validation of HYDRUS-1D, the model was used to investigate interactive effects of various levels of irrigation salinity and nitrogen application rates on tomato yield, nutrients uptake by tomato plants and nitrate leaching below the root zone. Both irrigation water salinity and nitrogen application rates significantly affected the crop yield. Use of potable water is recommended at least once during a growing season to leach the salts below the root zone at or before the flowering in order to avoid/delay the salinity buildup and minimize yield loss. Nitrogen application at or below the rate of 300 Kg/ha is recommended to avoid both the environmental pollution and human health risks.

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GENERAL INTRODUCTION

Motivation and Background

Food Surge

The current world population of 7.5 billion is increasing at an alarming rate and expected to reach 8.5 billion by 2030, 9.7 billion by 2050 and 11.2 billion by 2100 (FAO, 2009), and there is a great need to increase the food production as much as 70 percent by 2050 (United Nations, 2017) to feed this massive population. Increasing quantities of water are obligatory along with other provisions to accomplish this goal. On the other hand, the availability of potable water for agricultural use is declining continuously (Cai and Rosegrant, 2003) as better-quality water gains priority for household consumption. It has been predicted that 60% of the global population will undergo water shortage by the year 2025 (Qadir et al., 2007). This increased demand of more water to irrigate crops to cope with the food security issue, especially when fresh-water resources are limited, has led to a rush of interest in the use of low-quality or saline water for irrigation in agriculture (Bouwer, 1994; Khroda, 1996; Ragab, 1996).

Any unfavorable condition that negatively affects plant growth and development is termed as plant stress. Biotic and abiotic stresses are two different types of stresses faced by the plants. The biotic factors include diseases and damage to plants through other living organisms like insect pest attack, and this aspect has been addressed quite effectively by the evolution of significant pesticides, insecticides, and different management practices. The abiotic stresses originate from the surrounding environment, water and salinity, are the

two most common abiotic stresses causing extensive losses to agricultural production globally.

Extent of Salinization

The beginning of the 21st century is marked by global scarcity of water resources, environmental pollution and increased salinization of soil and water. Salinity is among the major limitations for plant growth and productivity all around the globe and the damage caused by high salinity is witnessed as either loss of plant productivity or plant death. Soil salinization is the result of different soluble salts accumulation in the root zone. Soil salinity is defined as a measurement of the total soluble salts in soil, and soil with an electrical conductivity of saturated paste extracts above 4 dS m^{-1} is termed as saline soil (Munns and Tester, 2008). Globally, 20% of total cultivated land (62 million hectares (Gies, 2017) an area equal to the size of France) and 33% of irrigated agricultural land have been reported to be afflicted and degraded by high salinity (Machado and Serralheiro, 2017). Additionally, soil salinization is increasing at a rate of 10% annually and more than 50% of the arable land would be salinized by the year 2050 (Jamil et al., 2011). California's San Joaquin Valley, the southern half of the 450-mile-long Central Valley that spans most of the length of the state, and Indus Basin in Pakistan represents some of the worst areas affected by soil salinity (Gies, 2017). Approximately 4.5 million acres of cropland in California have been reported to be affected by saline soils or saline irrigation water (Letey, 2000). Westlands Water District, an agency that allocates water to farmers in different counties in central California, retired 88,000 acres as the soil is now too saline to grow food

crops (Gies, 2017). The scenario in Pakistan is also alarming where 1.89 out of 19.43 Mha irrigated cropland is salt affected (Alam et al., 2000).

Plant Growth and Salinity

Water is an important constituent of cell and plays an important role in almost all biochemical processes. Roots are the only organs that can meet the plant's water requirement through absorption. High salt concentration in the root zone impedes the water movement from soil to aerial parts of the plant by reducing the available water for plant uptake (Khataar et al., 2018), and affects plant growth by posing different detrimental effects on plants. The first type of negative effect is osmotic stress. High salt concentration alters the water potential in the root environment causing osmotic stress that makes harder for roots to extract water from the soil (Munns and Tester, 2008) and it increases the energy that plant must expend to acquire water needed for their survival, growth, and development. Another way the salinity negatively affects the plant growth is causing specific ion toxicities and nutritional imbalances or a combination of these factors. High salt concentrations in the soil can alter the nutrient balance in the plant and/or interfere with the uptake of some essential mineral nutrients due to reduced water uptake from the soil leading to nutrient deficiency. Plant nutrient deficiencies and nutritional imbalances may be triggered by the higher concentration of Na^+ and Cl^- in the soil solution derived from ion competition (i.e., Na^+/Ca^{2+}, Na^+/K^+, Ca^{2+}/Mg^{2+}, and Cl^-/NO^{3-}) in plant tissues (Machado and Serralheiro, 2017). Injurious concentrations of Na^+, Cl^- and SO_4^{2-} can cause specific ion toxicities that negatively affects plant growth. Accumulation of these injurious ions may inhibit photosynthesis by damaging chloroplasts, protein synthesis, and inactivate

different enzymes (Machado and Serralheiro, 2017). Salinity also setbacks some physiological activities of plants such as increasing in respiration rate that directly affects the plant growth. (Tahir et al., 2018).

The adverse effects of salinity on plants can be moderated to some extent by increasing the water availability to the plant through proper irrigation and drainage management, proper nutrient availability and lowering the evaporation rate of the plant (Syvertsen and Levy, 2005).

Salinization in Irrigated Cropland

Soil salinization is becoming increasingly a concern and most widespread problem in many irrigated areas of the world. Soil parent materials, climate, and topography are not the only sources of soil salinity buildup but different anthropogenic sources such as improper irrigation practices along with improper quantity and quality of irrigation water often lead to soil salinization (Kitamura et al., 2006). In irrigated agriculture, salinization generally occurs when soluble salts from the irrigation water accumulate in soil due to insufficient leaching, high water tables and/or high evaporation rates.

It is inevitable that some salts will accumulate in the root zone since all waters used for irrigation always contain some soluble salts, but the concentrations of accumulated salts depend on the water sources. The higher the salt concentration in irrigation water, the faster will be the soil salinization process. Principle processes leading to salt accumulation in irrigated agriculture are bare soil evaporation and plant transpiration. Both the processes remove water from the soil and leave the salts behind, resulting in an increase of salts concentrations in the remaining soil water (Corwin et al., 2007; Gonçalves et al., 2006).

Hence, higher evaporation and/or transpiration rate can further enhance the soil salinization process.

Although irrigation with saline water relieves fresh-water resource shortages in varying degrees, improper management of saline water (such as the use of saline water with extreme salinity or insufficient irrigation with saline waters) may result in combinations of water and salinity stress leading to secondary salinization and other soil problems. Nevertheless, successful use of saline water up to 11 dS m^{-1} for a number of crops has been reported (Rhoades, 1992). Water management, irrigation system, soil type, and salinity distribution can all affect crop production. Quality of irrigation water can also influence soil fertility and water use efficiency as well as crop productivity and soil characteristics (Alomran et al., 2012). Thus it is essential to develop suitable water management strategies in order to attain maximum yields from the crops irrigated with saline water (Pasternak and De Malach, 1995).

Plant Growth and Nitrogen

Plant's foremost requirements for their life cycle are mineral nutrients and energy from the sunlight. Nitrogen is of prime importance for the plants as it is a major component of chlorophyll, the compound which plays a key role in photosynthesis to produce plant's food from water and carbon dioxide in the presence of sunlight. It is also a key element in structural conformation of plants being a basic constituent of proteins, enzymes and nucleic acids (Maathuis, 2009).

Nitrogen is taken up by the plants from the soil as both ammonium and nitrate ions but most of the nitrogen is taken up as nitrate due to its abundance (Hageman, 1984), and pervasive nitrification in cultivated lands. Nitrate moves freely toward plant roots as they absorb water. On the other hand, nitrogen is one of the most limiting nutrients in vegetable production, especially in crops with high nitrogen demand like tomato (Bustamante and Hartz, 2015). The nitrogenous fertilizers use efficiency by crops for conventional N application methods was reported to be less than 50% by Karaman et al. (2005), while Min et al., (2011) found it to be only 18%. Vegetable production often requires more nitrogen than cereal crops and due to low nitrogen use efficiency while nitrogen absorption is also inhibited by root zone salinity. Hence, there is potential for nitrate leaching and groundwater contamination leading to adverse environmental impacts (Zhu et al. 2005).

Nitrogen is one of the essential macronutrients in all biological materials and alterations in its nutrition and metabolism have particular importance. These alterations can lead to deficiency or accumulation of special nitrogen compounds under salinity stress. Plants contain much higher nitrogen than any other element, often 3 to 4 percent in their above-ground tissues, with the exception of carbon, hydrogen, and oxygen that do not play a significant role in most soil fertility management programs. In addition, salinization/sodification and nitrate leaching to aquifers are two of the leading threats to the environment. Therefore, it is very important to develop agricultural management practices to cope with salinity while at the same time, optimizing nitrogen use to improve nitrogen use efficiency and reduce nitrate leaching potential.

Effects of Salinity and Nitrogen on Tomato Production

Tomato is the second most valuable crop, 19% of all vegetable consumption only behind potato at 23% (Reimers and Keast, 2016), as well as the second most commonly grown vegetable in the world after potato (Dorais et al., 2008). Tomato production requires enormous amount of water (Peet and Welles, 2005) and nitrogen (Bustamante and Hartz, 2015) for optimal growth and yield. Tomato crop is grown in different climates ranging from the tropics to within a few degrees of the Arctic Circle (Teka, 2013) and is considered a cash crop for medium-scale commercial farmers.

Florida and California account for 76 percent of United States' production of field-grown tomatoes, while California shares 30 percent of the country's supply of fresh-market tomato. Tomatoes can be used in numerous ways in both fresh and processed forms that include ketchup, sauces, pastes, and juice. High nutritional value along with potential health benefits of tomato has drawn an increased interest towards the use of fresh tomato as well as tomato-based products among consumers (Nasir et al., 2015).

Tomato is sensitive to moderate salinity level up to 2.5 dS m^{-1} for most of the commercial cultivars (Tahir et al., 2018). All stages of plant development including seed germination, vegetative growth and reproduction show sensitivity to salt stress and economic yield is reduced under salt stress (Jamil et al., 2011).

Various fertilizers play a significant role in crop production. An adequate supply of essential nutrients can considerably ameliorate plant growth, quality and their nutritional values (Souri and Dehnavard, 2017). Both nitrogen and water are vital factors for tomato growth and fruit quality (Wang and Xing, 2016). In general, nitrogen application increases

the crop yields and its application in higher quantities is usually considered essential to achieve higher crop yield (Wang et al., 2008; Badr et al., 2012), but it's over-application may also cause high nitrate leaching, contaminating groundwater (Song et al., 2009; Min et al., 2011; Sun et al., 2013), and alter the nitrate content in tomato fruit (Yang et al., 2006; Zotarelli et al., 2009).

Modeling as a Management Tool

Modeling is becoming more and more efficient tool for water resources management. Different numerical models have been used to simulate water and nutrients uptake by plants under various environment, soil, and crop conditions. The models not only can help in irrigation scheduling and calculating crop water requirements but also can be used to assess crop response to different environmental stresses like water and salinity stresses (Adam et al., 2011). Hence these models can become an important decision-making tool for water managers and farmers to accomplish sustained food production. With the help of such models, long-term effect of water and fertilizer management on soil and crop can be quickly achieved. In this way, they can help to develop the best management practices to maximize crop water and nitrogen use.

Research Objectives

The overall objective of this study was to evaluate and develop the saline water irrigation and nitrogen fertilization management practices to be implemented in future applications, with the goal to increase tomato yield and improve fruit quality by increasing root water and nutrient uptake in areas with water shortage. To achieve the overall objective of this dissertation, specific objectives are:

- To evaluate the effect and interactive effect of irrigation water salinity and nitrogen application rate on tomato growth, yield and fruit quality by greenhouse pot experiment.
- To calibrate and validate the HYDRUS-1D model with the data obtained from the experimental study; and to evaluate the effects of various other levels of irrigation water salinity and nitrogen application rates on crop yield, soil salinity, and nitrate leaching using the validated HYDRUS-1D model, and
- To identify the optimal level of irrigation water salinity and nitrogen application rate for optimal crop yield and minimum nitrate leaching.

To address the above three specific objectives, this dissertation consisting of three chapters was written to present experimental and modeling studies to explore the effect of saline water irrigation with nitrogen fertilization on tomato growth and yield. In the first chapter, a greenhouse pot experiment was performed to evaluate the interactive effect of irrigation water salinity and nitrogen application rate on tomato growth, yield and fruit quality. In the second chapter, the objective was to calibrate and validate the HYDRUS-1D model with the data obtained from the first study. In the last chapter, validated

HYDRUS-1D model was used to investigate interactive effects of various levels of irrigation water salinity and nitrogen application rates on tomato yield, nutrients uptake by tomato plants and nitrate leaching below the root zone.

Results from my current dissertation research can help us to understand, manage and plan saline water irrigation practices to be implemented in future practical applications, with the goal to increase tomato yield, root water, and nutrient uptake in areas with water shortage as well as to reduce nitrate leaching below the root zone.

Chapter 1

GREENHOUSE EXPERIMENT

ABSTRACT

Tomato is a crop with the greatest economic importance in the world's food crops and salinity stress causes a reduction in the quantity and quality of crop production. Today, the main challenge in the world of agriculture is to sustain the continuously growing global population, and it is becoming more and more difficult due to climatic change, as this imposes further abiotic stress. The objectives of this study were to find out the effects of three salinity and three nitrogen levels on tomato growth, production, and fruit quality. The study was initiated at the greenhouse of the Department of Environmental Sciences, University of California, Riverside. It used a completely randomized design (CRD) with three replications. The salinity treatments were: 1= Control (Irrigation with half-strength Hoagland solution), 2= Irrigation with saline water having an electrical conductivity of 2 dS m^{-1}, 3= Irrigation with saline water having electrical conductivity 4 dS m^{-1}. The three nitrogen levels were 80, 100 and 120% of recommended N application. The results showed that the effects of various levels of salinity were highly significant ($P < 0.01$) on the yield parameters (number of fruits per plant, fruit length, fruit volume, individual fruit weight, and total tomato yield per plant), while the effects of nitrogen levels and their interactions with salinity levels were found non-significant on these parameters. As regards the quality parameters of fruit firmness and fruit total soluble solids, the effects of salinity levels, nitrogen levels and their interactions with each other were highly significant ($P < 0.01$).

The highest individual fruit weight (27.98 g) was found in control treatment while the lowest individual fruit weight (20.49 g) was recorded in the 4 dS m^{-1} treatment. The plants in control treatment produced the highest total fruit yield per plant (2259.7 g; $p <$

0.01), whereas the lowest yield (1211.9 g) was obtained from the higher level of saline water treatment (4 dS m^{-1}). The effect of different salinity levels of irrigation water on total soluble solid was also significant. The significantly highest total soluble solids (6.85) was shown in the treatment receiving saline water (4 dS m^{-1}), whereas the lowest (5.55) in control. It was concluded that if potable water is not available for irrigation, saline water with 2 dS m^{-1} can be used with minimum reduction in tomato yield. As regards nitrogen, it was found that 80% N of the recommended rate for tomato production is sufficient.

1.1 Introduction

1.1.1 Food Security

According to the United Nations' Department of Economic and Social Affairs, the current world population of 7.5 billion is expected to reach 8.5 billion by 2030, 9.7 billion in 2050 and 11.2 billion in 2100. To feed this huge population, there is an immense need to increase food production (Howell, 2001; Chen et al., 2011). This requires increasing quantities of water to produce more and more food to feed the growing world population. On the other hand, the availability of fresh-water for agricultural use is declining continuously (Cai and Rosegrant, 2003) as better-quality water gains priority for household consumption. It has been predicted that 60% of the global population will suffer water shortage by the year 2025 (Qadir et al., 2007). This increased demand of more water to irrigate crops to cope with the food security issue, especially when fresh-water resources are limited, has led to the use of low-quality or saline water for irrigation in agriculture (Bouwer, 1994; Khroda, 1996; Ragab, 1996).

1.1.2 Soil salinity

Soil salinization is the result of various soluble salts accumulating in the root zone of the soil. Globally, 20% of total cultivated and 33% of irrigated agricultural lands have been reported to be afflicted and degraded by high salinity (Machado and Serralheiro, 2017). Additionally, soil salinization is increasing at a rate of 10% annually and more than 50% of the arable land would be salinized by the year 2050 (Jamil et al., 2011). It is a major problem for crop production in arid and semi-arid regions, with high summer temperatures and low rainfall. Irrigation is essential to achieve economically valuable crop productions

in arid and semi-arid regions (Ashour and Al-Najar, 2012), while the conventional sources of good quality water are limited in these regions of the world. Soil salinization is becoming increasingly a concern and most widespread problem in many irrigated areas of the world. In irrigated agriculture, salinization generally occurs when soluble salts from the irrigation water accumulate in soil due to insufficient leaching, high water tables and/or high evaporation rates. High salt concentration in the root zone soil, after a certain limit, becomes harmful to crops, as it reduces the crop yields and worsens the fruit quality.

It is inevitable that some salts will accumulate in the root zone since all waters used for irrigation mostly contain soluble salts, but the concentrations of accumulated salts depend on the water source. The higher the salt concentration in irrigation water, the faster will be the soil salinization process. Principle processes leading to salt accumulation in irrigated agricultural lands are bare soil evaporation and plant transpiration. Both the processes remove water from the soil and leave salts behind, which results in the increase of salts concentrations in the remaining soil water (Corwin et al., 2007; Gonçalves et al., 2006). Hence, higher evaporation and/or transpiration rate can further enhance the soil salinization process.

Although irrigation with saline water relieves fresh-water resource shortages in varying degrees, improper management of saline water (such as the use of saline water with extreme salinity or insufficient irrigation with saline waters) may result in a combination of water and salinity stresses that leads to the secondary salinization and other soil problems. Successful use of saline water up to 11 dS m^{-1} for a number of crops has been reported (Rhoades, 1992). Water management, irrigation system, soil type, and

salinity distribution can all affect crop production. Quality of irrigation water can also influence soil fertility and water use efficiency, as well as crop productivity and soil characteristics (Alomran et al., 2012). Thus it is essential to develop suitable water management strategies in order to attain the maximum yields from the crops irrigated with saline water (Pasternak and De Malach, 1995).

1.1.3 Tomato and Salinity

Tomato (*Lycopersicon aesculentum* Mill.) belongs to the *Solanaceae* family and is a major vegetable crop that has attained tremendous popularity in recent past. Tomato is a rich source of minerals, vitamins, organic acids, essential amino acids and antioxidants (Toor et al., 2006; Savic et al., 2008; Erba et al., 2013). Studies have shown that it can lower the risk of getting some human diseases such as cancer, cardio-vascular diseases and aging (Dorais et al., 2008; Al-Amri, 2013). It is categorized as the second most valuable vegetable crop (FAO, 2011) as well as second most commonly grown vegetable in the world after potato (Dorais et al., 2008), and one of the high water demanding crops in terms of water consumption (Peet and Welles, 2005). It is being grown in almost every country of the world in outdoor fields, as well as widely grown in greenhouses in arid and semi-arid areas where saline water is the only source of irrigation and in areas where salinity conditions already prevail (Reina-Sanchez et al., 2005).

Cuartero and Fernández-Muñoz (1998) and Amjad et al. (2014) reported tomato as moderately sensitive to salinity and its maximum soil salinity (electrical conductivity of saturated soil extract, EC_e) tolerant level (without any yield reduction) is 2.5 dS m^{-1} (Maas and Hoffman, 1977; Campos et al., 2006). Varying effects of salinity have been reported

at different developmental stages of plant growth. High salinity distresses plant growth and development resulting in reduced crop productivity or complete crop failure by increasing the osmotic stress, ion toxicity, water deficit, and/or nutritional imbalance (Jamil et al., 2011). It also lessens the availability of phosphorus (P) by suppressing P uptake by plant roots (Grattan and Grieve, 1998). Jia et al. (2008) reported the decreased accumulation of calcium (Ca) and potassium (K) in the plant leaf tissues with increasing salinity, but this decrease was less in plants with high salt tolerance than that in plants with a low salt tolerance level. Cuartero and Fernández-Muñoz (1998) observed tomato yield reduction when the plants were irrigated with a nutrient solution of EC 2.5 dS m^{-1} or higher.

Del Amor et al. (2001) conducted a greenhouse study where tomatoes (cv. Daniela) were drip irrigated with nutrient solutions of four salinity levels (0, 20, 40, 60 mM NaCl) initiated at three different plant growth stages (16, 36 and 66 days after transplantation). They found the increase in salinity tolerance of tomato plants with delayed application of salinity, while salinity applied at 16 DAT had a greater effect on the final yield than when salinity was applied 36 and 66 days after transplantation. Campos et al. (2006) compared the effect of five levels of irrigation water salinity (1, 2, 3, 4, and 5 dS m^{-1}) on industrial tomatoes and reported that the commercial and total yields reduced by 11.9 and 11.0%, respectively, upon each unit increase in the salinity of the irrigation water, while fruit quality increased with the increasing salinity. Reduction in total fruit yield (49.7 %) has been observed at higher salinity levels (12 dS m^{-1}) in comparison with the control (1.2 dS m^{-1}), while a moderate level (2.4 dS m^{-1}) had no significant effect in this regard (Alsadon et al., 2009). According to Olympios et al. (2003), increasing EC of irrigation water

reduced about 20.3, 30.2 and 49.0% crop yield and 2.9, 12.2 and 20.1% plant height, respectively, for the three salinity levels (3.7, 5.7 and 8.7 dS m^{-1}), in comparison with the control treatment (1.7 dS m^{-1}), but it had no significant effect on the vegetative growth. However, salinity may enhance fruit quality by increasing sugar concentration and dry matter content.

1.1.4 Germination

Tomatoes can be planted in the fields as transplanted seedlings or they can be seeded directly. Due to their small seed size, it is very difficult to accomplish uniform plant density and high emergence rate when they are seeded directly in the field. To achieve uniform plant density, tomatoes are mostly transplanted, which also can avoid salinity effect on germination, as the first exposure of crops to salinity stress occurs at the germination stage (Demir and Mavi, 2008).

Olayinka et al., (2016) reported the decrease in germination percentage with the increasing salt concentrations from 86.7% in the control to 73.3% in 10 mM, 70 % in 50 mM and 23.3 % in 100 mM NaCl solution, while seeds treated with 250, 500 and 1000 mM sodium chloride did not germinate. Cuartero and Fernández-Muñoz (1998) reported that in direct-seeded plots, increasing NaCl concentration drastically decreased the germination percentage in most cultivars. Only a few genotypes were able to germinate at higher salt concentrations and that too with decreased germination percentage. This suggests that different genotypes differ in their ability to germinate at different salinity levels within *L. esculentum*.

