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# Salt transfer under irrigation with treated wastewater in semi-arid Tunisia

A field study in Tunisia

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Hanna Lundqvist  
Emma Nilsson



Division of Water Resources Engineering  
Department of Building and Environmental Technology  
Lund University

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## Abstract

A continuously growing population in the world has resulted in more agricultural activity in arid- and semi-arid areas where it once was harder to cultivate crops. Due to the high evaporation and the lack of rainfall in these areas it is necessary to irrigate the fields. In some areas it has become more and more common to use treated wastewater as an alternative irrigation source. When the soil is irrigated with saline treated wastewater, some of the salt will be concentrated in the soil. Excessive soil salinity can e.g. limit the plant water uptake, thus decreases the crop production, and it could lead to severe soil degradation. However, it is possible to use moderately saline water for irrigation without a significant risk for severe soil salinization if certain rules for water and soil management are established, implemented and followed.

Therefore the main objective of this thesis is to do an assessment of the soil salinity in agricultural soil as a result of irrigation with treated wastewater. This master thesis will also try to estimate the effects on the soil salinity after a major rainfall event. This will be done with a field study that was conducted outside the city of Nabeul in the north-east of semi-arid Tunisia during 2 months.

The soil salinity assessment done in this thesis can only be considered a qualitative one and the result can only be seen as an indication of an increase or decrease in the soil salinity over this particular field. However, the indications can be a help when deciding the objectives and limitations on future studies in this area. It has been concluded that a general increase in the soil salinity after two irrigation events cannot be seen. However, it was concluded that a small decrease in soil salinity could be seen already after 57.5 mm of rain. This indicating that the Tunisian winter rains can leach the soil from the salts added during irrigation, and that there is no significant risk of soil salinization in this field.

**Keywords:** Soil salinity, Tunisia, irrigation, EM38, treated wastewater, agriculture, soil salinity assessment, ECe, ESAP.





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Lunds universitet

Lund University

Faculty of Engineering, LTH

Departments of Earth and Water Engineering

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The MFS Scholarship Programme offers Swedish university students an opportunity to carry out two months' field work in a developing country resulting in a graduation thesis work, a Master's dissertation or a similar in-depth study. These studies are primarily conducted within subject areas that are important from an international development perspective and in a country supported by Swedish international development assistance.

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The responsibility for the accuracy of the information presented in this MFS report rests entirely with the authors and their supervisors.

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Local MFS Programme Officer



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Emma Nilsson





## Abbreviations and glossary

<b>Bulk average</b>	The average over the entire depth, 0-1.5 m in this field study.
<b>Calibration</b>	The process of fitting a model to the data.
<b>CRDA</b>	Regional Department for Agricultural Development
<b>Coefficient of variation (CV)</b>	A standardized description of a frequency distribution of the observations (Nielsen & Wendroth, 2003).
<b>EC</b>	Electrical conductivity
<b>ECa</b>	Apparent soil electrical conductivity
<b>ECe</b>	Soil saturation extract electrical conductivity
<b>Electrical conductivity</b>	A measure of how easy an electrical current can pass through a substance.
<b>EM</b>	Electromagnetic Induction
<b>EM38</b>	An apparatus for measuring the ECa in soil with EM.
<b>ESAP-Calibrate</b>	Software to estimate the ECe in soil from representative soil samples and EM38 measurements.
<b>ESAP-RSSD</b>	Software to generate soil sampling designs from EM38 measurements.
<b>ESAP-SaltMapper</b>	Software to map predicted ECe values in 1D and 2D.
<b>FAO</b>	Food and Agricultural Organization of the United Nations
<b>Field capacity</b>	The maximum amount of water that a given soil can retain against gravity.
<b>GDA</b>	Agricultural Development Association in Tunisia.
<b>INRGREF</b>	Tunisian National Research Institute for Rural Engineering, Water and Forestry
<b>Jack-knifed prediction</b>	A statistical tool to validate a model's performance.
<b>MLR</b>	Multiple Linear Regressions
<b>ONAGRI</b>	National Observatory of Agriculture of Tunisia
<b>ONAS</b>	The National Sanitation Utility of Tunisia
<b>Outlier</b>	A deviating value which can be removed from the data.
<b>PRESS score</b>	An indication of the accuracy of a model. Low PRESS score indicates good model accuracy.
<b>Principal component algorithm</b>	A transformation aiming to reduce the number of dimensions of the observations and simplifying the data (Härdle & Simar, 2007).
<b>R<sup>2</sup> value</b>	A coefficient that shows how much the variability in one variable depends on another variable (Nielsen & Wendroth, 2003). A high R <sup>2</sup> value indicates a good model.
<b>Root mean square error</b>	The root of the mean square error, which shows how close a fitted line is to the data points (Nielsen & Wendroth, 2003). A low RMSE indicates a good model.
<b>Soil salinity</b>	Inorganic solutes in the soil water solution.
<b>Salinization</b>	The process of salt accumulation in the soil.
<b>WHO</b>	The World Health Organization
<b>Wilting point</b>	The soil water content at which the plants cannot take up the water anymore and the plant wilts.
<b>USDA</b>	The United States Department of Agriculture
<b>USSL</b>	The United States Salinity Laboratory, a part of the Agricultural Research Service of USDA