Salinity not only lowers the germination percentage but it also prolongs the time needed to complete the germination (Hajer et al., 2006). Arbaoui et al., (2015) and Jamil et al., (2006) indicated the decrease as well as delay in seed germination in several plants including tomatoes under the influence of salt stress. Tomato seeds require 50 and 100% percent more time to germinate at 80 and 190 mM NaCl concentrations respectively in comparison with non-saline conditions (Ayers, 1952; Cuartero and Fernández-Muñoz, 1998). The main effect of salinity on seed germination is restricting water uptake by the seed, i.e. imbibition in the first phase of germination.

1.1.5 Root development

Roots are the most sensitive organs (Okusanya and Ungar, 1984; Waisel, 2012) being affected by salinity stress and the first responder to edaphic stresses (Snapp and Shennan, 1994) as they are in immediate contact with soil and water. Any change in the soil and water directly changes the growth, physiology, and morphology of roots and consequently disturbs the ion and water uptake as well as the activity of hormones which communicate with the shoots. Inhibition in root growth affects the survival capability of the entire plant. Interestingly, over the long term, salinity affects shoot growth more than root growth (Maas and Grattan, 1999).

Salt stress decreases the root biomass in tomato, and salinity induced reduction in root biomass differs in different tomato genotypes at different salinity levels (Cuartero and Fernández-Muñoz, 1999; Cruz and Cuartero, 1990; Snapp and Shennan, 1994). These differences are not apparent at higher salinity levels of 13 dS m^{-1} or above (Cruz and Cuartero, 1990). Jamil et al. (2006) and Olayinka et al. (2016) also reported a reduction in

root growth in response to increasing salt concentration. Reduced root growth under salt stress could be due to the low water potential of root environment, cell growth restriction, and/or nutritional imbalance resulting in cell death.

1.1.6 Shoot development

Salt stress slows down the shoot growth in tomato plants and it has been observed that the growth of older leaves is less affected than the younger leaves. Tomato plants are most sensitive to salinity at the seedling stage and can adapt to salinity stress with time at moderate, but not high salt concentrations (Cruz and Cuartero, 1990). Parvin et al. (2015) and Azarmi et al. (2010) reported the reduction in plant height, leaf number and branch number per plant with increased level of salinity. Generally, the reduction in shoot growth is higher than in root growth (Oliveira et al., 2013). Under saline conditions, plant growth, shoot root dry weight ratio and relative water content decreased in both cultivated and wild tomato species, but the decrease was smaller in the wild relatives (Tal, 1971). Hajer et al. (2006) also reported the reduction in fresh and dry shoot and root weights in response to increasing salinity. They observed the significant reduction in the plant height in response to increasing salinity level at four weeks until the end of the experiment. Parvin et al. (2015) reported that leaves and stem dry weight decreased significantly with increasing salinity levels but the reduction in leaf dry weight might be due to a reduction in leaf area (Van Ieperen, 1996) rather than the leaf number.

Reduced leaf growth under salt stress has been attributed to the reduction in cell wall rheological characteristics, cell turgor, and photosynthetic rate. Salinity causes a rapid decrease in leaf water potential while a slower decrease in osmotic potential is unable to

counterbalance this change in water potential (Yeo et al., 1991; Stirzaker et al., 1997). Salinity induced water stress could limit the growth of plants whereas salt-specific effects could result in injuries in leaf tissues (Munns, 1993; Alarcon et al., 1994). Thus, plant species and genotypes that are can absorb more water from soil under low water potential would adapt better to salinity stress.

1.1.7 Fruit yield and quality

Salinity has a damaging effect on tomato productivity as it reduces fruit weight per plant (Parvin et al., 2015; Smith et al. 1992), fruit size and marketable yield (Del Amor et al., 2001). Saltwater irrigation showed a significant decrease in tomato yield by reducing fruit biomass (Flores et al., 2003), fruit number (Van Ieperen, 1996), and fruit size (Ehret and Ho 1986). Irrigation management for tomato with brackish water was studied by Pasternak and De Malach (1995) and they found 44% yield reduction in plants irrigated with the brackish water (EC_i 6.2 dS m^{-1}) as compared with fresh-water (EC_i 1.2 dS m^{-1}). The reduction in yield is less in field cultivation than in hydroponics for the same irrigation water salinity (Mitchell et al., 1991). This might be due to delay in the buildup of salinity in the soil.

However, Plaut (1997), Cuartero and Fernández-Muñoz (1998) and Del Amor et al. (2001) indicated that the reduction in yield was due to reduced mean fruit weight and smaller fruit size rather than fruit number, as salinity caused reduced water uptake, biochemical and physiological disturbances in the rooting medium (Azarmi et al., 2010). Reduction in tomato fruit size is attributed to the reduction in water content rather than in dry matter accumulation (Ehret and Ho, 1986). Higher irrigation water supplies

significantly influenced the main yield constituents (Tüzel et al., 1994; Dadomo et al., 1994), but have a tendency to reduce the dry matter content of the fruits.

Salinity is known to cause an osmotic drought resulting in decreased water uptake soon after salts are introduced into the root zone. As water accounts for more than 90% of fruit weight, the decrease in size can mainly be ascribed to a decrease in water accumulation in the fruit. Fruit size affecting the yield and quality of tomatoes can be controlled by proper water management (Cahn et al., 2003). Suitable irrigation methods and irrigation management approaches can minimize the negative effects of irrigation water salinity and may enhance crop productivity as well as fruit quality.

It is generally believed that soil salinity improves tomato fruit quality. For tomato, fruit quality is a somewhat ambiguous term and should be precisely defined depending on its usage and consumer. Soluble sugars and acids accumulated in fleshy fruits determine the taste and represent more than half of the total dry matter in tomato (Ripoll et al., 2014). Reduced water uptake, under the influence of salinity stress improved the tomato fruit quality characteristics by improving the taste, total soluble solids, sugar contents, vitamin C concentration, titratable acidity, and fruit juice pH (Ullah et al., 1994; Petersen et al., 1998; Veit-Köhler et al., 1999; Leonardi et al., 2004; Azarmi et al., 2010) that are important for both processing as well as fresh market, while other characteristics (taste and shelf life) are important for fresh market only (Azarmi et al., 2010). Similar findings have also been reported by Petersen et al. (1998), Plaut and Grava (2000), Del Amor et al. (2001), Dorai et al. (2001), and Flores et al. (2003). An almost two-fold increase in starch contents during early fruit development was found to be the source of higher sugar content in the ripen fruit

treated with saline water (Gao et al., 1998). The accumulation of sugars and organic acids might be responsible for increased titratable acidity and decreased pH of the fruit juice. Del Amor et al. (2001) reported increased concentrations of total anion Cl^- and NO_3^- in tomato fruits in response to increase in the salinity level from 2 to 8 dS m^{-1}, but fruit K^+, Na^+, Ca^{2+}, and Mg^{2+} contents were reduced significantly by increasing salinity levels.

Salinity also produces blossom end rot which makes tomato fruits unacceptable for both processing industry and fresh market (Cuartero and Fernández-Muñoz, 1999). Petersen et al. (1998) reported the tomato fruit's physical characteristics as a quality parameter being affected by different salinity levels. They found an increase in fruit firmness with increasing salinity in the root zone.

Different genetic, environmental, and agronomic factors, including plant nutrition, as well as their interaction, controls the tomato fruit's quality (Dorai et al., 2001). In arid and semi-arid regions of the world, where tomato is an important crop, salinity and nutrient concentrations affect the fruit quality in addition to yield.

1.1.8 Plant Growth and Nitrogen

Plants' foremost requirements for their life cycle are mineral nutrients and energy from the sunlight. There are certain elements called essential mineral nutrients that are vital for plant growth and development. These elements are of prime importance in various biological functions. Although essential mineral nutrients are vital for plant survival, excessive soluble salts in soil have adverse effects on plants.

Nitrogen (N) plays an important role in many physiological and metabolic activities. It is also a key element in structural conformation of plants being a basic constituent of proteins, enzymes and nucleic acids (Maathuis, 2009). Nitrogen is the most limiting element for plant growth, potential biomass production during the whole growing season, and potential yield in most natural soils. Nitrogen fertilization is significant for tomato growth as it mollifies the stress on crops and consequently improves yields. It has a positive influence on fruit quality if applied in the proper amount.

Nitrogen is the vital constituent to increase yield and improve quality especially in horticultural crops (Luna et al., 2014). Both ammonium and nitrate are readily taken up by plants. The most abundant form of nitrogen in cultivated soils is nitrate (Hageman, 1984), and it is highly susceptible to leaching and denitrification losses. Nitrate uptake and transport have been found sensitive to salinity (Peuke et al., 1996; Flores et al., 2000). Reduced N uptake may lead to significant consequences for nitrate assimilation in the plants and increased nitrate leaching to groundwater.

Irshad et al. (2008) also reported a significant effect of saline water on plant nitrogen concentration. They found that nitrogen application has a positive correlation with soil salinity i.e. soil salinity increased with the higher application of nitrogen. Excessive N application leads to enhance the deleterious effects of soil salinity on plant growth and yield. Optimal use of irrigation water and nitrogen is one of the most significant agricultural management in balancing crop yield and water use efficiency in the arid region. In general, nitrogen application increases the crop yields and improve crop qualities (Wang et al., 2008; Badr, et al., 2012) but it may also cause high nitrate leaching to contaminate

groundwater (Song et al., 2009; Min et al., 2011; Sun et al., 2013), and may alter the nitrate content in tomato fruits (Yang et al., 2006; Zotarelli et al., 2009; Wang et al., 2012).

A straightforward practice to avoid salinity buildup is to use excessive irrigation water (Ayers and Westcot, 1989). This will increase salt leaching out of the root zone and reduce salt buildup in the soil profile. Conversely, excess irrigation also increases the loss of nutrients, especially nitrate, and often deteriorates the quality of groundwater (Wichelns and Oster, 2006; Castanheira and Serralheiro, 2010), as well as reduces water and nutrient use efficiency (Díez et al., 2000).

The nitrogenous fertilizers use efficiency by crops for conventional methods of N application, was reported to be less than 50% by Karaman et al. (2005), while Min et al. (2011) found it was only 18%. Applying the precise nitrogen rate to maximize crop production is not easy, as the optimal nitrogen rate differs significantly both among various soils as well as among different crop varieties for the same soil. Various crop nitrogen uptake rates ranging from 200 to more than 450 Kg/ha (Scholberg et al., 2000; Blaesing et al., 2006; Erdal et al., 2006), and nitrogen fertilizer requirements ranging from 100 to 224 Kg/ha (Tei et al., 2002; Hartz and Bottoms, 2009; Zotarelli et al., 2009) have been reported to optimize the tomato fruit production. This huge inconsistency can be attributed to the large variability of the environmental and crop management aspects, from one field to another, and the diversity that exists among the different crop varieties. Tomato is a long season and one of the most water-demanding crop (Du et al., 2017). Optimum fruit yield of tomatoes can be achieved if the soil is kept steadily moist and with N available during periods of high demands (Scholberg et al., 2000).

1.2 Hypothesis and Objective

In this study, it was assumed that high levels of salinity decrease the tomato growth, fruit yield, and quality while higher levels of nitrogen fertilization compensate some of the loss caused by irrigation water salinity.

Salinity influences the available water for plant uptake and this, in turn, influences the nitrogen uptake. Numerous studies have been done independently about the response of tomato yield and fruit quality to saline water irrigation and N fertilization, but their interactive effect on the growth, yield, and fruit quality parameters still needed to be assessed. Hence there is a need to explore the interactive effect of saline water irrigation and nitrogen fertilization to optimize the tomato growth, yield and fruit quality through proper irrigation and N fertilization management. The study was aimed at determining if tomato growth, yield, and quality could be improved by manipulation of different irrigation water salinity levels and nitrogen fertilization rates.

1.3 Material and Methods

A pot experiment was conducted in this study in the greenhouse at the University of California, Riverside. Tomato was used as the study plant and the experiment included nine treatments representing different combinations of three irrigation water salinity levels and three nitrogen fertilization rates.

1.3.1 Soil Collection, Packing, and its Basic Properties

Bulk soil was collected from the upper 30 cm of the experimental field at the Citrus Research Center, University of California, Riverside. The collected bulk soil was air dried and passed through 10 mm sieve. Based on the soil particle size analysis (hydrometer method, Bouyoucos, 1927) the soil was classified as sandy loam. The electrical conductivity (µS m^{-1}) of soil was determined with an EC meter in an extract (1:5) after shaking for 3 mins.

Plastic pots used in this experiment were 30 cm in height, 28 cm in diameter with a hole in the bottom center with the fiberglass wick to facilitate the drainage water collection. For each pot, a pre-determined amount of soil (Amount of soil = Bulk density * Volume) for bulk density of 1.25 g cm^{-3} was added in small increments to obtain uniform packing. As a pretreatment, the soil was irrigated with equal amounts of 4% W/W water of EC = 1 dS m^{-1} one day before the tomato seedling transplantation.

Table 1.1. Physico-Chemical Properties of Soil

Soil Properties		**Value**
Textural Class		Sandy Loam
Sand		56%
Silt		28%
Clay		16%
EC (Soil Water extract 1:5)	($\mu S\ m^{-1}$)	279
pH (Soil Water extract 1:5)		6.24
Sodium (Na^{+})	(ppm)	16.88
Calcium (Ca^{++})	(ppm)	11.21
potassium (K^{+})	(ppm)	3.50
Magnesium (Mg^{++})	(ppm)	2.32
Phosphorous (P^{-})	(ppm)	0.24
Chloride (Cl^{-})	(ppm)	11.62
Nitrate (NO_3^{-})	(ppm)	28.67
Sulfate ($S0_4^{=}$)	(ppm)	24.36

1.3.2 Environmental Conditions

The average temperature and relative air humidity inside the greenhouse were maintained at 25 ± 2°C and 75 ± 2% respectively, throughout the growing season.

1.3.3 Treatments

Plants were irrigated with two saline water treatments (2 and 4 dS m^{-1}) and one control treatment (half-strength Hoagland solution). Saline water stock solution was added to the control treatment to raise the irrigation water salinity up to desired levels of EC = 2 and 4 dS m^{-1}, and the saline water stock solution was prepared by using NaCl, Na_2SO_4, $CaCl_2$, and $MgSO_4$ in molar proportion of 0.54, 0.33, 0.11, and 0.02 respectively. This composition is in line with the saline soil used by Iqbal et al., (2015).

Three irrigation water treatments were factorially combined with the three levels of nitrogen fertilization and arranged in a completely randomized design with three replications. Tomato crop was fertilized with three nitrogen rates; viz 80, 100 and 120% of the recommendation for the pot experiment (100 mg Kg^{-1} soil) made by Novais et al. 1991. Nitrogen was applied in the form of Urea in three equal splits, i.e. with the first irrigation after transplantation, at the start of flowering and at the start of fruiting.

Table 1.2. Summary of experimental treatments

Treatments	**Nitrogen Levels**		
	80% N	**100% N**	**120% N**
Control	S1N1	S1N2	S1N3
2 dS m^{-1}	S2N1	S2N2	S2N3
4 dS m^{-1}	S3N1	S3N2	S3N3

Table 1.3.Chemical composition of different irrigation waters

Chemical composition of Irrigation Waters				
		Control	2 dS m^{-1}	4 dS m^{-1}
Sodium (Na^{+})	(ppm)	1.79	295.12	711.80
Calcium (Ca^{++})	(ppm)	32.74	59.96	95.71
potassium (K^{+})	(ppm)	28.32	26.80	21.63
Magnesium (Mg^{++})	(ppm)	7.74	8.77	10.38
Phosphorous (P^{-})	(ppm)	2.98	2.46	1.68
Chloride (Cl^{-})	(ppm)	2.58	364.12	978.47
Nitrate (NO_3^{-})	(ppm)	230.03	167.18	113.63
Sulfate ($S0_4^{=}$)	(ppm)	35.78	459.44	1173.83

1.3.4 Irrigation

Plants were irrigated weekly for the first 7 weeks and every 4th day for the remaining growing season depending on the crop Water Use (ET_a). Et_a was measured

gravimetrically by weighing the pot according to the method of FAO irrigation and drainage paper No. 56 by Allen et al. (1998) and the required ET_a water plus extra water for leaching requirement (LR) was added to the pots. The leaching requirement was calculated by the equation developed by Rhoades (1974) as a guideline for calculating LR based on irrigation water salinity and crop salt tolerance.

$$LR = \frac{EC_{iw}}{5EC_e - EC_{iw}}$$

1.3.5 Data Collection

Plant height and the leaf area were measured three times during the mid-growing season before fruiting. Shoot fresh and dry biomass was determined at the end of the experiment when fruits were harvested. Fully mature red to orange colored fruits were harvested every 4th day before the irrigation and at the end of the harvesting season, total fruit yield per plant (g), the total number of fruits per plant and average fruit weight (g) were determined. Random fruit samples (three fruits) were taken from each harvest for three times at the peak of harvest to determine fruit firmness. Later, these samples were used for laboratory analyses.

The homogenized fruit's juice was subjected to the total soluble solids (TSS, expressed as $^{\circ}$Brix at 20 $^{\circ}$C) determination using a portable refractometer and the titratable acidity determination by titration against NaOH using phenolphthalein as indicator according to the method described in AOAC (Helrich, 1990).

1.3.6 Statistical analysis

Statistical analysis of the data (ANOVA) was conducted and differences between the means were compared for significance using a Revised Least Significant Difference (LSD) test at 0.05 levels as described by Snedecor and Cochran (1989).

1.4 Results and Discussion

Soil salinity is one of the most important abiotic factors controlling crop yields in the arid and semi-arid irrigated areas. Plant growth was significantly affected by irrigation water salinity for most of the plant growth parameters. Higher yields were recorded in the treatments with lower irrigation water salinity as compared to higher irrigation water salinity.

Nitrogen application increased different tomato growth and yield parameters while this increase was not significantly different. Fruit firmness was the only parameter that was significantly different for different levels of nitrogen application. The effect of nitrogen along with the irrigation water salinity reported in the literature was found inconsistent. Papadopoulos and Rendig (1983) reported the positive response to increasing N levels for the tomato plants irrigated with nutrient solution having electrical conductivity of 1dS m^{-1} for the root and shoot dry weights and also for fruit fresh weight, but they found increasing N fertilization ineffective in counteracting the negative effects on growth associated with the buildup of salinity levels in the soil. Mori et al. (2008) found that nitrogen and salinity interaction was not significant for both the growth and yield parameters.

Badr and Talaab (2008) reported an increment in different growth parameters of tomato plants with the increase in N fertilization, even under moderate salinity conditions

while Vieira et al. (2016) found interaction in salinity and nitrogen fertilization only for the leaf area. On the other hand, Al-Harbi et al. (2008) reported the significant effect of salinity and nitrogen level for different growth parameters while the interaction was significant only for the number of leaves and seedling fresh and dry weight.

1.4.1 Shoot Length (cm)

Data collected on the shoot length of tomato as influenced by various levels of salinity and nitrogen (Appendix 1) showed that the effects of various salinity levels were significant ($P< 0.05$), while the effects of various nitrogen levels and their interactions with salinity levels were found non-significant.

Comparing the different levels of salinity on the shoot length of tomato (Table 1.4), it was observed that the treatment with 2 dS m^{-1} (41.22 cm) was at par with the control treatment (42.39 cm). However, both the treatments were significantly different from the higher level of salinity i.e. 4 dS m^{-1}(17.19). The decrease in shoot length due to higher salinity level of 4 dS m^{-1} was 59.44 %.

The results for the shoot length are in line with the results reported by Nangare et al. (2013) and Malash et al. (2008). Carvalho et al. (2015) reported that the plant height decreased with increasing irrigation water salinity and this decrease became more significant when irrigation water of electrical conductivity equal or higher to 3.5 dS m^{-1} was used. Vieira et al. (2016) also reported the reductions in the height of plants irrigated with water of 4.5 dS m^{-1}, compared to those under EC_{iw} of 0.3 dS m^{-1}. Oliveira et al. (2007), evaluated the effect of saline water irrigation on different production characteristics of tomato and observed the decrease in plant height of 4.76 cm per unit increase in electrical

conductivity of irrigation water, with reduction percentages of 18, 22, 26, 40 and 78% for the salinity levels of 5.7, 6.8, 8.3, 12.7 and 24.5 dS m^{-1} in the irrigation water.

Table 1.4. Effect of irrigation water salinity and nitrogen fertilization on tomato growth parameters.

Treatments		**Shoot length (cm)**	**Shoot fresh weight (g)**	**Shoot dry weight (g)**	**Leaf area index**
Control	80% Nitrogen	41.67	848.72	113.07	143.92
	100% Nitrogen	42.50	897.07	114.54	141.45
	120% Nitrogen	43.00	921.30	118.10	151.06
	Mean	42.39a	889.03a	115.24a	145.48a
EC 2 dS m^{-1}	80% Nitrogen	41.00	816.89	105.58	134.13
	100% Nitrogen	41.33	840.44	109.36	129.33
	120% Nitrogen	41.67	906.18	112.69	137.34
	Mean	41.22a (-2.76%)	854.50a (-3.88%)	109.21a (-5.23%)	133.60a (-8.17%)
EC 4 dS m^{-1}	80% Nitrogen	37.33	419.72	61.19	91.59
	100% Nitrogen	38.17	508.00	71.55	89.58
	120% Nitrogen	39.17	527.82	77.44	88.79
	Mean	17.19b (-59.44%)	485.18b (-45.43%)	70.06b (-39.21%)	89.99b (-38.14%)
Mean	80% Nitrogen	40.00	695.11ab	93.28a	123.21a
	100% Nitrogen	40.67	748.50a	98.48a	120.12a
	120% Nitrogen	41.28	695.11ab	102.74a	125.73a

Means followed by similar letter(s) in respective row or column do not differ significantly from one another.
Number in the parenthesis shows the percent increase or decrease.

In another study, with increasing N doses and different saline levels, Badr and Talaab (2008) observed a rise in the growth of tomato plants with the increasing N doses, even under moderate salinity conditions. Hajer et al. (2006) also observed the reduction in tomato seedling height with the increasing irrigation water salinity and this reduction was significant starting from the age of four weeks until the end of the experiment. Similar findings were reported by Parvin et al. (2015) regarding the plant height of tomato at

different days after transplantation and the reduction observed was quite incremental with increasing NaCl concentrations.

According to Gulzar et al. (2003), the stress caused by the excess of ions, in general, reduces CO_2 assimilation, stomatal conductance, transpiration and photosynthesis and, consequently, tends to hamper plant development. Mostly Plant growth is affected by the soil salinities due to a reduction in the osmotic potential of the soil solution, along with the possibility of the occurrence of ionic toxicity and/or nutritional imbalance due to unnecessarily higher accumulation of certain ions in plant tissues.

1.4.2 Shoot Fresh Weight (g)

The results regarding the effects of various levels of salinity and nitrogen on the fresh shoot weight (Appendix 2.2) showed that the effects of salinity levels were highly significant ($P< 0.01$), while the effects of various nitrogen levels and their interactions on shoot fresh weight were found non-significant.

The effect of higher irrigation water salinity on tomato growth is also reflected in declining plant biomass. Comparing the effects of salinity levels with one another (Table 1.4), it can be seen that fresh shoot mass of the 2 dS m^{-1} treatment was comparable with that of the control, while both of these treatments were significantly different from 4 dS m^{-1} treatment. The highest shoot fresh weight (889.03 g) was obtained from the control and the lowest shoot fresh weight (485.18 g) was obtained from the 4 dS m^{-1} treatment. The decrease in shoot fresh weight was 3.38 and 45.43% in 2 and 4 dS m^{-1} treatments, respectively, over control. The significant declining effect in shoot fresh weight at 4 dS m^{-1} treatment can be due to its adverse effects on the vegetative growth and it may be an

outcome due to osmotic as well as ion-specific effects. Hajer et al. (2006) found that the values of the fresh seedling weight of the three different tomato cultivars were generally lowered with the increasing salinization comparing with the control.

1.4.3 Shoot Dry Weight (g)

Similar to the shoot fresh weight of tomato plants, the effect of different salinity levels on shoot dry weight (Appendix 3) of tomato was highly significant ($P < 0.01$), whereas the effect of various nitrogen levels and their interactions on shoot dry weight, was found to be non-significant.

Regarding the effect of various levels of salinity (Table 1.4), it can be visualized that the treatment with 2 dS m^{-1} was at par with control, while both these treatments were significantly different from the treatment with a higher irrigation water salinity level of 4 dS m^{-1}. The significantly lowest shoot dry weight (70.06 g) was recorded in treatment with irrigation water salinity of 4 dS m^{-1} (39.21 % lower than that of the control).

These results are in agreement with the findings of the Malash et al. (2008) who reported that dry weights of plants irrigated with the irrigation water salinity of 0.55 dS m^{-1} were not significantly different from those irrigated with the irrigation water salinity of 3 dS m^{-1}, while they were significantly different from the dry weights of plants irrigated with the irrigation water salinity of 4.5 dS m^{-1}. Similar results were reported by Hajer et al. (2006) for three different tomato cultivars.

1.4.4 Leaf Area (cm^2)

Analysis of variance (ANOVA) of the leaf area data showed that the effect of salinity levels on leaf area was highly significant ($P< 0.01$), while the effect of different nitrogen levels and their interactions with salinity levels were not significant (Appendix 4).

By comparing the leaf areas in treatments of three salinity levels (Table 1.4), it was found that the leaf area of 2 dSm^{-1} treatment (133.60 cm^2) was comparable with that of the control treatment (145.48 cm^2). However, the leaf area in the 4 dS m^{-1} (89.99 cm^2) was significantly lower than that of the control (38.14 % decrease).

Vieira et al. (2016) observed that the leaf area of cherry tomato decreased linearly with the increase in irrigation water salinity and reduction of 9.21% per unit increase in EC_{iw}. Tester and Davenport (2003) related the decrease in leaf area of plants cultivated under saline conditions to the reduction in water availability and uptake, which affects cell division and elongation. The excess of salts in the root zone might have negative effects on plant growth, because of the higher osmotic effect outside the roots and restriction in the water flow from the soil to the plants, which is necessary for survival and production under saline stress conditions (Silva et al., 2008).

1.4.5 Total Fruit Yield per Plant

Our results about the total tomato fruit yield per plant (Appendix 2.5) showed that the effect of salinity levels on the total fruit yield per plant was highly significant ($P< 0.01$), while the effects of nitrogen levels and the salinity × nitrogen interaction on the total fruit yield of tomatoes per plant were found non-significant.

Table 1.5. Effect of irrigation water salinity and nitrogen fertilization on tomato fruit yield parameters

Treatments		Total fruit yield per plant (g)	Number of fruits per plant	Average fruit weight (g)	Fruit length (mm)	Fruit volume (cm^3)
Control	80% Nitrogen	2122.49	77.67	27.42	50.16	38.79
	100% Nitrogen	2255.62	81.67	27.68	50.40	39.04
	120% Nitrogen	2400.89	84.00	28.84	50.56	39.24
	Mean	2259.70a	81.11a	27.98a	50.37a	39.02a
EC 2 dS m^{-1}	80% Nitrogen	1920.98	65.67	29.97	50.47	39.14
	100% Nitrogen	1989.51	69.67	28.94	51.05	39.99
	120% Nitrogen	2053.84	74.33	27.81	52.61	41.29
	Mean	1988.10b (-12.01%)	69.89b (-13.83%)	28.90a (-3.65%)	51.38a	40.14a
EC 4 dS m^{-1}	80% Nitrogen	1115.70	58.00	20.12	40.74	30.43
	100% Nitrogen	1246.99	60.67	20.60	41.08	30.84
	120% Nitrogen	1273.02	62.67	20.73	42.14	31.43
	Mean	1211.90c (-46.36%)	60.44c (-25.48%)	20.49b (-26.77%)	47.12b (-6.45%)	30.90b (-20.81%)
Mean	80% Nitrogen	1719.70a	67.11a	25.84a	47.12a	36.12a
	100% Nitrogen	1830.70a	70.67a	25.74a	47.51a	36.62a
	120% Nitrogen	1909.20a	73.67a	25.80a	48.44a	37.32a

Means followed by similar letter(s) in respective row or column do not differ significantly from one another.
Number in the parenthesis shows the percent increase or decrease.

It can be seen that the total fruit yield of tomatoes per plant in various levels of salinity treatments differed significantly from one another (Table 1.5). The significantly highest total fruit yield of tomatoes per plant (2259.7 g per plant) was recorded in control treatment as against the total yield of 1988.1 and 1211.9 g per plant, respectively, in 2 and 4 dS m^{-1} irrigation water salinity treatments, which represent 12.1 and 46.36% reductions, compared with the control treatment. There was a significant and linear decrease in the total fruit yield of tomatoes per plant as the salinity level increased from control to 4 dS m^{-1}.

Our results regarding the effects of salinity levels are in agreement with the work of other researchers who reported that salinity levels above 2 dS m^{-1} reduced the total fruit yield of tomato significantly. Cuartero and Fernández-Muñoz (1999) also indicated that the tomato yields reduced when the plants were irrigated with a nutrient solution of EC 2.5 dS m^{-1} or higher, and they attributed the yield reduction to the decrease in average fruit weight and/or number of fruits.

Campos et al. (2006) also reported that total fruit yield of tomato reduced by 11% upon each unit increase in the salinity of the irrigation water. Reduction in total fruit yield (49.7%) of tomato has also been observed at higher salinity levels (12 dS m^{-1}) in comparison with the control (1.2 dS m^{-1}), while a moderate salinity level (2.4 dS m^{-1}) of irrigation water had no significant effect in this regard (Alsadon et al., 2009). According to Olympios et al. (2003), increasing EC of irrigation water from 1.5 to 3.2 dS m^{-1} reduced about 45% tomato yield. Al-Harbi et al. (2015) also reported yield reduction in plants irrigated with water of 3.6 dS m^{-1} as compared with that of irrigated with water of 0.9 dS m^{-1}. Ahmed et al. (2017) published their work reporting that the significantly highest total fruit yield was recorded in plants irrigated with fresh-water and significant yield reduction was observed in plants irrigated with saline water of EC = 4 dS m^{-1} and higher. Elamin and Al-Wehaibi (2005) observed that the most sensitive plants may suffer physiological damages, with subsequent significant yield loss, while moderately sensitive to tolerant plants are still able to produce acceptable yields. Nangare et al. (2013) observed the 11.51% and 25.84% decrease in yield when irrigation water salinity was 6.3 and 9.1 dS m^{-1} as compared with fresh-water (EC = 0.38 dS m^{-1}). Malash et al. (2008) also reported that that

the tomato fruit yield per plant significantly reduced with the application of saline irrigation water of EC = 3.0 and 4.5 dS m^{-1} as compared to irrigation water of EC = 0.55 EC = 2 dS m^{-1}. Yield reduction has been attributed to reduced photosynthesis, high energy and carbohydrate expenditure in osmoregulation under salt stress conditions (Shani and Dudley, 2001).

The results regarding the effect of nitrogen levels on the total fruit yield of tomatoes per plant (Table 1.5) showed that 80% of the recommended level of nitrogen seems better as there was no significant increase in yield at higher N application rates.

1.4.6 Number of Fruits per Plant

Data collected on the number of fruits per plant as affected by various levels of salinity and nitrogen (Appendix 6) showed that the results for salinity levels were highly significant ($P < 0.01$), while the results for nitrogen levels and their interactions with salinity levels were not significant.

Comparing the salinity levels with one another (Table 1.5), it was observed that all the three EC levels differed significantly from one another as regards their effect on the number of fruits per plant. The control treatment was found with the significantly highest number of fruits per plant (81) and it decreased linearly as the salinity level was increased at a significant level of $p < 0.01$. The reduction in the number of fruits per plant was 13.83 and 25.48% at 2 and 4 dS m^{-1}, respectively.

Though the results for nitrogen levels were non-significant, (Table 1.5), there was a little linear increase in the number of fruits per plant as N application rate increases from

80% of recommended nitrogen to 120% of recommended nitrogen. However, it can be visualized from these results that the application of 80% of the recommended level of nitrogen seems better under the greenhouse conditions.

Inconsistencies have been found in the literature regarding the number of fruits per plant as influenced by the salinity. Li et al. (2001) and Eltez et al. (2002) reported that moderate salinity had no effect on the number of fruits per plant and the yield reduction was entirely due to smaller fruit size. However, their results are inconsistent with the study of Adams and Ho (1989), Van Ieperen (1996) and Al-Busaidi et al. (2009) who reported that the decline in number of fruits per plant was a result of increasing salinity. The reduction in number of fruits per plant in this study might be related to the reduced number of flower per truss and per plant in higher salinity treatments (Magán et al., 2008). This has also been reported by Cuartero and Fernández-Muñoz (1999) who indicated that the number of tomato fruits/plant depended on the number of trusses/plant, and the number of flowers/truss and the number of trusses/plant decreased as irrigation water salinity, as well as salinization period increased.

1.4.7 Average Fruit Weight (g)

Average fruit weight was obtained by dividing the total fruit yield per plant by the number of fruits per plant. The analysis of variance (ANOVA) table (Appendix 7) showed that the average fruit weight was significantly affected by the various salinity levels ($P < 0.01$), whereas nitrogen levels and interactions between salinity and nitrogen were found non-significant.

As regards the effect of various levels of irrigation water salinity on the average fruit weight (Table 1.5), it can be seen that the highest average fruit was recorded in the treatment receiving irrigation water salinity of 2 dS m^{-1} (28.90 g), being at par with control treatment (27.98 g) but they were significantly higher than that of treatment with 4 dS m^{-1} (20.5 g). Moreover, the average weight was linearly reduced with the increase in salinity level. There was a 26.77% reduction in average fruit weight in case of 4 dS m^{-1} irrigation water salinity level, in comparison with that of control treatment.

This significant reduction in average fruit weight for 4 dS m^{-1} treatment can be due to the adverse effect of salinity on the total fruit yield per plant rather than the number of fruits per plant. The results for the mean fruit weight are in line with the findings of Al-Harbi et al. (2015) who reported that average fruit weight decreased when irrigation water of 3.6 dS m^{-1} was applied, as compared with that when irrigation water salinity of 0.9 dS m^{-1} was used. Malash et al. (2008) also reported a significant reduction in average tomato fruit weight in plants irrigated with saline water.

1.4.8 Fruit Length (mm)

Data recorded on the fruit length of tomato as influenced by various levels of irrigation water salinity and nitrogen application (Appendix 8) showed that the effects of salinity on fruit length were highly significant ($P < 0.01$) while the effects of nitrogen levels and their interactions with salinity levels were found non-significant.

Comparing the various levels of irrigation water salinity (Table 1.5), it was found that 2 dS m^{-1} (51.38 mm) was comparable with control (50.37 mm) and these treatments

had significantly higher fruit length than that of 4 dS m^{-1} (47.12 mm). The reduction in fruit length at 4 dS m^{-1} irrigation water salinity was 6.45 % over control.

The findings of Ahmed et al. (2017) support the present results as they reported that the plants irrigated with fresh-water produced longer fruits than the plants irrigated with waters of higher irrigation water salinity. It can be explained that salinity might have decreased the photosynthetic activities and prepared insufficient food for plant growth and fruit enlargement. High levels of Na^+ can also cause an imbalance in uptake and utilization of other cations and disruption of chloroplasts, which results in reduced photosynthesis (Katerji et al., 1998).

1.4.9 Fruit Volume (cm^3)

Data obtained on the effect of various levels of irrigation water salinity and nitrogen application on the fruit volume of tomato (Appendix 9) showed that the results were highly significant ($P < 0.01$) for the irrigation water salinity levels whereas the effects of nitrogen rates and their interactions with salinity levels were found non-significant.

Looking at the various levels of salinity on the fruit volume of tomato (Table 1.5), it can be visualized that the 2 dS m^{-1} (40.14) was at par with control treatment (39.02) and both of these treatments were significantly different from 4 dS m^{-1} (30.92). The reduction in fruit volume at 4 dS m^{-1} was 20.81 % over the control treatment. This reduction might be due to the adverse effect of salinity on the number of leaves per plant and disruption of chloroplasts resulting in reduced photosynthetic activity of tomato plants and synthesis of food.

High salinity distresses plant growth and productivity by increasing the osmotic stress, ion toxicity, and alterations in soil physical and chemical properties (Keren, 2004), as well as triggering an imbalance of nutritional cations in plant tissues (Gad, 2005).

1.4.10 Fruit Water Content (%)

Data collected on the fruit water content of tomato as influenced by various levels of irrigation water salinity and nitrogen levels (Appendix 10) indicated that the results regarding salinity levels were highly significant ($P < 0.01$), while the main effects of nitrogen levels and their interactions with various levels of salinity were found non-significant.

Comparing the various levels of salinity on the fruit water content (Table 1.6), it can be visualized that all three levels of salinity were significantly different from one another. The significantly highest level of fruit water content (93.45%) and the significantly lowest fruit water content of 91.64% were recorded in control treatment and irrigation water salinity of 4 dS m^{-1} treatment respectively. The decrease in fruit water content of 0.81 and 1.94% was recorded in the case of 2 and 4 dS m^{-1} treatment over control treatment.

This decrease in fruit water content due to the use of saline water can be explained on the basis of making osmotic adjustments (Ahmed et al., 2017). Soluble salts lower the osmotic potential of the soil water, thus lower leaf water potential is required to sustain transpiration (Leone et al., 2000). In other words, plants spend more energy on the uptake of water.

Table 1.6 Effect of irrigation water salinity and nitrogen fertilization on tomato fruit quality.

Treatments		Fruit water content (%)	Fruit firmness (pound force, lbf)	Fruit TSS (°Brix)
Control	80% Nitrogen	93.02	1.01	5.81
	100% Nitrogen	93.66	1.09	5.50
	120% Nitrogen	93.72	1.12	5.34
	Mean	93.45a	1.07c	5.55c
EC 2 dS m^{-1}	80% Nitrogen	92.67	1.07	6.15
	100% Nitrogen	92.69	1.28	6.10
	120% Nitrogen	92.74	1.33	6.10
	Mean	92.70b (-0.81%)	1.23b (14.95%)	6.11b (10.09%)
EC 4 dS m^{-1}	80% Nitrogen	92.11	1.22	6.97
	100% Nitrogen	91.56	1.39	6.58
	120% Nitrogen	91.24	1.62	7.02
	Mean	91.64c (-1.94%)	1.41a (31.78%)	6.85 (23.42%)
Mean	80% Nitrogen	92.11a	1.10c	6.31a
	100% Nitrogen	91.56a	1.25b (13.63%)	6.06b
	120% Nitrogen	91.24a	1.36a (23.63%)	6.15b

Means followed by similar letter(s) in respective row or column do not differ significantly from one another. Number in the parenthesis shows the percent increase or decrease.

1.4.11 Fruit Firmness

Data recorded on the effect of various levels of salinity and nitrogen on the fruit firmness of tomato (Appendix 11) showed that the effects of irrigation water salinity levels, nitrogen levels, and their interactions were highly significant ($P < 0.01$). Comparing the various levels of salinity with one another (Table 1.6), it can be visualized that all three levels of irrigation water salinity were significantly different from one another. The fruit firmness of tomato was significantly and linearly increased with the increase in the salinity

level. The increase in fruit firmness over control was 14.95 and 31.78 %, respectively due to 2 and 4 dS m^{-1} treatments.

As regards the effect of various levels of nitrogen on the fruit firmness (Table 1.6), it can be seen that all three levels of nitrogen were significantly different from one another. The fruit firmness was increased linearly as the nitrogen level was increased from 80 % to 120 % N. The increase in fruit firmness over treatment with 80 % nitrogen was 13.63 and 23.63 % by applying 100 and 120 % N.

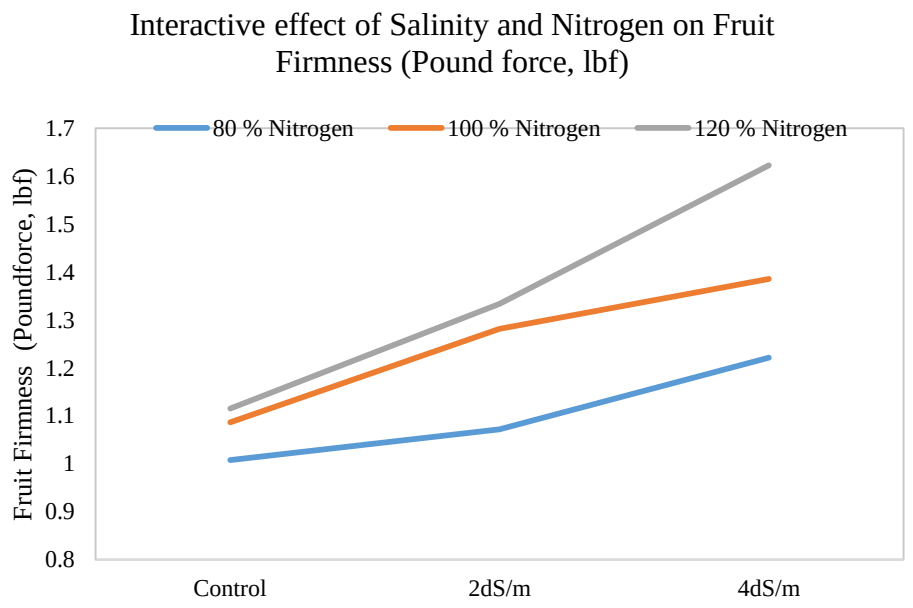

Figure 1.1. Interactive effect of salinity and nitrogen on Fruit firmness (Pound force, lbf)

The interactions between salinity levels and nitrogen levels on the fruit firmness of tomato (Fig.1.1) showed that the highest level of nitrogen produced tomatoes with significantly greater fruit firmness at three levels of irrigation water salinity. The significantly lowest fruit firmness was recorded in tomato treated with 80 % N at different

levels of salinity. The trend in fruit firmness of tomato in various levels of N at various levels of salinity was the same.

1.4.12 Fruit Total Soluble Solids (TSS)

Data obtained on the total soluble solids (TSS) of tomato fruit as influenced by various levels of salinity and nitrogen (Appendix 12) showed that the effects of salinity, nitrogen, and their interactions were highly significant ($P < 0.01$). For the salinity effect (Table 1.6), it is clear that all three levels of salinity differed significantly from one another. Total soluble solids of tomato fruits were increased linearly as the salinity level increased ($p < 0.01$). The total soluble solids in the 2 and 4 dS m^{-1} treatments were 10.09 and 23.42%, respectively, higher than that of the control treatment.

80% N treatment produced significantly higher fruit TSS (Table 1.6) than those of the other two N treatments (3.96% lower in the 100% and 2.53% lower in 120% N). The tomato fruit TSS values of the 100 and 120% treatments were nearly equal.

For the salinity and nitrogen interaction effect, it was shown that the tomato fruit had significantly highest soluble solids in the lowest level of N (80% N) at all the three levels of salinity. The significantly lowest soluble solids were found in tomato fruit produced by 120% N at control irrigation water salinity.

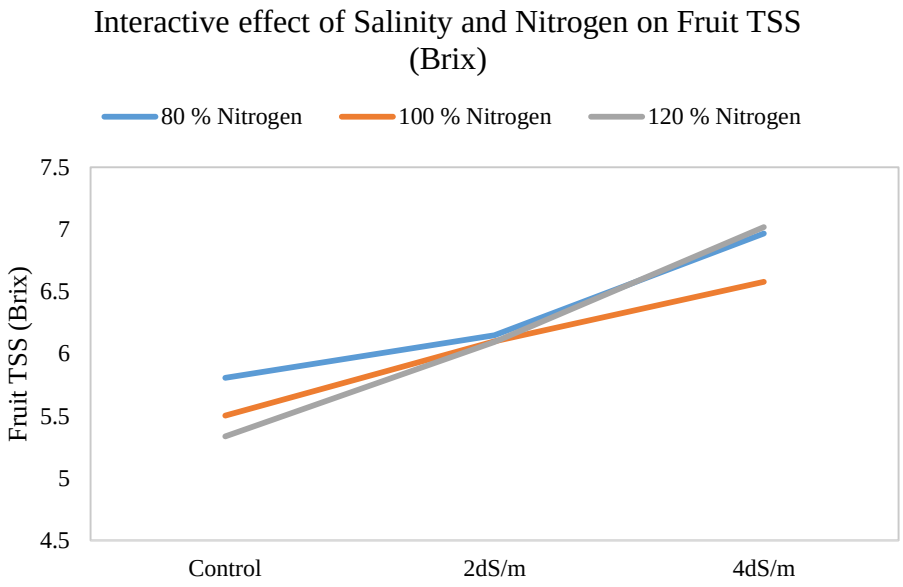

Figure 1.2. Interactive effect of salinity and nitrogen on Fruit TSS (Brix^0)

Our observations about the effect of salinity levels on the total soluble solids agreed with the findings by Ahmed et al. (2017) who reported that the total soluble solids increased linearly with salinity levels of irrigation water. Likewise, our results were similar to the findings obtained by Al-Harbi et al. (2015); Nangare et al. (2013) and Malash et al. (2008). Moreover, Munns (2002) reported an active accumulation of solutes (mainly ions and organic molecules) under saline conditions.