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**Appendix II – Water balance**

**Appendix III – Real crop water need**

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## 1. Introduction

The world economy, and the welfare of its citizens, is greatly dependent on the agricultural sector and its development. The continuously growing population will most likely put more strain on the agricultural sector in the future, and the sector has to produce more in order to support the world's citizens. This has resulted in more agricultural activity in arid- and semi-arid areas where it was once harder to cultivate crops. Due to the high evaporation and the lack of rainfall in these areas it is necessary to irrigate the fields to increase the agricultural production. However, there is often already a shortage of water in these areas and alternative water resources might have to be considered. In some areas it has become more and more common to use treated wastewater as an alternative irrigation source.

One of the first countries to reuse the wastewater was USA and the state of California, who started reusing its wastewater for agricultural and landscaping purposes already in the 1890s. However, today one of the world leading countries when it comes to using treated wastewater irrigation is Israel, who reclaims more than 60 % of the treated wastewater. Japan is also a country with a high rate of reusing urban wastewater for agriculture, parks, golf courses and sporting fields. In Mexico 350 000 ha is irrigated with wastewater. However, only 11 % of this wastewater is treated first, and some of the crops that are irrigated are vegetables and cereals. In Oman, 50 % of the wastewater is treated and 90 % of this water is then used for agricultural purposes. In North Africa, Tunisia has been a pioneer in reusing wastewater for irrigation. Tunisia have expressed fairly ambitious plans for wastewater reuse in the future with the hopes of being able to irrigate about 20,000 to 30,000 ha with treated wastewater by 2020 (Hamilton, et al., 2007).

Treated wastewater is in general more saline than conventional fresh water resources and could have severe effects on the soil and the crops (Hamilton, et al., 2007). Under irrigation with treated wastewater, more salt is added to the soil and when the evapotranspiration takes place, some of the salt will be concentrated in the soil (Tanji & Kielen, 2002). Excessive soil salinity can, for example, limit the plant water uptake, and thus decreases the crop production which could lead to severe soil degradation. The risk of severe soil salinization will also depend on the soil properties and the local soil and water management (Bouksila, 2011). Salinization is regarded to be one of the major reasons for desertification and soil degradation, and the soil can be so badly damaged by this process that it cannot be used for growing crops (Land Management and Natural Hazards Unit, 2010). Also, if the quality of the wastewater is not properly managed it might be a source of pathogens. However, according to Bouksila (2011) it is possible to use moderately saline water for irrigation without a significant risk for severe soil salinization if certain rules for water and soil management are established, implemented and followed. Before establishing such a water and soil management plan an extensive assessment of the soil salinity and its cause have to be made. The objectives of such a plan should aim to achieve effective agricultural practices, save water, increase the crop production, prevent soil salinity and ensure sustainable land development.

## 1.1. Tunisia

Tunisia is located in the very north of Africa and is considered to be an economically important country in this region (see Figure 1.1). The country has Mediterranean climate in the north and desert climate in the south. The annual precipitation varies from 594 mm in the North to 289 mm in the Center to 156 mm in the South (Bahri, 2002). The more extensive rain in the North is mostly due to the mountains in this region. About 10 million people live in Tunisia and most of the population is concentrated to the northern and eastern parts of the country, and about 67 % of the people live in cities. The largest city is the capital Tunis. In the south it is only the oases that are populated. The area of Tunisia is 16,415,000 m<sup>2</sup> and the country borders to Algeria, Libya and the Mediterranean Sea (Utrikespolitiska Institutet, 2012).