The progressive response of irrigation with saline water on TSS content of fruits possibly arise as an effect of reduction in water intake by the fruits (Al-Yahyai, 2010). In general, an increase in water salinity has increased the value of total soluble solids whereas the moisture content decreases gradually. From the present results, it was observed that there was a strong negative correlation between the fruit water content and the total soluble

solids of tomato fruit (r = -0.94). It is obvious from our work that the salinity levels of irrigation water reduced the fruit water content which in turn increased the total soluble solids of tomato fruit. Zhai et al. (2015) reported a positive relationship between the fruit soluble solids and irrigation water salinity and observed the increase in tomato fruit total soluble solid under the saline water irrigation (5.5 dS m^{-1}) treatment in their study. Increase in sugar concentration per fruit has been observed due to increase in the electrical conductivity (EC) of soil, either by applying a high ionic solution or by restricting watering (Beckles, 2012).

1.5 CONCLUSIONS

The following conclusions could be drawn from the present greenhouse pot experiment:

1. Salinity levels significantly affected all the yield components of tomato and high salinity had a detrimental effect on tomato growth and yield. The treatment with 2 dS m^{-1} irrigation water salinity was comparable with the control treatment, while the treatment with 4 dS m^{-1} irrigation water significantly reduced and had the lowest tomato yield and quality values. The effects of nitrogen level and salinity-nitrogen interaction on various yield and quality parameters were found non-significant.
2. The effect of salinity levels on the total yield of tomato was highly significant. The control treatment produced the significantly highest total tomato yield and it decreased linearly with increase in salinity level. The treatment with 4 dS m^{-1} produced the significantly lowest total tomato fruit yield per plant.
3. The effects of salinity levels, nitrogen levels, and salinity-nitrogen interactions were highly significant on fruit firmness and fruit total soluble solids. The fruit firmness was higher in the 100 and 120% N treatment than that in the 80% N treatment, while the total soluble solids decreased linearly with increase in N level.
4. Higher salinity levels improved the quality of tomato fruit. The fruit firmness and fruit total soluble solids increased linearly as salinity level increased.
5. Higher fruit firmness was observed in the highest N level at all three levels of salinity. On the other hand, higher total soluble solids were observed in the lowest level of N level at all three levels of salinity.

6. There was a strong correlation between the tomato fruit water content and fruit total soluble solids (R^2 = 0.88). The significantly lowest tomato fruit water content was found in tomato receiving 4 dS m^{-1} water while the significantly highest fruit total soluble solids in the same treatment. This effect was attributed to water stress in tomato plants, and
7. Nitrogen effects on various tomato yield and quality parameters were found non-significant. It means that 80% N application rate was sufficient under the greenhouse condition and nitrogen above this level is beneficial.

We conclude that if potable water is not available, saline irrigation water with electrical conductivity of 2 dS m^{-1} or lower can be used for tomato production without scarifying tomato yield and quality.

Chapter 2

HYDRUS-1D CALIBRATION AND VALIDATION

ABSTRACT

Evaluation of the effects of irrigation water quality and quantity on soil salinity and drainage fluxes are necessary to plan and manage irrigation schemes under different soil and climatic conditions. Different analytical and numerical models have been developed to predict water flow and solute transport in the vadose zone. Model results can be very helpful in decision making to plan and manage different irrigation and fertilization schemes. HYDRUS-1D model simulates water flow and solute transport in vadose zone soil. In this study, we used HYDRUS-1D to evaluate the data obtained from the greenhouse pot experiment of Chapter One.

The model was able to successfully simulate drainage flux, soil water storage, root zone salinity, as well as yield reductions due to salinity stress based on root water uptake. Observed and HYDRUS-1D predicted values were compared using different statistical parameters and our results showed a close agreement between the observed and model predicted values. This indicates the applicability of HYDRUS-1D to simulate water movement, and storage as well as salinity buildup in the soil profile.

2.1 Introduction

2.1.1 Water Flow and Solute Transport

Water flow and solute transport in vadose zone soil, involve very complex processes. A variety of methods exist to evaluate the influence of irrigation water quality and existing irrigation management on water flow and solute transport. Traditionally soil samples were taken and laboratory analyses of soil samples were carried out to determine the salinity distribution and leaching in soils. Nevertheless, these classical methods are time-consuming, expensive, and require a lot of effort, still can't completely cover the various aspects at the field scale (Rasouli et al., 2012). On the other hand, scientists and water and environmental managers are increasingly becoming more interested in the use of computer models to study these complex processes in the soil (Raine et al., 2007; Phogat et al., 2010) to develop management and plans.

To explore the effects of irrigation water quality and environmental factors on soil properties, solute transport to groundwater, and crop yield, conceptual models can play a very important role. Over the recent past, the scientific community has impressively shown great devotion, by spending considerable time and resources, in the development of analytical and numerical models (Wagenet and Hutson, 1987; Jarvis, 1994; van Dam et al., 1997; Ahuja et al., 2000; van den Berg et al., 2002; Šimůnek et al., 2008). Modeling of subsurface water flow and the transport of major soluble ions in and below the root zone is becoming a valuable research tool to predict crop response to irrigation regimes, ground-water quality, implement better irrigation and fertilization strategies, and assess salinization and alkalization risks.

The water and solute transport processes in soils can be represented by a series of governing equations. For water movement in soils, the Richards' (1931) equation is generally used which can be solved either analytically or numerically. While for the solute transport, use of Fickian-based convection-dispersion equation is very common. To explore root water and nutrient uptake, a sink term is usually included in these equations to account for the effects of water and osmotic stresses (Feddes and Raats, 2004; Šimůnek and Hopmans, 2009). These classical equations surely are important tools for describing water and solute transport in the vadose zone, and for analyzing specific laboratory or field experiments involving unsaturated water flow and solute transport. Simulation models are essential tools for extrapolating information from a limited lab and/or field experiment to a different crop, irrigation methods, soil types, and environmental conditions, as well as to different water management schemes.

2.1.2 Water flow and Plant Water Uptake

One-dimensional saturated and unsaturated water flow can be described by Richards' equation with the assumptions that the air phase plays an insignificant role and thermal gradient in the liquid flow process can be ignored:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S(z,t) \qquad (2.1)$$

where θ is the volumetric soil water content [L^3L^{-3}], t is time [T], z is the vertical space coordinate [L], h is the pressure head [L], K is the hydraulic conductivity [LT^{-1}], and S is the sink term accounting for water uptake by plant roots [$L^3L^{-3}T^{-1}$]. The unsaturated soil

hydraulic properties are described using the van Genuchten-Mualem functional relationships (Van Genuchten, 1980).

The sink term, S, is calculated using the macroscopic approach introduced by Feddes et al. (1978). In this approach, the potential transpiration rate, T_p [LT^{-1}], is distributed over the root zone using the normalized root density distribution function, β (z,t) [L^{-1}], and multiplied by the dimensionless stress response function, α (h, h_ϕ, z, t), accounting for water and osmotic stresses (Feddes et al., 1978; Van Genuchten, 1987; Šimůnek and Hopmans, 2009):

$$S\left(h,h_\phi,z,t\right)=\alpha\left(h,h_\phi,z,t\right)S_p\left(z,t\right)=\alpha\left(h,h_\phi,z,t\right)\beta\left(z,t\right)T_p\left(t\right) \qquad (2.2)$$

where S_p (z, t) and S (h, h_ϕ, z, t) are the potential and actual volumes of water removed from unit volume of soil per unit of time [$L^3\ L^{-3}\ T^{-1}$], respectively, and α (h, h_ϕ, z, t) is a prescribed dimensionless function of the soil water (h) and osmotic (h_ϕ) pressure heads ($0 \leq \alpha \leq 1$). The actual transpiration rate, T_a [$L\ T^{-1}$], is then obtained by integrating Eq. (2.2) over the root domain LR:

$$T_a=\int_{L_R}S\left(h,h_\phi,z,t\right)dz=T_p\int_{L_R}\alpha\left(h,h_\phi,z,t\right)\beta\left(z,t\right)dz \qquad (2.3)$$

One factor among the others that cause a reduction in potential root water uptake is water stress. Water stress is a function of irrigation, which may lead to the insufficient or excessive supply of water to the crop. Root water uptake reduction due to water stress, α_1(h), is described using the model developed by Feddes et al. (1978):

$$\alpha_1(h) = \begin{cases} 0, & h > h_1 \; or \; h \le h_4 \\ \dfrac{h - h_1}{h_2 - h_1}, & h_2 < h \le h_1 \\ 1, & h_3 < h \le h_2 \\ \dfrac{h - h_4}{h_3 - h_4}, & h_4 < h \le h3 \end{cases} \tag{2.4}$$

where h_1, h_2, h_3, and h_4 are the threshold parameters. Water uptake is at the potential rate when the pressure head is between h_2 and h_3, drops off linearly when $h > h_2$ or $h < h_3$, and becomes zero when $h < h_4$ or $h > h_1$. Soil water pressure head parameters are available for tomato in HYDRUS-1D internal database, based on the work of Wesseling et al. (1991).

Further reduction in potential root water uptake can be caused by osmotic stress arising from the use of saline waters. Root water uptake reduction due to salinity stress, $\alpha_2(h_\phi)$, is described using the Maas's (1990) threshold and slope function. The threshold-slope salinity stress model is implemented in the standard HYDRUS modules as:

$$\alpha_2(h_\phi) = \begin{cases} 1, & EC \le EC_T \; or \; h_\phi \ge h_{\phi T} \\ 1 - (EC - EC_T)\,0.01s & EC > EC_T \\ or & or \\ 1 + (h_\phi - h_{\phi T})\,s^* & h_\phi < h_{\phi T} \end{cases} \tag{2.5}$$

respectively, where EC_T is the salinity threshold (dS m^{-1}), which corresponds to the value of the electrical conductivity (EC), below which root water uptake occurs without a reduction, h_ϕ is the corresponding threshold value given in terms of the osmotic head [L],

and s and s* are the slopes determining root water uptake decline per unit increase in salinity. We used the threshold-slope salinity parameters for tomatoes which are provided in HYDRUS-1D, based on work by Maas (1990).

We also assumed the multiplicative effects of the water and salinity stresses, i.e., $\alpha(h, h_{\phi}) = \alpha 1(h)\alpha 2(h_{\phi})$ (van Genuchten, 1987), so that different stress response functions could be used for the water and salinity stresses. The combined effect of the two stresses is always greater when the multiplicative approach is considered in comparison to the additive approach (Oster et al., 2011).

2.1.3 Solute Transport

A wide variety of models exists that can simulate water flow and solute transport in the unsaturated soil. Different packages or software of soil water movement, either specifically or with modules inside have been put forward and developed in recent several decades. Most vadose zone models consider the transport of only one solute, and severely simplify other chemical interactions. They usually use empirical adsorption isotherms to account for the comparatively complex processes like adsorption and cation exchange. They typically ignore other processes such as precipitation/dissolution and biodegradation or simulate these processes by invoking simplified first- or zero-order rate equations. Multiple solutes and their different interactions, such as precipitation/dissolution and competition for sorption sites, is considered by only a few models. (Šimůnek and Valocchi, 2002).

Simultaneous simulation of multiple solutes can be either independent of each other (P and/or K) or subject to the first-order decay reactions (nitrogen species). The first-order decay chain of urea is described as follows (Tillotson et al., 1980):

$$\begin{array}{ccccccc} & & \text{gas} & & & & \\ & & \uparrow & & & & \\ NH_2CONH_2 & \rightarrow & NH_4^+ & \rightarrow & NO_2^- & \rightarrow & NO_3^- \begin{array}{l} \nearrow N_2 \\ \searrow N_2O \end{array} \end{array} \qquad (2.6)$$

Urea is hydrolyzed by heterotrophic bacteria to form ammonium, which is sequentially nitrified by autotrophic bacteria to nitrite and nitrate. Ammonium is a volatile species that can also be present in the gas phase (gas). Since the nitrification from nitrite to nitrate is a much faster reaction than nitrification of ammonium, both nitrification reactions are often lumped, thereby neglecting the nitrite species.

One-dimensional advective-dispersive chemical transport under transient flow in a variably-saturated soil is defined in HYDRUS-1D as:

$$\frac{\partial \theta c_k}{\partial t} + \rho \frac{\partial \bar{c}_k}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c_k}{\partial z}\right) - \frac{\partial q c_k}{\partial z} + \phi_k - S c_{r,k} \qquad (2.7)$$

where θ is the volumetric water content [L^3L^{-3}], c, $\overline{C}$ and c_r are solute concentrations in the liquid phase [ML^{-3}], solid phase [MM^{-1}], and sink term [ML^{-3}], respectively, ρ is the soil bulk density [ML^{-3}], q is the volumetric flux density [LT^{-1}], D is the hydrodynamic dispersion coefficient [L^2T^{-1}], ϕ represents chemical reactions of solutes involved in a sequential first-order decay chain, such as nitrification of nitrogen species [$ML^{-3}T^{-1}$], and subscript k represents chemical species present in our study (EC, Urea, N-NO_3^-, and N-

NH_4^+). The last term of Eq. (2.7) represents a passive root nutrient uptake (Šimůnek and Hopmans, 2009).

The parameter ϕ in Eq. (2.7), represents nitrification of the N-NH_4^+ species to N-NO_3^-, and appears in Eq. (2.7) for N-NH_4^+ and N-NO_3^- species as follows, respectively:

$$\phi_{N-NH_4^+} = -\phi_{N-NO_3^-} = -\mu_{w,N-NH_4^+}\theta c_{N-NH_4^+} - \mu_{s,N-NH_4^+}\rho\bar{c}_{N-NH_4^+} \tag{2.8}$$

where μ_w and μ_s are the first order rate constants for solutes in the liquid and solid phases [T^{-1}], respectively. In our study, we considered only the nitrification process from N-NH_4^+ to N-NO_3^-. Other reactions, such as the nitrification from N-NO_2^- to N-NO_3^-, the volatilization of N-NH_4^+ and subsequent N-NH_4^+ transport by gaseous diffusion, mineralization of crop residues and soil humus, and the denitrification of N-NO_3^- into N-N_2 or N-N_2O, were neglected. Some of these reactions, such as mineralization of crop residues and soil humus, simply cannot be described with sequential first-order decay chain reactions, while others occur at a rate so fast that they are often lumped, such is the case of the nitrification from N-NO_2^- to N-NO_3^- (e.g., Hanson et al., 2006).

The standard HYDRUS solute transport module accounts for the relatively complex processes of adsorption and cation exchange by means of empirical linear or nonlinear adsorption isotherms. In our application, the adsorption isotherm relating c and $\bar{C}$ in Eq. (2.7) is described using the following linear equation:

$$\overline{c_k} = K_{d,k}\, c_k \tag{2.9}$$

where $K_{d,k}$ [L^3M^{-1}] is the distribution coefficient of a chemical species k.

The parameter C_r in the last term of Eq. (2.7) is the dissolved nutrient concentration taken up by plant roots in association with root water uptake, and is defined as:

$$c_r(z,t) = \min[c(z,t), c_{\max}] \qquad (2.10)$$

where c_{max} is a priori defined maximum concentration of the root uptake. We considered unlimited passive nutrient uptake for nitrogen species, which means that c_{max} was set to a larger concentration value than the dissolved concentrations, c, allowing all dissolved nutrients to be taken up by plant roots, and zero uptake for other species (EC), which means that c_{max} was set to zero. Since root nitrogen uptake likely involves both passive and active mechanisms (e.g., Šimůnek and Hopmans, 2009), considering only passive uptake will likely underestimate the total N uptake. By integrating passive nutrient uptake over the root domain, LR, we obtained an equation similar to Eq. (2.3), given as:

$$P_a(t) = T_p(t)\int_{L_R} \alpha(h, h_\phi, z, t)\beta(z,t)\min[c(z,t), c_{\max}]dz \qquad (2.11)$$

where P_a is the passive root nutrient uptake for the whole root domain ($ML^{-2}T^{-1}$) (Šimůnek and Hopmans, 2009).

Unidirectional or one dimensional (1D) water flow and solute transport models (Shao et al. 1998; Abbassi et al. 2003) are useful for a large number of applications. Water flow in the soil in pot/column study is essentially one-dimensional, i.e. vertical. Therefore, 1-D models can very well describe the process of water and salt movement in this kind of experiments. Hence, the HYDRUS-1D (Šimůnek et al. 2005) computer software which simulates one directional variably saturated-unsaturated water flow, heat movement and the transport of solutes is a good choice to be used in these type of studies.

2.1.3 HYDRUS-1D

Numerical simulation with HYDRUS has provided a fast and precise way for exploring soil water and solute transport processes laterally and vertically. The one, two, and three-dimensional HYDRUS (HYDRUS-1/2/3D) simulates water movement, solute transport and heat transfer in soils (Šimůnek et al. 1998, 2012; Šimůnek and Bradford 2008). The standard solute transport module of the HYDRUS-1D model (Šimůnek et al., 2008a), considers the transport of one or multiple solutes, which can be either independent or involved in sequential first-order decay reactions. This module has been used for a wide range of applications in research and irrigation management (e.g., Phogat et al., 2010; Yurtseven et al., 2013; Tan et al., 2014; Wang et al., 2018). It has also been used to simulate the fate of nutrients in soils by evaluating and comparing different irrigation and fertilization schemes for various crops (e.g., Hanson et al., 2006; Li et al., 2015; Xu et al., 2015). Kanzari et al (2018) validated the HYDRUS-1D in the field conditions for water flow and salts transport in a semi-arid region and stated that model is a good and reliable tool to simulate water flow and solute transport. Li et al (2014) and Sutanto et al. (2012) used the soil hydraulic parameters estimated by RETC as initial estimates and calibrated and validated the HYDRUS-1D to simulate water flow and solute transport in the direct seeded and transplanted rice fields. Qu et al. (2014) used HYDRUS-1D to inversely optimize soil hydraulic parameters using the data obtained for soil water content from field measurements to evaluate the variability of the soil water content. Lv et al. (2014) calibrated HYDRUS-1D by inversely optimizing soil hydraulic parameters using soil moisture measurements obtained from TDT probes.

2.2 Material and Methods

2.2.1 Experimental Setup and Measurements

A pot experiment was conducted in the greenhouse to mimic the water and salt movement using irrigation water with three levels of salinity, i.e. EC_{iw} of 0.6 (half-strength Hoagland solution), 2, and 4 dS m^{-1} in sandy loam soil. Plastic pots used in this experiment had 30 cm height, 28 cm diameter with a hole at the bottom center with the fiberglass wick to facilitate the leaching. A pre-determined amount of soil was added to each pot maintaining the bulk density of 1.25 g cm^{-3} (Amount of soil=Bulk density x Volume). The soil was added in small increments to obtain uniform packing. Soil particle size was analyzed using the hydrometer method in the laboratory. The electrical conductivity (µS m^{-1}) of soil was determined with an EC meter in an extract (1:5) after shaking for 3 mins. Three nitrogen application rates were imposed on each level of the salinity and all the treatments were replicated three times, which resulted in a total 27 pots (3 EC's × 3 N × 3 Rep) (See Chapter 1 for details).

Tomato crop was irrigated weekly for the first 7 weeks and every 4th day for the remaining growing season depending on the crop Water Use (ET_a). Et_a was measured gravimetrically in the pots by weighing the pots according to the method of FAO irrigation and drainage paper No. 56 by Allen et al. (1998) and the required quantity of water along with the extra water for leaching was added to the pots. Plants were fertilized with three nitrogen rates; 80, 100 and 120 percent of the recommendation for the pot experiment (100 mg Kg^{-1} soil) made by Novais et al 1991. Nitrogen was applied in the form of urea in three

equal splits i.e. with the first irrigation after transplantation, at the start of flowering and at the start of fruiting.

2.2.2 Modeling Approach

Modeling of water flow and solute transport was carried out for all experimental pots using HYDRUS-1D. The HYDRUS-1D software package (Šimůnek et al., 2008) numerically simulates one-dimensional (1D) variably saturated water flow, solute, and heat transport. Numerical simulations with HYDRUS has provided a fast and precise way for exploring soil water and solute transport processes laterally and vertically. The standard solute transport module of the HYDRUS-1D model (Šimůnek et al. 2013), considers the transport of one or multiple solutes, which can be either independent or involved in sequential first-order decay reactions. This module has been used for a wide range of applications in research and irrigation management (Phogat et al. 2010; Yurtseven et al. 2013; Li et al. 2014; Tan et al. 2014; Wang et al. 2018). It has also been used to simulate the fate of nutrients in soils by evaluating and comparing different irrigation and fertilization schemes for various crops (Hanson et al. 2006; Li et al. 2015; Xu et al. 2015).

Kanzari et al. (2018) validated the HYDRUS-1D in the field conditions for water flow and salts transport in a semi-arid region and stated that model is a good and reliable tool to simulate water flow and solute transport. Li et al. (2014) used the soil hydraulic parameters estimated by RETC as initial estimates and calibrated and validated the HYDRUS-1D to simulate water flow and solute transport in the direct seeded and transplanted rice fields. Qu et al. (2014) used HYDRUS-1D to inversely optimize soil hydraulic parameters using the data obtained for soil water content from the field

measurements to evaluate the variability of the soil water content. Li et al. (2014) calibrated HYDRUS-1D by inversely optimizing soil hydraulic parameters using soil moisture measurements obtained from TDT probes. Zerihun et al. (2005) used HYDRUS-1D to simulate soil water flow under basin irrigation to improve management and found the satisfactory performance of the model results.

The initial soil water content was set to field capacity. Atmospheric and free drainage conditions were defined as boundary conditions at the surface and the bottom of each pot, respectively. Time variable boundary conditions (ET) were specified using data collected during the greenhouse experiment. All the water lost from the pot was assumed as transpiration while the evaporation from the pot was neglected.

Soil hydraulic properties were predicted from neural network pedotransfer functions of Rosetta module coupled in HYDRUS-1D based on the soil particle size distribution (% sand, silt, and clay) and bulk density. The particle size distribution of the soil was obtained through laboratory experiment using the hydrometer method (Bouyoucos, 1927).

In the standard HYDRUS solute transport module, nitrate (N-NO_3^-) and ECsw were assumed to be present only in the dissolved phase (K_d = 0 cm^3g^{-1}), while ammonium (N-NH_4^+) was assumed to adsorb to the solid phase using a distribution coefficient K_d of 3.5 cm^3g^{-1}. The first order decay coefficients μ_w and μ_s, representing nitrification from N-NH_4^+ to N-NO_3^- in the liquid and solid phases, were set to be 0.2 d^{-1}. The parameters K_d, μ_w, and

μ_s were taken from a review of published data presented by Hanson et al. (2006), and represent the center of the range of reported values.

Root depth in the pots was set to 30 cm and the root density was assumed to decrease linearly with depth. Soil water pressure head parameters in the Feddes et al. (1978) model used the default values in the HYDRUS-1D internal database, i.e., h_1=-15, h_2=-30, h_3=-800 to -1500, h_4=-8000 cm. In the Maas (1990) function, the salinity threshold (EC_T) for tomatoes corresponds to a value of 2.5 dS m^{-1} for EC_e, and a slope (s) of 9. These values were converted internally in the GUI into the electric conductivity of soil water (at the field capacity) as follows: $EC_{sw}=ke*EC_e$, where *ke* is approximately 2 (Skaggs et al., 2006).

2.2.3 Model Calibration and Evaluation

Initially, the soil hydraulic parameters, including saturated (θs) and residual water content (θr), α, n and the saturated hydraulic conductivity (K_{sat}) were obtained using the neutral network pedotransfer functions of the Rosetta module based on the soil particle analysis and bulk density (Table 2.1).

Table 2.1. Initial and final values of soil hydraulic parameters

	θr (cm^3 cm^{-3})	**θs (cm^3 cm^{-3})**	**A (cm^{-1})**	***n***	**Ks (cm d^{-1})**	***l***
Initial	0.056	0.430	0.016	1.467	46.350	0.500
Final (mean)	0.027	0.430	0.073	1.467	76.022	0.231

θs is saturated water content (cm^3 cm^{-3}); θr is residual water content (cm^3 cm^{-3}); α is air entry parameter (cm^{-1}); n is pore size distribution index (-); Ks is saturated hydraulic conductivity (cm/day); and *l* is pore connectivity (-).

Note: We fitted the soil hydraulic parameters θ_r, α, n, K_{sat}, and *l* simultaneously.

Both the graphical and statistical approaches were used for the evaluation of model performance. In the graphical or visual check, measured and simulated values were plotted in the same graph. Different statistical techniques such as the coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE) and Nash–Sutcliffe modeling efficiency (NSE) were used in this study to compare modeling results with the observed values. The mean absolute error (MAE) given by

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |S_i - O_i|}{n} \qquad (2.12)$$

describes the difference between observed values (Oi) and model simulations (Si) in the units of a particular variable, with N being the number of observations. The root mean square error (RMSE) given by

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(S_i - O_i)^2}{n}} \qquad (2.13)$$

where RMSE is the square root of the mean square error, also given in the units of a particular variable. In general, RMSE ≥ MAE. The closer the root mean square error (RMSE) is to 0, the more accurate the model is.

The degree in which the RMSE value exceeds MAE is usually a good indicator of the presence and extent of outliers. The Nash–Sutcliffe modeling efficiency (NSE) (Nash and Sutcliffe, 1970) is calculated by

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (Oi - Si)^2}{\sum_{i=1}^{n} (Oi - \overline{O})^2} \qquad (2.14)$$

where Oi is the observed value, Si is the simulated value and $\overline{O}$ is the mean of observed values. *NSE* can range from –∞ to 1. An efficiency of 1 (*NSE* = 1) means a perfect match

between the simulated and the measured data while efficiency of 0 (*NSE* = 0) indicates that the model predictions are as accurate as the mean of the measured data. Whereas an efficiency of less than 0 (*NSE<0)* shows that the measured mean is a better predictor than the model. Therefore, the closer *NSE* is to 1, the more accurate the model is.

2.3 Results and Discussions

One of the major weaknesses of modeling efforts is the lack of calibration and validation by experimental data. In this study, the implementation of a pot experiment that evaluated water dynamics, provided a means of calibrating and validating the HYDRUS-1D model. The HYDRUS-1D model simulation results were evaluated against measured data using the statistical measures discussed above to provide information about how well the model approximated the collected experimental data.

2.3.1 Cumulative Drainage Flux

The observed cumulative drainage fluxes and the corresponding values simulated by the HYDRUS-1D during the entire growing periods are illustrated in Figures 2.1, 2.2 and 2.3 for different levels of irrigation water salinity and nitrogen application rate (One replicate out of three). The HYDRUS-1D simulated cumulative drainage fluxes were generally in very good agreement with the measured values in all the treatments. Table 2.2 shows the statistical parameters on the model performance and the strong correlation between simulated and measured values were observed. In general, the MAE and RMSE values increased while the R^2 values decreased with the increasing level of irrigation water salinity.

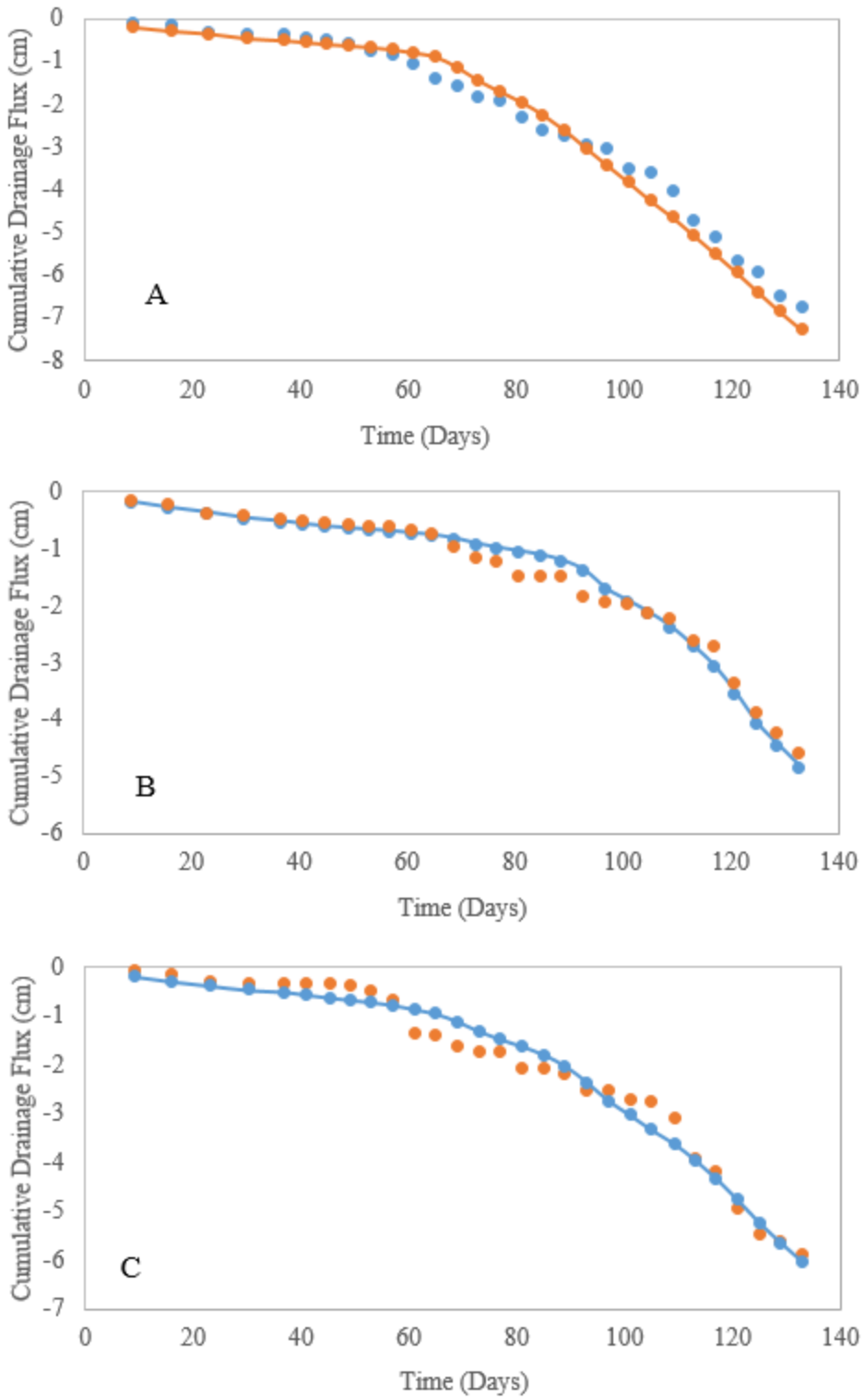

Figure 2.1 Simulated and observed cumulative drainage fluxes for the Control salinity treatment at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed —●— Simulated)

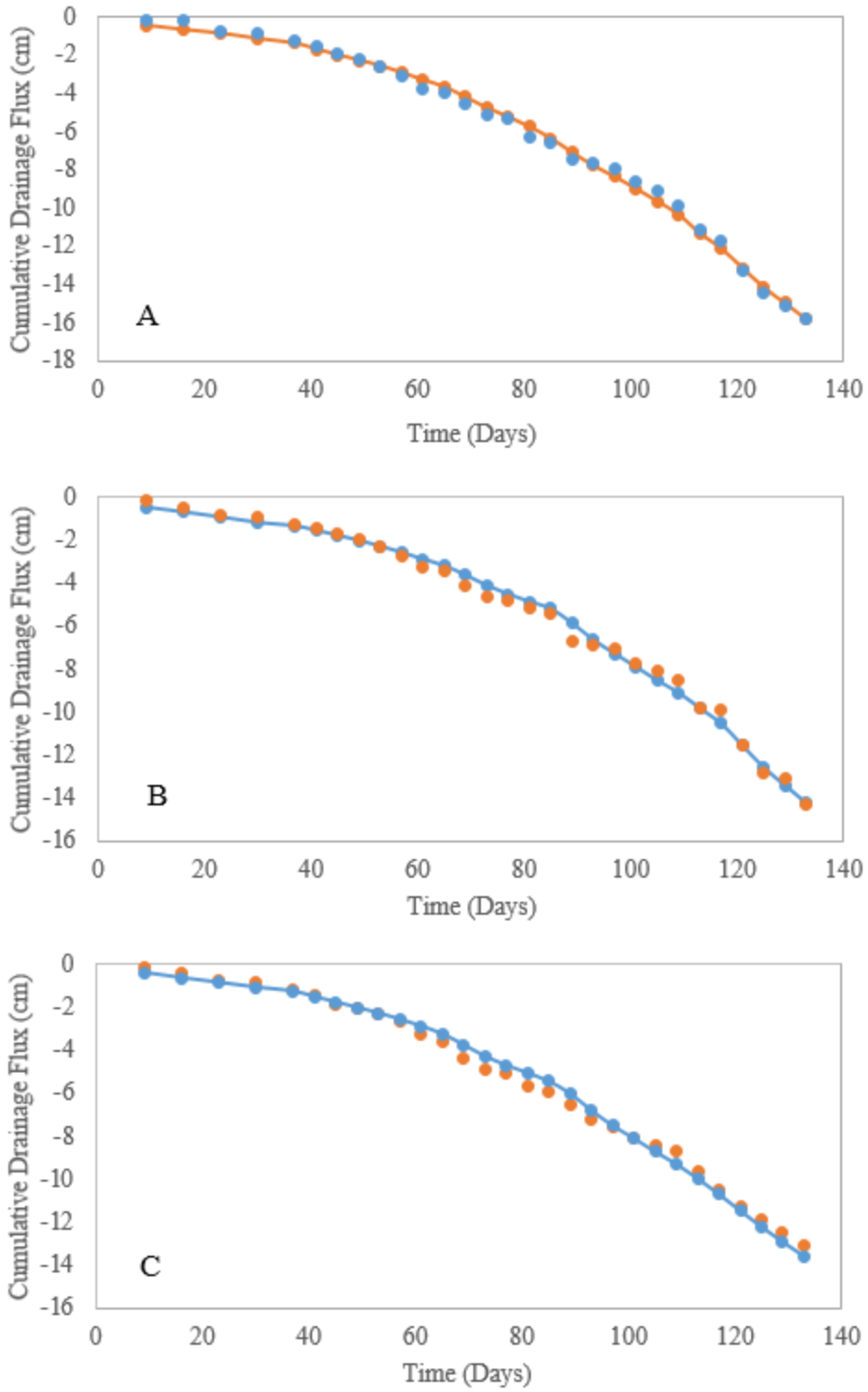

Figure 2.2. Simulated and observed cumulative drainage fluxes for the irrigation water salinity of 2 dS m^{-1} at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed —●— Simulated)

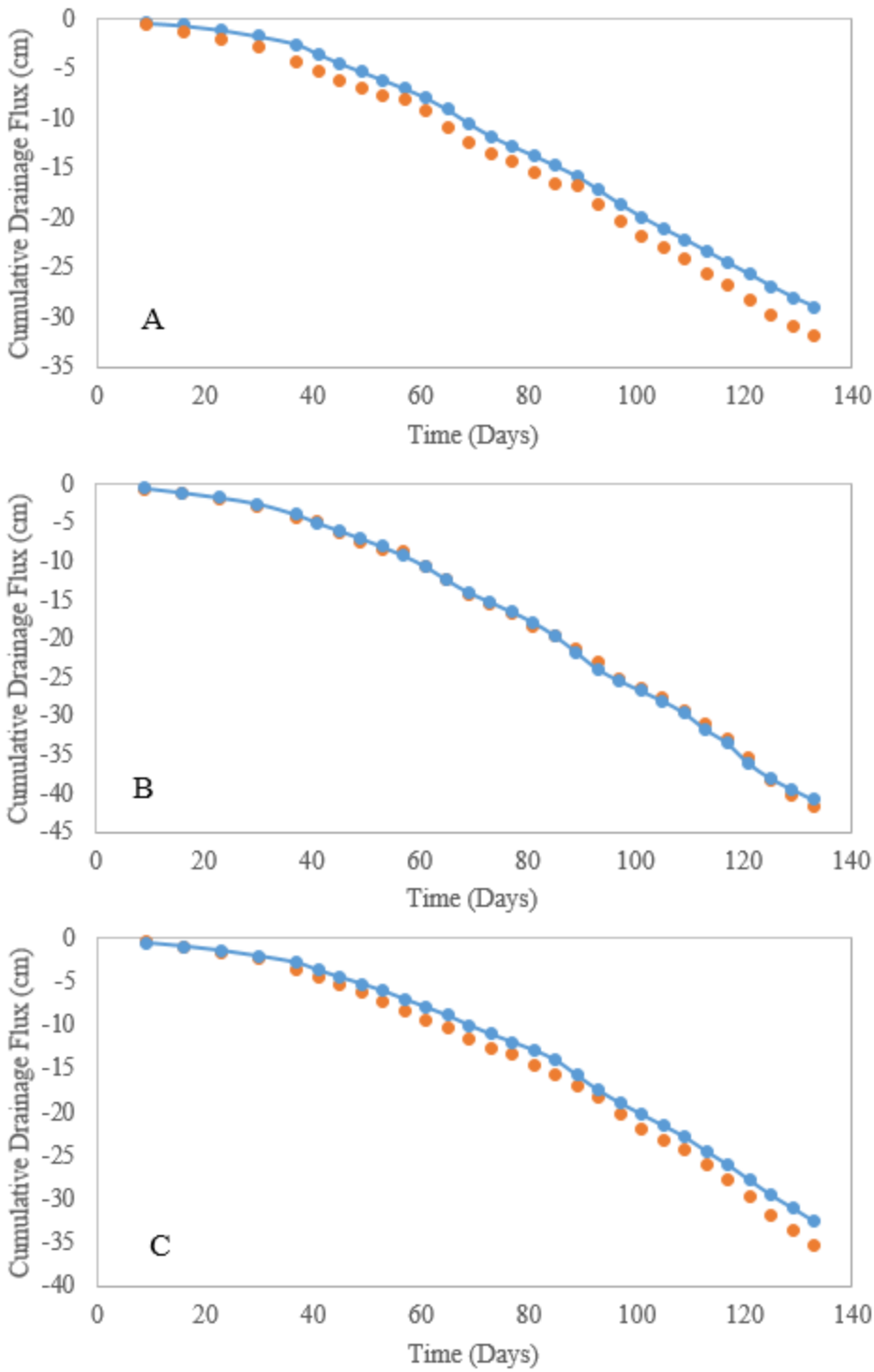

Figure 2.3 Simulated and observed cumulative drainage fluxes for the irrigation water salinity of 4 dS m-1 at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed —●— Simulated)

An overall regression coefficient (R^2) of 0.987 was obtained between the simulated and measured drainage fluxes for all the 27 pots (9 treatments x 3 Replication) while the maximum and minimum R^2 were 0.994 and 0.975 respectively. The RMSE values for the control ranged from 0.31 to 0.34, which indicates the reliability of the model for the water movement in the soil. The RMSE values for the 2 dS m^{-1} treatment were also less than 0.5, but for the dS m^{-1} treatment, it was (above or near one) slightly higher. The NSE value ranged from 0.970 to 0.992 while the mean NSE was 0.984 for the cumulative drainage fluxes.

Our results agreed with the HYDRUS-1D model performance reported by Wang et al. (2018), who reported R^2 values ranging from 0.944 to 0.999 for the vertical infiltration of water in different types of soil. Similar results (RMSE values ranging from 0.10 to 0.20) have been reported for the drainage fluxes by Phogat et al. (2010), who irrigated the rice crop with irrigation water of different salinity levels, and compared the measured and HYDRUS-1D model predicted values.

The model performance for control treatment was better than that for 2 dS m^{-1} treatment. The worst goodness-of-fit between measured and simulated drainage fluxes occurred for the 4 dS m^{-1} treatment.

Table 3.2. Results of the statistical analysis between the measured and simulated cumulative drainage fluxes obtained for different irrigation water salinity and nitrogen application levels

	S0			**S1**			**S2**			**Min.**	**Max.**	**Mean**
	N0	**N1**	**N2**	**N0**	**N1**	**N2**	**N0**	**N1**	**N2**			
R^2	0.979	0.975	0.976	0.993	0.993	0.992	0.990	0.990	0.994	0.975	0.994	0.987
MAE (cm)	0.26	0.25	0.27	0.33	0.36	0.33	1.25	0.83	0.70	0.25	1.25	0.51
RMSE (cm)	0.31	0.33	0.34	0.42	0.47	0.41	1.53	1.13	0.93	0.31	1.53	0.65
NSE (cm)	0.978	0.970	0.974	0.992	0.991	0.991	0.976	0.989	0.992	0.970	0.992	0.984

Table 3.3. Results of different statistical analysis between the measured and simulated volumetric water content obtained for different irrigation water salinity and nitrogen application levels

	S0			**S1**			**S2**			**Min.**	**Max.**	**Mean**
	N0	**N1**	**N2**	**N0**	**N1**	**N2**	**N0**	**N1**	**N2**			
R^2	0.891	0.923	0.953	0.945	0.922	0.957	0.816	0.899	0.968	0.816	0.968	0.919
MAE (cm^3 cm^{-3})	0.014	0.013	0.011	0.010	0.015	0.009	0.019	0.014	0.006	0.006	0.019	0.012
RMSE (cm^3 cm^{-3})	0.019	0.018	0.016	0.013	0.020	0.012	0.022	0.017	0.008	0.008	0.022	0.016
NSE (cm^3 cm^{-3})	0.81	0.873	0.889	0.92	0.844	0.93	0.668	0.823	0.963	0.668	0.963	0.858

Good agreement between the observed and simulated values of cumulative drainage fluxes indicates that HYDRUS-1D model can be satisfactorily used to predict leaching requirement for different irrigation water salinity levels to avoid the salt build up in the root zone.

2.3.2 Volumetric Water Contents

The observed volumetric water contents and the corresponding simulated values by HYDRUS-1D are illustrated in Figures 2.4, 2.5 and 2.6 for different levels of irrigation water salinity and nitrogen application rates. The HYDRUS-1D simulated volumetric water contents were in satisfactorily good agreement with the measured values in all the treatments as indicated by the statistical parameters (Table 2.3). In general, the MAE and RMSE values increased while the R^2 values decreased with the increase in irrigation water salinity.

The R^2 value for the volumetric water contents varied from 0.816 to 0.968 with an average value of 0.919. Gonçalves et al. (2006) reported the R^2 value of 0.60 for the volumetric water contents by fitting a linear model to the data in his study of water and solute transport in soil lysimeters irrigated with waters of different quality. Our results showed better correspondence between the measured and simulated values than that of Gonçalves et al. (2006), as we used the option of inverse parameter optimization in our study to obtain the calibrated values of different soil hydrodynamic parameters (Šimůnek et al., 2005).

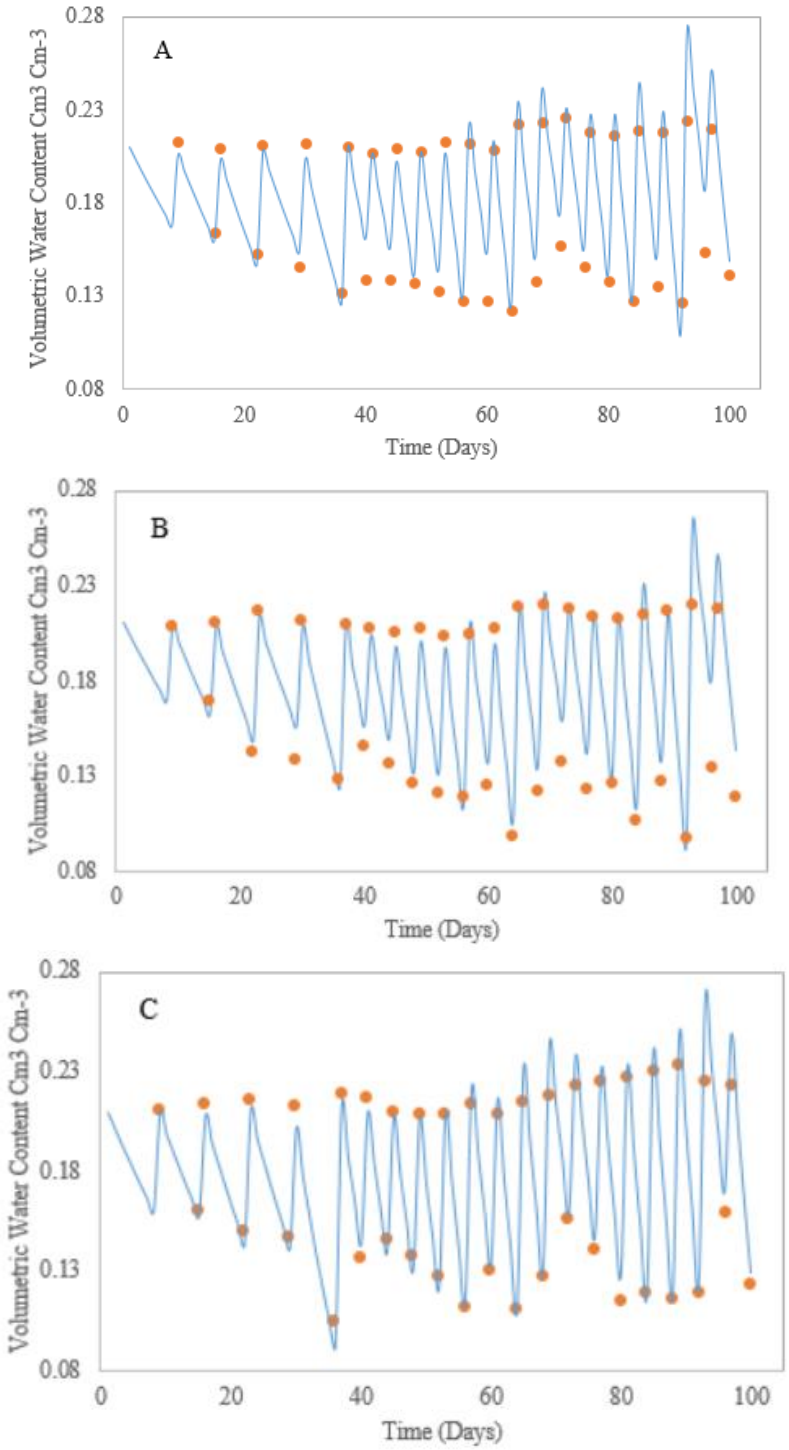

Figure 2.4 Simulated and observed volumetric water content for the Control salinity treatment at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed ——— Simulated)

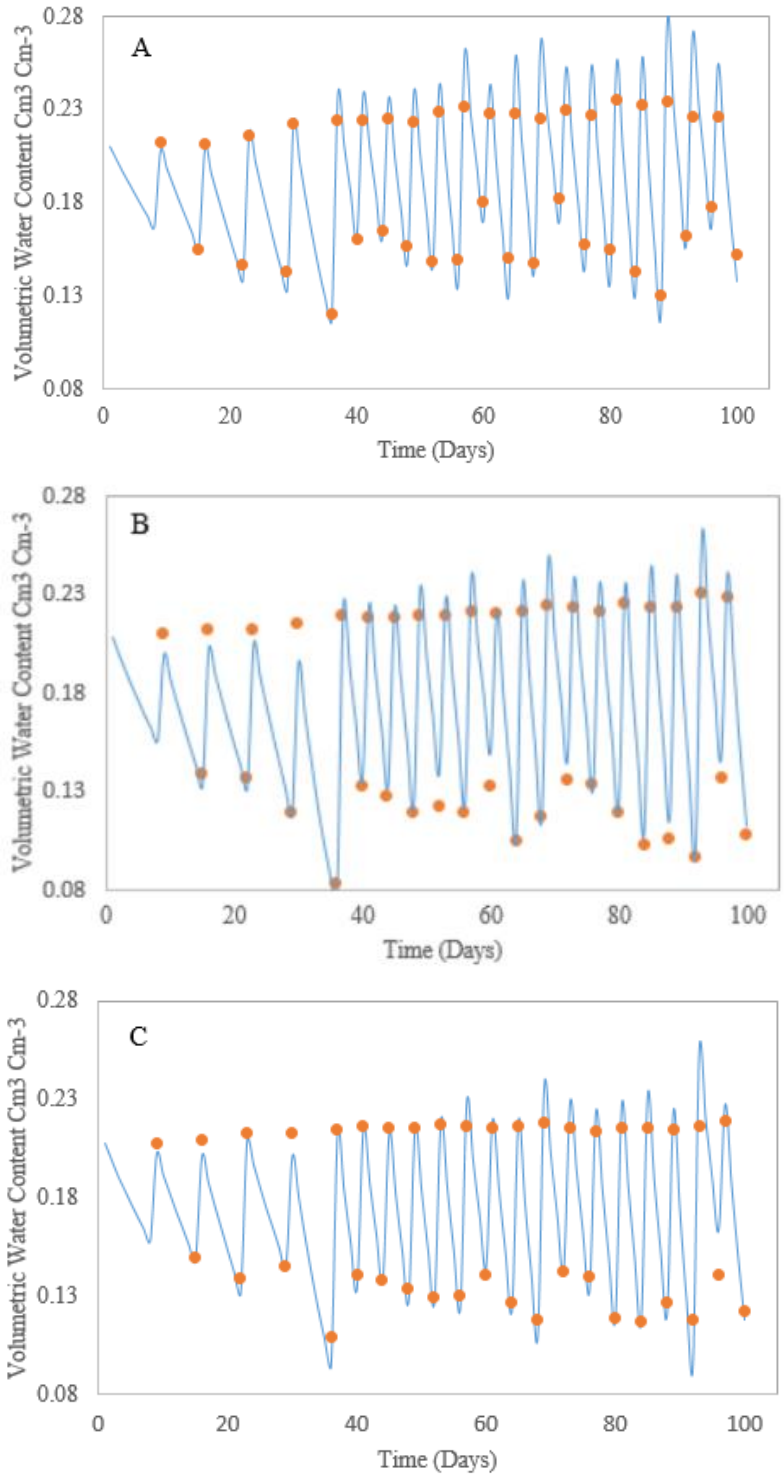

Figure 2.5. Simulated and observed volumetric water contents for the irrigation water salinity of 2 dS m^{-1}at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed —— Simulated)

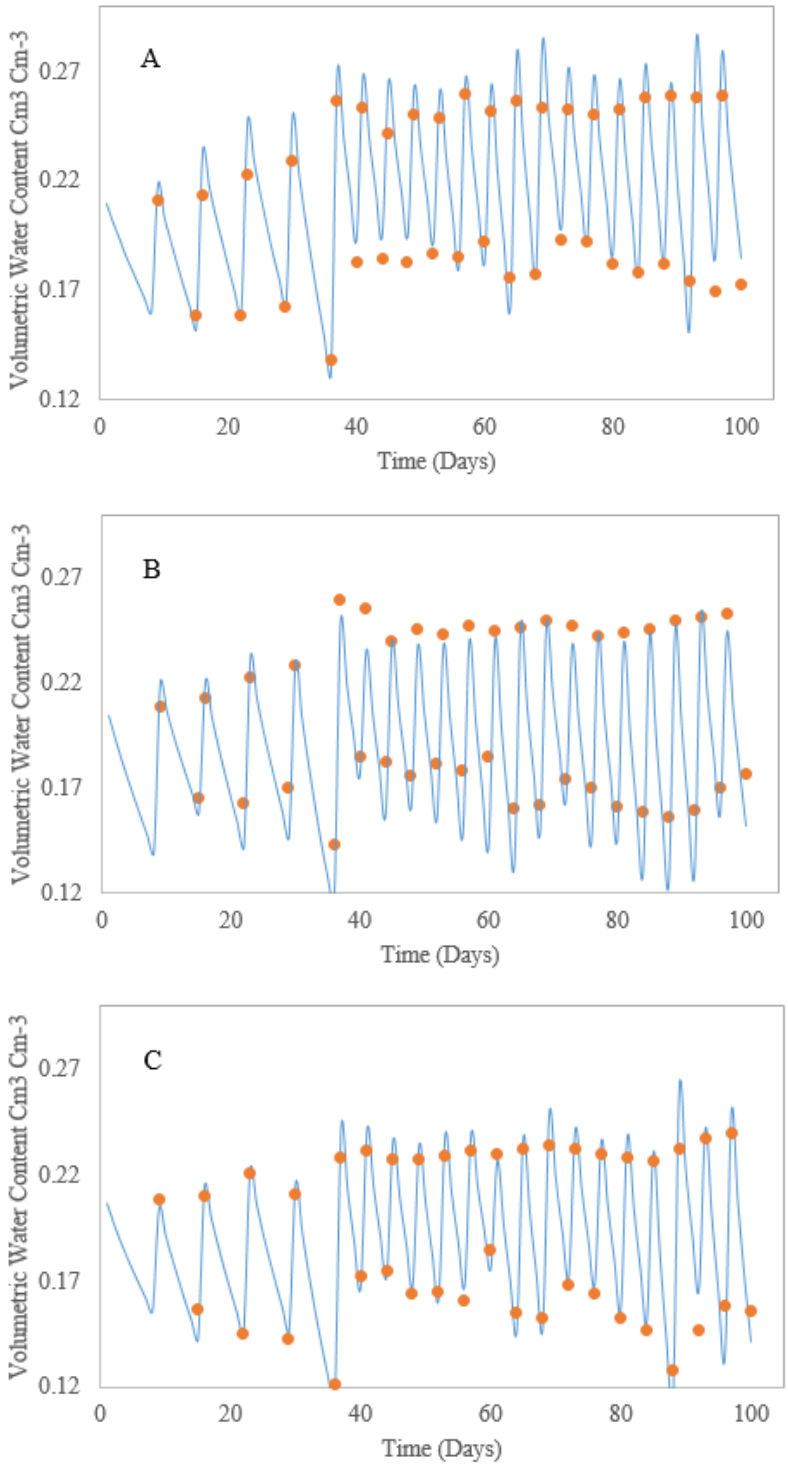

Figure 3.6. Simulated and observed volumetric water contents for the irrigation water salinity of 4 dS m^{-1}at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed —— Simulated)

The RMSE values for all the experimental treatments oscillated from 0.008 to 0.022 with a mean value of 0.016. Tan et al. (2013) reported no significant variations between measured and simulated water contents between paddy plots under different N fertilization. The RMSE values were smaller than those observed (0.10 to 0.12) by Kanzari et al. (2018) who validated that the HYDRUS-1D in the field conditions for water flow and salts transport in a semi-arid region.

Some small differences between measured and simulated water contents can be explained by the fact that the average water contents were obtained by weighing the pots and subtracting the plant biomass, which might not be very accurate due to the fact that plant biomass cannot be precisely measured in the pots. However, the simulated water contents, overall, agreed well with measured water contents since the statistical parameters for the model performance were found to be good.

2.3.3 Salinity of Drainage water

Root zone salinity is an important factor affecting plant water uptake and crop yield. Salinity concentration above crop salinity tolerance level can significantly reduce crop yield and crop water use efficiency. The observed and HYDRUS-1D predicted electrical conductivities of drainage water were compared. The observed salinity increased with time in all the treatments, while salinity stress developed earlier in treatment having irrigation water salinity of 4 dS m^{-1} than that in the other two treatments. The simulation was done on a daily basis for the whole growing season but the values were compared for the selected days when drainage water was collected from the pots.

Results of different statistical parameters for the model performance on the salinity of drainage water are given in Table 2.4. The predicted values of drainage water EC showed a good agreement with the measured data. However, the model predicted higher salinity in almost all the treatments (Figures 3.7, 3.8 and 3.9) in comparison with the observed salinity.

The R^2 between the observed and predicted salinity concentrations in drainage water varied from 0.910 to 0.975 with a mean value of 0.942. Overall R^2 decreased with the increasing concentration of applied irrigation water salinity level. Mean MAE value for all treatments was 1.17 while the maximum and minimum MAE values were 1.87 and 0.35 respectively. The RMSE values for the electrical conductivity of drainage water ranged from 0.43 to 2.16 with an overall average of 1.36. The NSE values for the electrical conductivity of drainage water were closer to 1 and ranged from 0.632 to 0.969 with an average value of 0.814, indicating that the model can reasonably predict the observed salinity at the bottom of the pots.

HYDRUS-1D predictions of root zone salinity during the growing season are satisfactory and the model can be successfully used to predict the salinity buildup in the root zone due to saline water irrigation.

Table 3.4. Results of different statistical analysis between the measured and simulated electrical conductivity of drainage water obtained for different irrigation water salinity and nitrogen application levels

	S0			**S1**			**S2**			**Min.**	**Max.**	**Mean**
	N0	**N1**	**N2**	**N0**	**N1**	**N2**	**N0**	**N1**	**N2**			
R^2	0.975	0.947	0.969	0.922	0.923	0.935	0.910	0.948	0.948	0.910	0.975	0.942
MAE (dS m^{-1})	0.35	0.919	0.62	1.81	1.87	1.86	1.12	0.83	1.19	0.35	1.87	1.17
RMSE (dS m^{-1})	0.43	1.08	0.73	2.07	2.16	2.15	1.42	1.01	1.26	0.43	2.16	1.36
NSE (dS m^{-1})	0.969	0.845	0.934	0.695	0.632	0.700	0.844	0.891	0.818	0.632	0.969	0.814

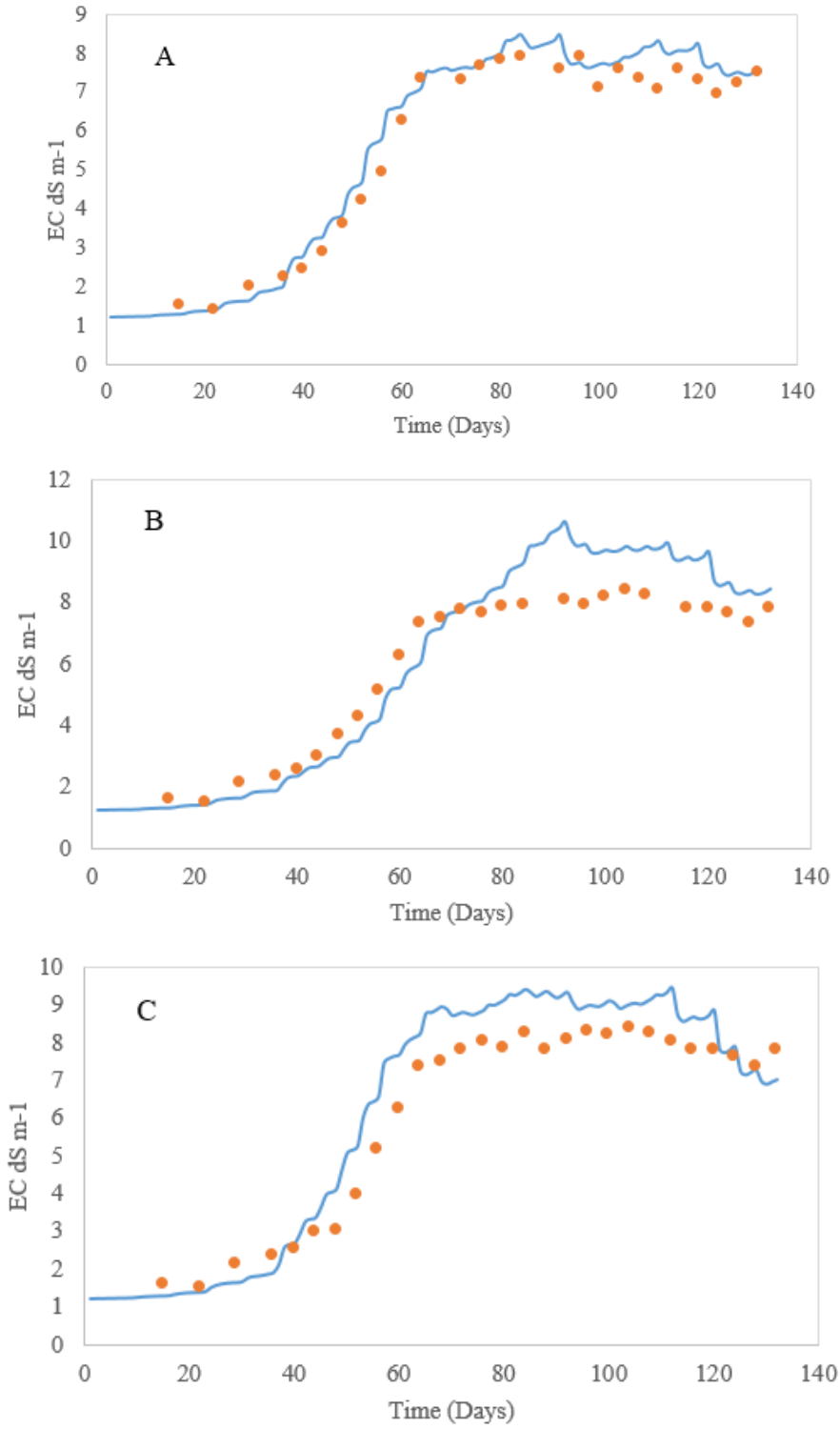

Figure 2.7. Simulated and observed electrical conductivities of the drainage water for the Control salinity treatment at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed —— Simulated)

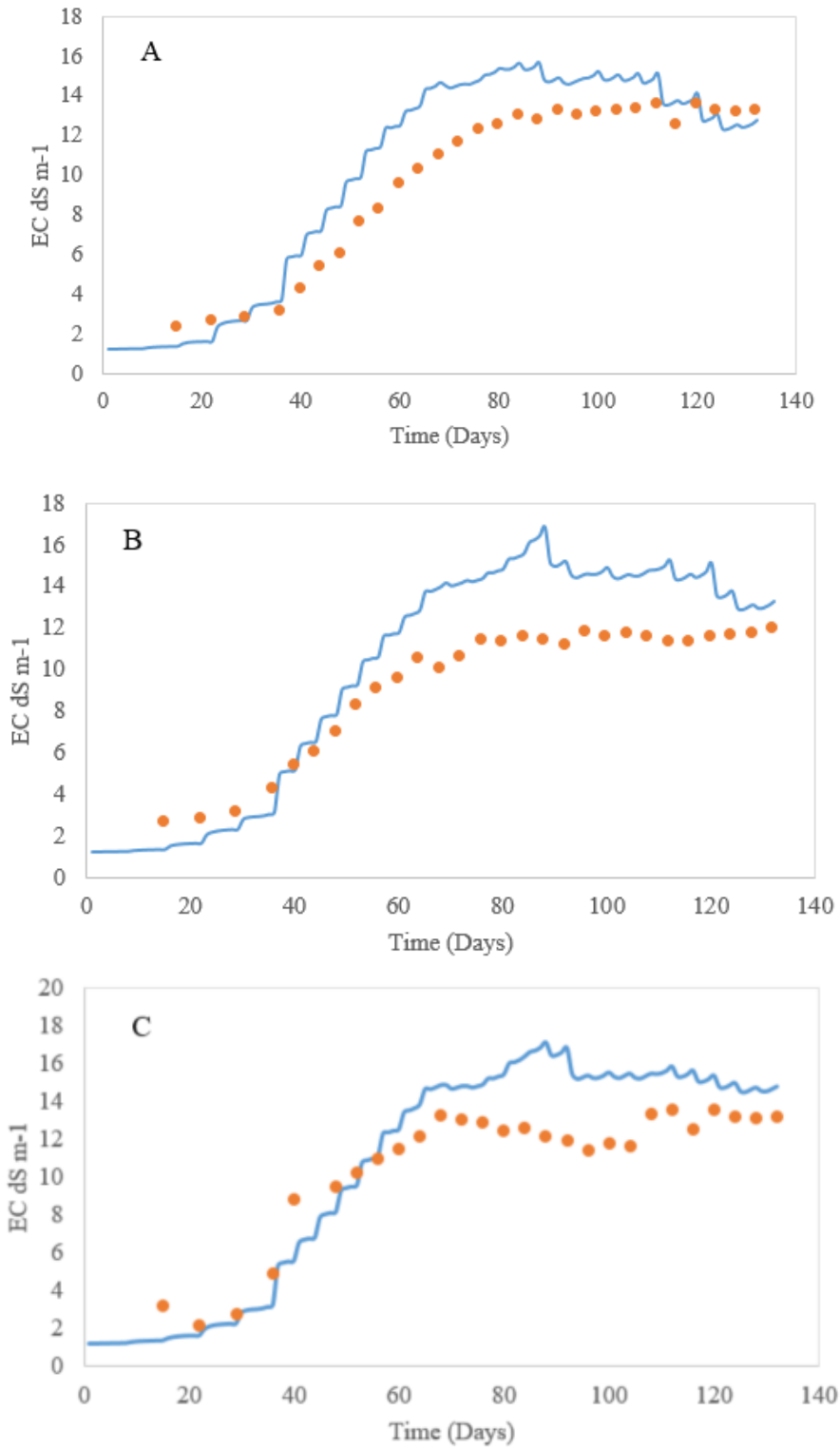

Figure 2.8. Simulated and observed electrical conductivities of the drainage water for the irrigation water salinity of 2 dS m^{-1} at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed ——— Simulated)

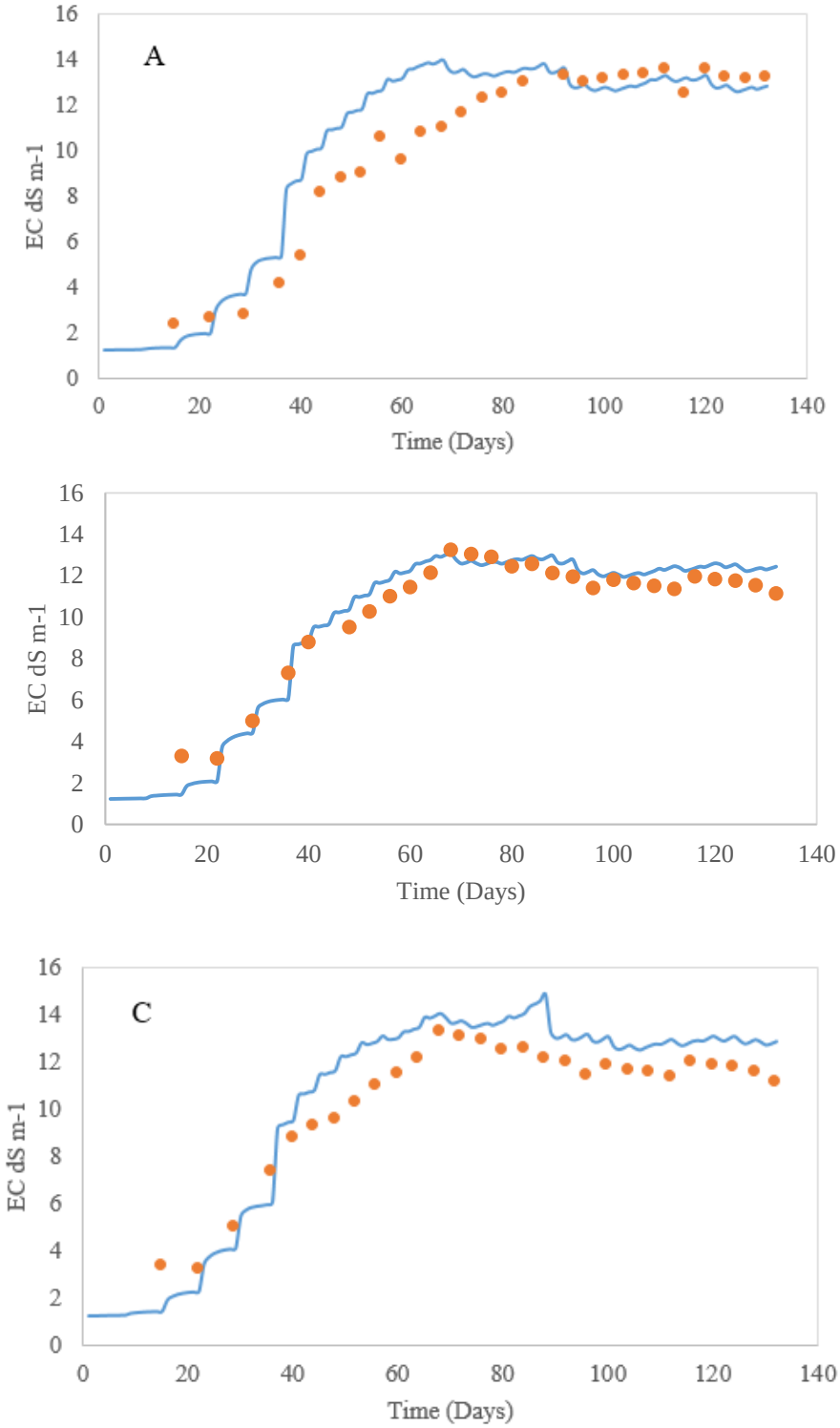

Figure 2.9. Simulated and observed electrical conductivities of the drainage water for the irrigation water salinity of 4 dS m^{-1} at A: 80% nitrogen, B: 100% Nitrogen and C: 120% nitrogen application (● Observed —— Simulated)

3.3.3 Relative Crop Yield

The relative yield was estimated from a function of actual and potential crop water uptake without any stress using the equation given below proposed by Jensen (1968).

$$Y_r = \frac{Y}{Y_m} = \frac{T_i}{T_p} \qquad (2.15)$$

where Yr = relative yield; Y = actual yield; Ym = maximum attainable yield without any stress; Ti = actual transpiration (crop water uptake) and Tp = potential transpiration (Potential crop water uptake)

Potential crop water uptake predicted by the HYDRUS-1D for the control treatment was used to compare the mean actual crop water uptake for the 2 and 4 dS m^{-1} irrigation water salinity treatments and then calculated the relative yield.

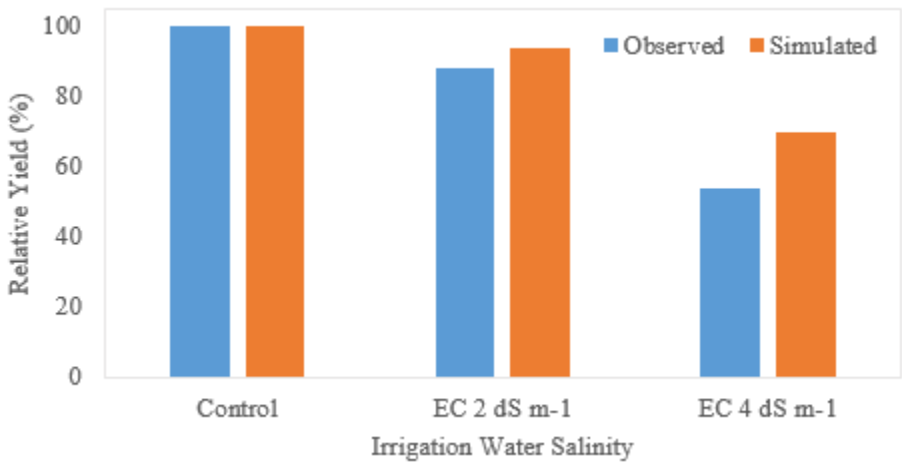

Figure 2.10 Simulated and observed relative yield for different irrigation water salinity levels

HYDRUS-1D predicted yields were then compared with the observed actual yields. The predicted yields were slightly higher than the observed yield. In comparison with the

control treatment, the observed yield reductions in 2 and 4 dS m^{-1} irrigation water salinity treatments were 12.01 and 46.36%, respectively (Table 1.5), while the reduction in relative yields predicted by HYDRUS-1D were 6.1 and 30.3%, respectively.

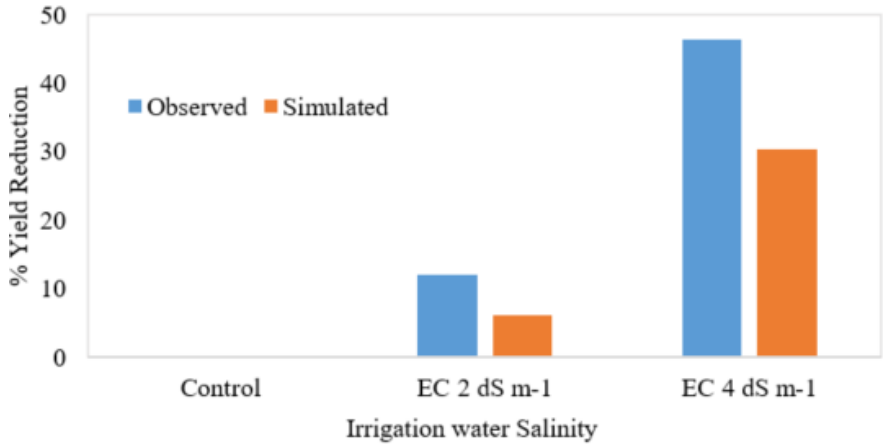

Figure 2.11 Simulated and observed yield reduction for different irrigation water salinity levels.

2.4 CONCLUSIONS

Our results indicated close agreement between the observed and model predicted values of cumulative drainage flux, volumetric water content, and salinity of drainage water. Observed and HYDRUS-1D predicted yields based on the crop water uptake also seems reasonable. This suggests that HYDRUS-1D can be used with confidence for simulating crop water uptake, relative yields and salinity buildup and can be meritoriously used to evaluate of the effects of saline water irrigation. The results thus obtained can be very helpful in decision making for the planning and management of saline irrigation water for tomato production under different soil and climatic conditions.

Chapter 3

HYDRUS-1D Simulations for other Scenarios

ABSTRACT

Pre-determination of water and salt transport in the root zone and their uptake by the plants in response to soil water and salinity under varying climatic and edaphic, factors is essential for the adoption of suitable salinity control measures. Prolonged and expensive field experiments, especially those conducted with a high number of treatments, can be evaluated through a highly accepted and well-proven model to sharpen the field tests and lower their overall costs.

Study of the different scenarios is an important tool for the management of the irrigation and fertilization scenarios after model calibration and validation. These type of studies can help us in decision making to plan, manage and execute different irrigation and fertilization strategies. Calibrated and validated HYDRUS-1D model was used to simulate the effect of different levels of irrigation water salinity and different nitrogen application rates on soil salinity buildup, crop water, and nutrient uptake. The aim of this study was to identify nitrogen application rate that was sufficient to optimize yield at different irrigation water salinity level keeping in view the nitrate leaching. We simulated six different levels of irrigation water salinity ranging from 1.5 to 5 ds m^{-1} and six levels of nitrogen application ranging from 100 Kg/ha to 350 Kg/ha.

3.1 Introduction

3.1.1 Irrigation with Low-quality saline waters

Arid and semi-arid regions are characterized by a climate with no or insufficient rainfall to sustain agricultural production and irrigation with surface or ground water is unavoidable for successful crop production in these regions of the world. Increase in food demand to feed the rapidly growing world population and reduction in the availability of fresh-water resources have led to the extensive utilization of lower-quality water for irrigation purpose (Raij et al., 2016) and the use of low-quality water to irrigate crops is more common in the arid and semi-arid areas (Rasouli et al., 2013). As an alternative to fresh-water, use of low-quality waters for irrigation, due to the presence of high concentrations of soluble salts, can pose serious threats to agricultural sustainability and food security by creating salt buildup in the root zone if used inappropriately. It may result not only in the decrease of crop yield (Rasouli et al., 2013) but also a reduction in soil water infiltration capacity (Kanzari et al., 2018). Such soil degradation can reduce soil fertility, leading to decreased crop yields.

3.1.2 Modeling as a tool for future prediction

Pre-determination of salt and water movement through the soil profile and prediction of crop response to soil water and salinity, subject to various climatic, edaphic, and agronomic factors (Ferrer and Stockle, 1999) is essential for the adoption of suitable salinity control measures. Almost throughout the world, agricultural research has the main focus on soil and water resource conservation. Salinization/sodification and nitrate leaching to aquifers are two of the leading threats to the sustainability of agricultural

production and environment. Therefore, it is now very important to develop agricultural management practices to cope with salinity while at the same time, optimizing nitrogen use to decrease its leaching potential.

Prolonged and expensive field experiments, especially those conducted with a high number of treatments, can be evaluated through a highly accepted and well-proven model to sharpen the field tests and lower their overall costs. A long-term analysis regarding water and fertilizer management can quickly be achieved by using computer models to evaluate the effects of different quality irrigation waters and fertilization approaches. Use of process-based simulation models that consider and integrate various climate, crop, and soil factors, have been reported as a useful tool for evaluating the best management practices for the use of low-quality saline irrigation waters (e.g., Ramos et al., 2012).

Different analytical and numerical models are available to evaluate the soil salinity, leaching, and nutrient uptake, etc. (e.g., Johnssonet et al., 1987; Hutson and Wagenet, 1991; Simunek et al., 2008; Doltra and Munoz, 2010). Study of different scenarios is a useful tool for the management of the irrigation and fertilization scenarios after model calibration and validation. Thus in this chapter, we employed the HYDRUS-1D that was calibrated and tested by our greenhouse experimental data to simulate the effects of various combinations of water quality and nitrogen application rate on water and nutrient uptake by the plants as well as the nitrate leaching below root zone. The aim was to identify nitrogen application rate that was sufficient to optimize yield at different irrigation water salinity level keeping in view the nitrate leaching.

3.2 Material and Methods

We simulated six different levels of irrigation water salinity (1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 ds m^{-1}) and six levels of nitrogen application rate (100, 150, 200, 250, 300 and 350 Kg/ ha). Urea fertilizer was used as source of nitrogen in this simulation. Significant HYDRUS-1D processes that were involved in our experiments has been described briefly in the previous chapter.

3.2.1 Input Data

3.2.1.1 Initial Conditions and Boundary Conditions

The initial soil water content was set to field capacity. Atmospheric and free drainage conditions were defined as boundary conditions at the surface and the bottom, respectively. The time variable boundary conditions were specified using meteorological data obtained from the California Irrigation Management Information System (CIMIS) for the station number 44 (U. C. Riverside). Potential evaporation (ET_p) and potential transpiration (T_p) fluxes for the time variable upper boundary condition were calculated from potential evapotranspiration (ET_p) using Beer's law that partitions the solar radiation component of the energy budget via interception by the canopy (Ritchie, 1972):

$$T_p = ET_P(1 - e^{-k*LAI}) \qquad (4.1)$$

$$E_p = ET_P e^{-k*LAI} \qquad (4.2)$$

where ET_P, T_p, and E_p are potential evapotranspiration, transpiration and evaporation fluxes [LT^{-1}], respectively, LAI is the leaf area index [-],and k is a constant governing the radiation extinction by the canopy [-] as a function of sun angle, the distribution of plants,

and the arrangement of leaves which is reported to be 0.60 for the tomato by Zhang et al. (2014) based on the work of Higashide (2009). Reference crop evapotranspiration (ET_p), was estimated using the following equation:

$$ET_P = ET_O * K_C \qquad (3.3)$$

where ET_O is reference evapotranspiration and K_C is the crop coefficient. K_C values of 0.6, 0.88, 1.15 and 0.9 for the four crop growth stages (Initial, 25 days; Developmental, 30 days; Mid, 40 days and late, 25 days) were obtained from the FAO Irrigation and Drainage Paper No. 56 (Crop Evapotranspiration; guidelines for computing crop water requirements) (Allen et al., 1998).

Additional water requirement to leach the salts below the root zone was calculated using the leaching requirement equation developed by Rhoades (1974):

$$LR = \frac{EC_{iw}}{5EC_e^* - EC_{iw}} \qquad (3.4)$$

where LR is the leaching requirement, EC_{iw} (dS m^{-1}) is the electrical conductivity of irrigation water, and EC_e^* (dS m^{-1}) is the linearly averaged root zone salinity of saturated extract for a given crop, and is related to Maas' salt tolerance EC thresholds for various crops (2.5 dS m^{-1} for tomato).

From the HYDRUS-1D simulations, we obtained the cumulative water and nutrient uptake by the plants and cumulative leaching of different nitrogen species. As the HYDRUS-1D doesn't have the module to predict the yield in response to nitrogen fertilization, we used nitrogen uptake curve reported by (Tei et al., 2002) to predict the

yield. Nitrogen uptake curve relating the total nitrogen uptake by the plants and total above ground biomass is given below.

$$N_{upt} = 45.3\ DW^{0.673} \qquad (3.5)$$

where N_{upt} is the total nitrogen uptake by the plant while DW represents the total above ground biomass produced by the plant.

3.2.2 Statistical analysis

Statistical analysis of the data (ANOVA) was conducted using two-factor full factorial design without replication and differences between the different treatment combinations were compared for significance using a Revised Least Significant Difference (LSD) test at 0.05 levels as described by Snedecor and Cochran (1989).

3.3 Results and Discussion

3.3.1 Crop yield

Both irrigation water salinity and nitrogen application rates significantly affected the crop yield (Fig 3.1). The increasing level of irrigation water salinity decreased the crop yield while crop yield increased with the increasing nitrogen application rate. Significantly highest crop yield was obtained with the highest level of nitrogen application (300 Kg/ha) and the lowest level of irrigation water salinity but it was not significantly different from that of the same level of irrigation water salinity and lower nitrogen application rate of 300 Kg/ha, neither different from that of the irrigation water salinity of 2 ds m^{-1} and the highest nitrogen application rate (300 Kg/ha).

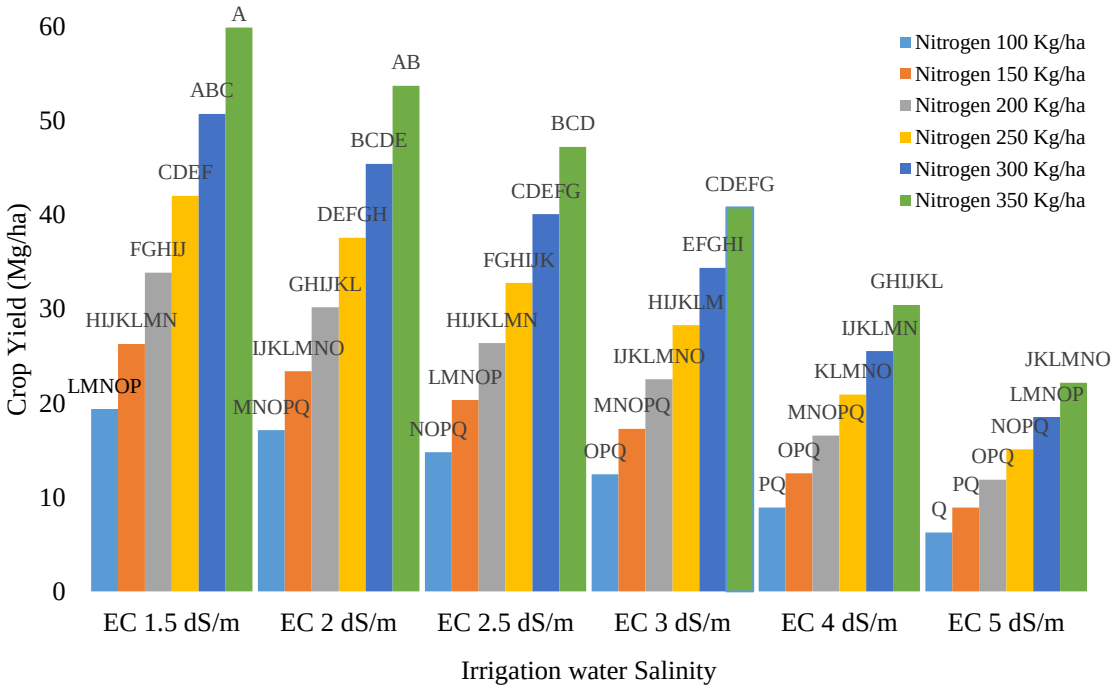

Figure 3.1. Crop yield (Mg/ha) as influenced by irrigation water salinity and nitrogen level
Means of the treatments followed by similar letter(s) do not differ significantly from one another.

The lowest yield was obtained with the highest level of irrigation water salinity (5 dS m^{-1}) at a nitrogen application rate of 100 Kg/ha, followed by the irrigation water salinity of 4 dS m^{-1} at the lowest level of nitrogen application rate of 100 Kg/ha. The yields from these two combinations were lower than, but not statistically different from that of 3 dS m^{-1} water at the nitrogen application rate of 100 Kg/ha. Badr et al. (2016) found significant differences among applied nitrogen levels on tomato crop yield, and nitrogen uptake and water use efficiency affected by planting geometry and level of nitrogen in an arid region in their study. They found that nitrogen supply tended to increase tomato fruit yield significantly up to the highest level of nitrogen (300 Kg/ha) application with all planting methods, but the magnitude of increase was relatively lower when the N application rate is over 240 Kg /ha. Increased nitrogen application also increased tomato nitrogen uptake with maximum nitrogen removal from the field under 300 Kg N/ha, which resulted in the higher fruit yield and dry biomass. However, nitrogen use efficiency consistently decreased as nitrogen application rate increased.

Similar results have been reported in another study of tomato yield, nitrogen uptake and use efficiency in relation to nitrogen fertilization levels by Giuffrida et al. (2012). They found 90% rise in yield from 0 Kg/ha to 500 Kg/ha nitrogen application and the yield response was related to the increase in fruit unit weight rather than the number of fruits per plant. A similar trend was recorded for the dry biomass at the rise of nitrogen supply. Parisi et al. (2006) conducted a study to evaluate the effects of different levels of nitrogen fertilization on yield and fruit quality in processing tomato. They found an increase in yield in response to increasing application of nitrogen fertilization from 0 to 250 Kg/ha, but there

were no significant differences in yield when N application was above 200 Kg/ha for the marketable and rotten yield. They also found an increase in the number of red ripe fruits per square meter up to 200 Kg-N/ha and then decreased, but further increase in N application rate (250 Kg/ha) did not result in significantly higher number of red ripe fruits per square meter.

Reduced yield can be related to the negative influence of salinity on the total nitrogen uptake by plants and soil nitrogen availability, leading to the reduced plant growth and consequently, lower yield (van Hoorn et al. 2001). High salinity is also often accompanied by high chlorine concentrations, which may leads to reduced nitrate uptake (Miura, 2013), resulting in reductions in plant growth and yield. Reductions in yield can also be recognized as the effect of damage to macromolecules including chlorophyll, leading to reduced photosynthetic activity and leaves senescence (Grattan and Grieve, 1998). The decrease in growth and yield can also be due to the increase in root to shoot ratio and nutritional deficiencies as a result of salinity induced stress on the plant (Djanaguiraman and Prasad, 2013).

3.3.2 Root zone salinity

Root zone soil salinity was only influenced by different levels of irrigation water salinity. As expected nitrogen application rates had little or no effect on the soil salinity. With applied leaching fraction, the model predicted daily root zone salt concentration for different levels of irrigation water salinity is depicted in Figure 3.2. In all the treatments, root zone salinity increased with the application of irrigation water salinity. At the end of the experiment, maximum root zone salinity was 5.67, 6.83, 7.80, 8.58, 9.69 and 10.44 for

irrigation water salinity of 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 5.0 dS/m^{-1} respectively, at 50 cm depth. The salinity build up was very rapid in treatments receiving irrigation water of higher salinity levels. There was only little increase in root zone salinity with the application of irrigation water of 1.5 dS/m^{-1} and for initial 80 days, it just reached up to 1.5 dS/m^{-1}. On the other hand, the same level of soil salinity (1.5 dS/m^{-1}) was achieved with irrigation water salinity of 4 and 5 dS/m^{-1} in just 40 and 45 days respectively. Min et al. (2016); Rahil et al. (2013); and Nagaz et al. (2013) also reported an increase in soil salinity with the application of saline irrigation water in their studies.

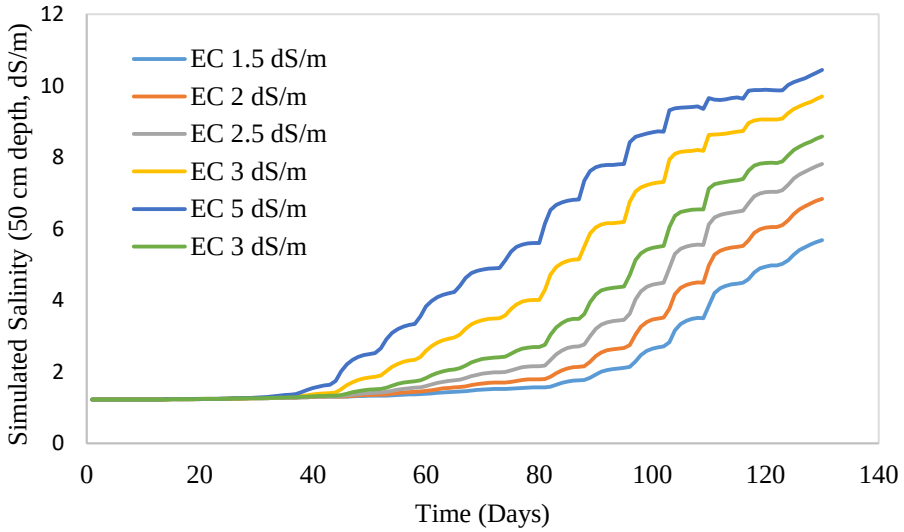

Figure 3.2. Simulated root zone soil salinity at 50cm depth as influenced by irrigation water salinity

3.3.3 Nitrate Uptake by the Plant

Different levels of irrigation water salinity and nitrogen application rates both significantly affected the nitrate uptake by the plants. Significantly highest nitrate uptake was observed in the treatment with the lowest level of irrigation water salinity and the

highest rate of nitrogen fertilization rate, followed by the irrigation water salinity of 2 dS m^{-1} at the highest rate of nitrogen application, and the latter was not statistically different (P>0.05) from the nitrogen application rate of 300 Kg/ha at the lowest level of irrigation water salinity i.e. 1.5 dS m^{-1}.

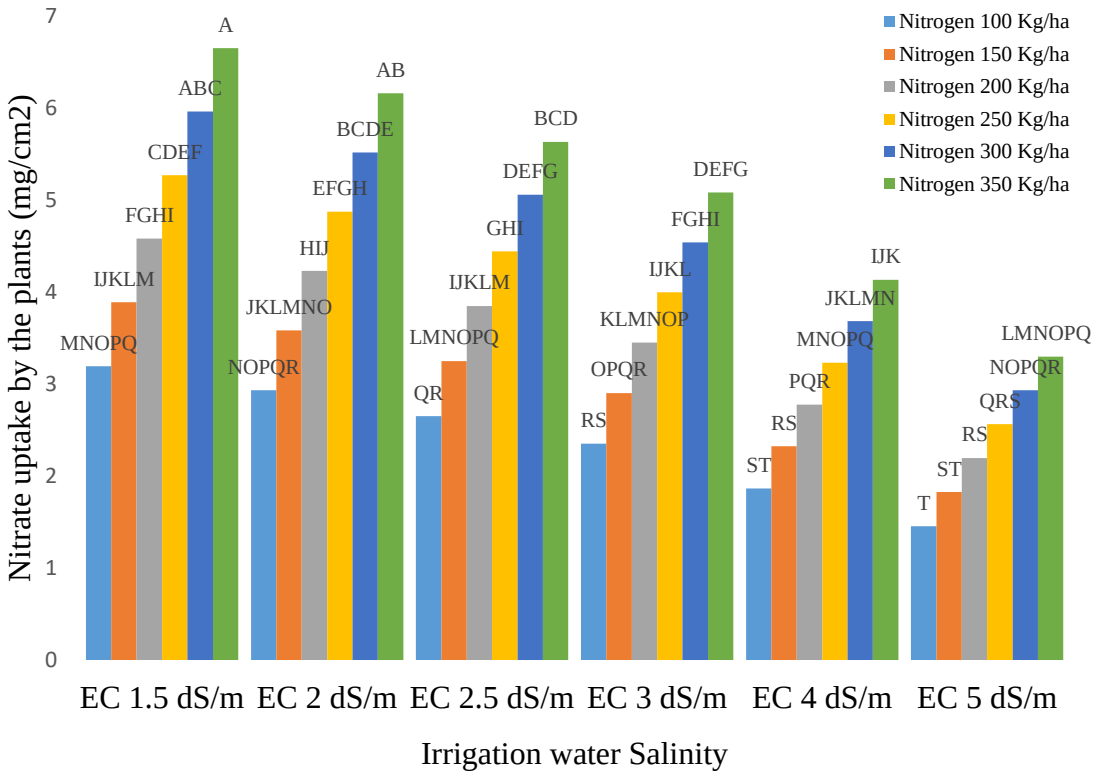

Figure 3.3. Effects of irrigation water salinity and nitrogen application rate on nitrate uptake by the plants (mg/cm^2)

Means of the treatments followed by similar letter(s) do not differ significantly from one another.

Similar results have been reported by Flores et al. (2002) for the reduction in nitrate uptake by the plants under salinity stress. They indicated that the reduction was higher in plants with roots fully exposed to saline condition in comparison with plants with all their

root system in non-saline solution and plants receiving the control solution in one half of the root system and saline solution in the other half.

Pessarakli and Tucker (1988) reported that reduction in total nitrogen uptake at various salinity levels. There is a direct competitive effect between NO_3^- and Cl^- uptake under salinity stress and salinity induces a reduction in the nitrate uptake in many plants especially under the condition of high Cl^- concentrations (Miura, 2013). Along with this competitive effect, state of the membrane and/or membrane proteins also reduces the nitrate uptake by changes in the plasmalemma integrity (Frechilla et al., 2001). The reduction in nitrate uptake can also be attributed to the reduced water uptake by the plants due to salinity stress.

3.3.3 Nitrate Leaching below the root zone

Nitrate leaching was significantly affected by the irrigation water salinity while different nitrogen application rates significantly affected the nitrate leaching only at the highest level of irrigation water salinity, while at other N application rates for all other levels of irrigation water salinity, nitrate leaching was not significantly different. Highest nitrate leaching was found in the treatment with 350 Kg/ha nitrogen application with irrigation water salinity of 5 dS m^{-1} followed by the nitrogen application of 300 Kg/ha at the same level of irrigation water salinity. Lowest nitrate leaching was observed in treatment with 100 Kg/ha nitrogen application with the lowest level of irrigation water salinity, and this was not statistically different from the treatments with different nitrogen application rates and the lowest level of irrigation water salinity.

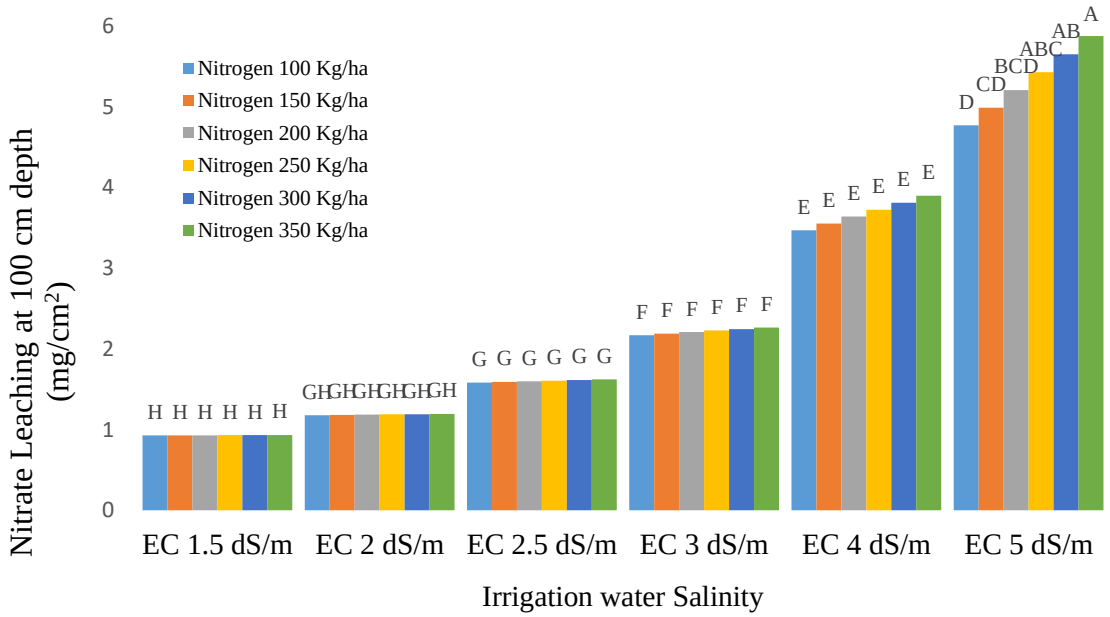

Figure 3.4. Effects of irrigation water salinity and nitrogen application rate on *nitrate leaching (mg/cm²)*
Means of the treatments followed by similar letter(s) do not differ significantly from one another.

So far no research has been conducted to evaluate the effects of N application rate and Irrigation water salinity on nitrate leaching in crop production. In a lysimeter study under the greenhouse conditions for the Bermuda turf grass, Bowman et al. (2006) observed the effect of nitrate leaching as influenced by irrigation water salinity and reported that neither the nitrogen level nor the irrigation water salinity affected the nitrate leaching.

3.3.4 Ammonium Uptake by the Plant

Ammonium uptake by the tomato plants was significantly different with different levels of irrigation water salinity as well as different rates of nitrogen application. Highest ammonium uptake was observed in treatments irrigated with water of highest salinity and fertilized with the highest nitrogen application rate, followed by the treatment irrigated

with the irrigation water salinity of 2 and 2.5 dS m^{-1} and fertilized with the highest N application rate, but this was at par with the plants irrigated with the irrigation water salinity of 3 dS m^{-1} and highest level of nitrogen fertilization. Ammonium uptake by the plants at the lowest level of nitrogen fertilization didn't differ significantly for different levels of irrigation water salinity, while the lowest ammonium uptake was recorded in plant irrigated with the highest level of irrigation water salinity.

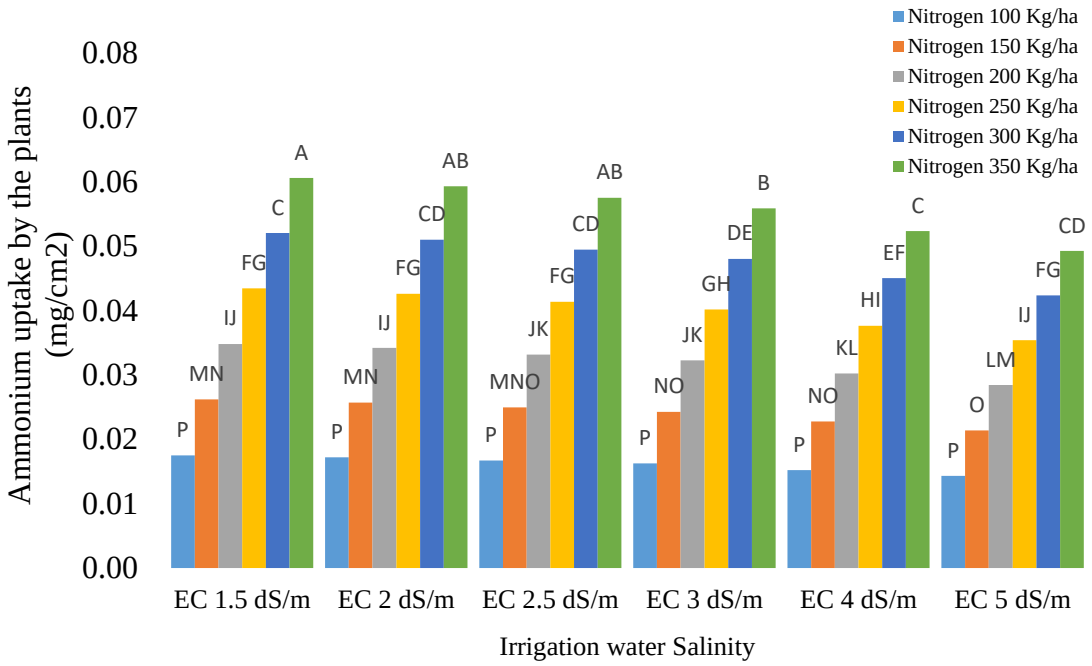

Figure 3.5 Effects of irrigation water salinity and nitrogen application rate on ammonium uptake by the plants (mg/cm2)

Means of the treatments followed by similar letter(s) do not differ significantly from one another.

Bowman et al. (2006) reported that Ammonium uptake reduced in both high and low nitrogen fertilized plants and this reduction was similarly affected by salinity. Total ammonium absorption by high-N cultures ranged from 42% to 76% of the total supplied

nitrogen depending on the salt level. Inhibition in ammonium uptake due to salinity stress could be the result of direct competition with sodium and to the depolarizing effect of sodium chloride on the plasmalemma (Miura, 2013).

3.3.5 Urea Uptake by the Plant

Urea uptake by the tomato plants was significantly affected by the level of irrigation water salinity as well as the nitrogen application rate. The highest urea uptake was found in plants irrigated with the salinity level of 1.5 and 2 dS m^{-1} with the highest rate of nitrogen fertilization which was statistically similar to that of plants irrigated with 2.5 dS m^{-1} irrigation water salinity with the highest nitrogen application rates followed by the plant irrigated with water of 3 dS m^{-1} at the highest nitrogen as application rate and the treatments irrigated with the lowest irrigation water EC and the nitrogen fertilization rate of 300 Kg/ha.

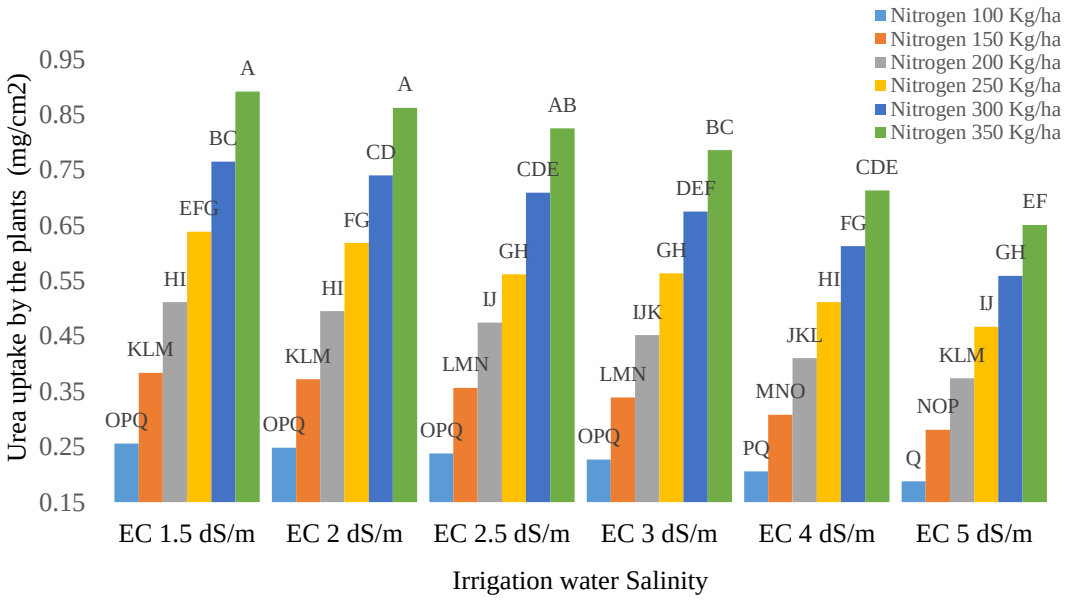

Figure 3.6. Effects of irrigation water salinity and nitrogen application rate on *urea uptake by the plants (mg/cm2)*

Means of the treatments followed by similar letter(s) do not differ significantly from one another.

3.4 CONCLUSIONS

The following conclusions could be drawn from the present HYDRUS-1D simulation studies:

1. Both irrigation water salinity level and nitrogen application rate significantly affected the crop yield. The highest yield was predicted with the lowest level of irrigation water salinity. Reduction in yield can be related to the salinity buildup in the root zone that lead to the reduced water and nutrient uptake.
2. Root zone salinity increased gradually with the application of saline irrigation water. Root zone salinity developed earlier with the irrigation water of higher salinity level. To avoid the salinity buildup, it is recommended to use the potable water at least once at or before the flowering to leach the salts below the root zone. This will also help to minimize the yield loss.
3. Both nitrate uptake and leaching increased with the increasing application of nitrogen. It has been reported that high nitrate concentrations accumulate in the edible parts of vegetables with excess application of nitrogen and their consumption can cause adverse effects on human health. Excessive N fertilizer yield/economic benefit gains but increase the nitrate content in fresh produces to potentially toxic level for human health. Therefore it is recommended to use nitrogen at or below the rate of 300 Kg/ha to avoid both the environmental pollution and human health risks.

Summary and Conclusion

Today, we are living in world whose population is increasing at an alarming rate and there is immense need to fulfil the food requirement of this growing population. Tomato is the second most valuable as well as widely grown crop after potato and requires enormous amount of water and nitrogen for optimal growth, quality, and yield. The overall objective of this study was to evaluate and develop best management practices to use saline water irrigating tomato and identify optimal nitrogen application rate in saline water irrigated soil, with the goal to improve tomato production by increasing root water and nutrient uptake in areas with water shortage.

A pot experiment was conducted in the greenhouse at the University of California, Riverside to investigate the effect of three salinity and three nitrogen levels on tomato growth, yield, and fruit quality (Chapter 1). The experiment used a completely randomized design (CRD) with three replications. Three salinity treatments (1. Control; irrigation with half-strength Hoagland solution, 2. Irrigation water salinity of 2 dS m^{-1}, 3. Irrigation water salinity of 4 dS m^{-1}) were factorially combined with three nitrogen levels (80, 100 and 120% of recommended N application rate). The results showed that the effects of various levels of salinity were highly significant ($P < 0.01$) on different growth parameters (shoot length, shoot fresh weight, shoot dry weight and leaf area index), as well as yield parameters (number of fruits per plant, fruit length, fruit volume, individual fruit weight, and total tomato yield per plant), while the effects of nitrogen levels and their interactions with salinity levels were found non-significant on these parameters. As regards the quality

parameters of fruit firmness and fruit total soluble solids, the effects of salinity levels, nitrogen levels and their interactions with each other were highly significant ($P < 0.01$).

Chapter 2 focused on the calibration and validation of HYDRUS-1D model. We used the drainage volumes and concentrations collected from the pots to inversely calibrate the soil hydraulic parameters, including saturated (θs) and residual water content (θr), α, n and the saturated hydraulic conductivity (K_{sat}). Validation of the calibrated parameters was done with the recorded data of water content and bottom salinity. Along with visual checks, observed values were compared with the HYDRUS-1D simulated values using different statistical techniques such as the coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE) and Nash–Sutcliffe modelling efficiency (NSE) to evaluate the model performance. Our results indicated a close agreement between the observed and model predicted values of cumulative drainage flux, volumetric water content, and salinity of drainage water.

HYDRUS-1D doesn't have a module to predict the yield in response to nitrogen application. The relative yield was obtained as a function of actual and potential crop water uptake. The observed and HYDRUS-1D predicted yields based on the crop water uptake also seems reasonable. This suggests that HYDRUS-1D can be used with confidence for simulating soil water regimes and salinity build-up due in saline water irrigates soil. Hence, HYDRUS-1D model was further used with confidence to evaluate of the effects of saline water irrigation and the results thus obtained can be very helpful in decision making for the planning and management of saline irrigation water for tomato cultivation under different soil and climatic conditions (Chapter 3).

Study of the different scenarios is an important tool for the management of the irrigation and fertilization scenarios after model calibration and validation. In chapter 3, we used the calibrated and validated HYDRUS-1D model to simulate the effect of different levels of irrigation water salinity and different nitrogen application rates on soil salinity buildup, crop water, nutrient uptake and crop yield. We simulated six different levels of irrigation water salinity ranging from 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 ds m^{-1} and six levels of nitrogen application ranging from 100, 150, 200, 250, 300 and 350 Kg/ha. To specify the time variable boundary conditions, meteorological data was obtained from the California Irrigation Management Information System (CIMIS) for the station number 44 (U. C. Riverside). From the model simulations we obtained the cumulative water and nitrogen uptakes by the plants, as well as cumulative leaching of different nitrogen species. The yield was predicted using the nitrogen uptake cure (Tei et al., 2002) that relates the total nitrogen uptake by the plants and total above ground biomass.

Both salinity and nitrogen application rates significantly affected the crop yield. Highest yield was predicted with the lowest level of irrigation water salinity, and the yield decreased with increasing salinity level of irrigation water. Root zone salinity increased gradually with the application of saline irrigation water. Root zone salinity developed earlier with the irrigation water of higher salinity level. To avoid salinity buildup, it is recommended to use potable water at least once at or before the flowering to leach the salts below the root zone. This will also help to minimize yield loss. If potable water is not available, saline irrigation water having electrical conductivity of 3 dS m^{-1} or lower can be used for tomato production with some yield reduction.

Both nitrate uptake and leaching increased with the increasing nitrogen application rate. It is unlikely to use excessive fertilizer to achieve any gain in terms of yield/economic benefits but increase the nitrate content can potentially affect human health. Therefore it is recommended to use nitrogen at or below 300 Kg/ha to avoid both the environmental pollution and human health risks.

This research was done in the greenhouse. Field environmental conditions, water management, and fertilizer application schemes may be quite different from greenhouse experiment. Thus future work is necessary to use field measurement data to assess the model capability to predict irrigation water salinity and nitrogen application rate on soil condition and crop growth as affected by management practices. Such efforts will help to develop useful tools for develop best management practices to sustain agricultural production in arid and semi-arid region.

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Appendixes

Appendix 1. Analysis of variance table for shoot length

Source	DF	SS	MS	F	P
Salinity	2	168.92	84.46	4.72	0.013
Nitrogen	20	14.70	7.35	0.41	0.665
Salinity*Nitrogen	4	2.18	0.54	0.03	0.998
Error	18	804.50	17.87		
Total	26	990.31			

Grand Mean 40.648 CV 10.40

Appendix 2. Analysis of variance table for shoot fresh weight

Source	DF	SS	MS	F	P
Salinity	2	902061	451030	66.28	0.000
Nitrogen	2	36867	18433	2.71	0.093
Salinity*Nitrogen	4	4049	1012	0.15	0.961
Error	18	122492	6805		
Total	26	1065469			

Grand Mean 742.90 CV 11.10

Appendix 3. Analysis of variance table for shoot dry weight

Source	DF	SS	MS	F	P
Salinity	2	10829.6	5414.79	37.48	0.000
Nitrogen	2	404.1	202.07	1.40	0.272
Salinity*Nitrogen	4	117.8	29.45	0.20	0.932
Error	18	2600.6	144.48		
Total	26	13952.1			

Grand Mean 98.170 CV 12.24

Appendix 4. Analysis of variance table for leaf area

Source	DF	SS	MS	F	P
Salinity	2	46098	23048.9	20.75	0.000
Nitrogen	2	426	212.9	0.19	0.826
Salinity*Nitrogen	4	352	88.0	0.08	0.988
Error	18	80022	1111.4		
Total	26	126897			

Grand Mean 123.02 CV 27.10

Appendix 5. Analysis of variance table for total fruit yield per plant

Source	**DF**	**SS**	**MS**	**F**	**P**
Salinity	2	5322133	2661067	68.94	0.000
Nitrogen	2	163220	81610	2.11	0.149
Salinity*Nitrogen	4	22267	5567	0.14	0.963
Error	18	694745	38597		
Total	26	6202365			

Grand Mean 1819.9 CV 10.80

Appendix 6. Analysis of variance table for number of fruits

Source	**DF**	**SS**	**MS**	**F**	**P**
Salinity	2	1926.74	963.37	9.27	0.001
Nitrogen	2	193.85	96.92	0.93	0.411
Salinity*Nitrogen	4	13.48	3.37	0.03	0.997
Error	18	1870.67	103.92		
Total	26	4004.74			

Grand Mean 70.481 CV 14.46

Appendix 7. Analysis of variance table for average fruit weight (g/plant)

Source	**DF**	**SS**	**MS**	**F**	**P**
Salinity	2	383.60	191.80	10.18	0.001
Nitrogen	2	0.043	0.02	0.00	0.998
Salinity*Nitrogen	4	11.03	2.75	0.15	0.962
Error	18	339.28	18.85		
Total	26	733.96			

Grand Mean 25.791 CV 16.83

Appendix 8. Analysis of variance table for fruit length (mm)

Source	**DF**	**SS**	**MS**	**F**	**P**
Salinity	2	552.75	276.37	19.66	0.000
Nitrogen	2	8.20	4.10	0.29	0.750
Salinity*Nitrogen	4	2.57	0.64	0.05	0.995
Error	18	253.02	14.05		
Total	26	816.56			

Grand Mean 47.688 CV 7.86

Appendix 9. Analysis of variance table for fruit volume

Source	DF	SS	MS	F	P
Salinity	2	457.60	228.80	14.63	0.000
Nitrogen	2	6.52	3.26	0.21	0.813
Salinity*Nitrogen	4	2.31	0.57	0.04	0.997
Error	18	281.55	15.64		
Total	26	747.99			

Grand Mean 36.688 CV 10.78

Appendix 10. Analysis of variance table for fruit water contents

Source	DF	SS	MS	F	P
Salinity	2	30.42	15.21	71.08	0.000
Nitrogen	2	0.04	0.02	0.10	0.903
Salinity*Nitrogen	4	4.07	1.01	4.76	0.002
Error	45	9.63	0.21		
Total	53	44.17			

Grand Mean 92.602 CV 0.50

Appendix 11. Analysis of variance table for fruit firmness

Source	DF	SS	MS	F	P
Salinity	2	14.05	7.02	78.56	0.000
Nitrogen	2	8.09	4.04	45.24	0.000
Salinity*Nitrogen	4	2.11	0.52	5.90	0.000
Error	720	64.41	0.08		
Total	728	88.67			

Grand Mean 1.2359 CV 24.20

Appendix 12. Analysis of variance table for fruit TSS (°Brix)

Source	DF	SS	MS	F	P
Salinity	2	69.37	34.69	207.40	0.000
Nitrogen	2	2.52	1.26	7.56	0.000
Salinity*Nitrogen	4	3.72	0.93	5.56	0.000
Error	234	39.13	0.16		
Total	242	114.76			

Grand Mean 6.1728 CV 6.63