Figure 1.1. Map over Tunisia (Google Earth, 2012).

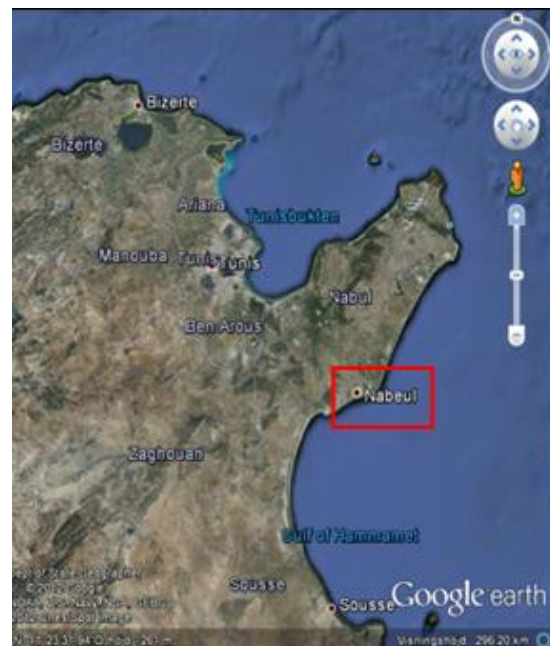


Figure 1.2. Map over northeast Tunisia with the city of the field study Nabeul marked in a red square (Google Earth, 2012).

The agricultural sector is of greatest importance to the Tunisian economy and about 65 % of the population is directly or indirectly associated with the agricultural sector. The agricultural sector consumes more than 80 % of the available water resources today, and over the last 60 years the irrigated area in Tunisia have increased remarkably to a total of 400 000 ha in 2010 (Bouksila, 2011). To meet the increasing demand of water treated wastewater have been used more and more as an irrigation source with the first project being implemented already in the 60s (Bahri, 2000). The development of irrigation networks adapted for irrigation with treated wastewater in Tunisia is ongoing and reused water is expected to account for about 10 % of the available water resources by the year 2015 (Al Atiri, 2009). Except for conserving valuable water resources, the nutrients contained in treated wastewater could also be an advantage when growing crops (Bahri, 1998). However, it is approximated that about 30 % of the irrigated areas in Tunisia are highly sensitive to salinization today (Bouksila, 2011). As was mentioned before, to lessen the risk for severe soil salinization from irrigation with treated wastewater, a soil and water management plan based on a soil salinity assessment is of significant importance in a country like Tunisia.

## 1.2. Problem statement and objectives

The studied area has a semi-arid climate, and the agricultural fields need to be irrigated. The treated wastewater used for irrigation is often of poor quality; it contains salts and large amounts of suspended solids. This, combined with poor farmer practices in the area, can result in high risk of soil salinization. This will have an effect on the sustainability of the agriculture. Therefore it is necessary to conduct a soil salinity assessment in this area.

The main objective of this master thesis is first to assess the effects of irrigation with treated wastewater and rainfall on the soil salinity; will there be a visible increase in the salt concentration in the soil after one and two irrigation events? Can any indications be seen that the winter rains are substantial enough to leach out the salts added by the irrigation during the irrigation season? Secondly, the objective is to try to understand the farmers' constraints and perception of treated wastewater use and soil management.

Another objective with this master thesis is to do an initial survey of the field. This can act as a base for the researchers at INRGREF for future studies on this field. A secondary objective is to use the EM38 instrument (Geonics Ltd, Ontario) together with the computer software ESAP (vs. 2.35, Lesch et al., 2006) to map the soil salinity and to make a small evaluation about their use and limitations in this area.

## 1.3. Methodology

To achieve the objectives presented above a field study was conducted outside the city of Nabeul in the north-east of semi-arid Tunisia during 2 months (see Figure 1.2). The field study consisted of four major data collecting campaigns in one agricultural field. The four data collecting campaigns aimed to represent the initial conditions, conditions after one irrigation event, two irrigation events and a larger rainfall event. The same in-field measurements were made during each of the campaigns. The last weeks of the study also included laboratory measurements of soil and water properties of the samples collected in the field. The field study also included interviews with local farmers, to get representative information about the farmer practice and how they perceive the problem with soil salinity. Also study visits to the regional Department for Agricultural Development, the regional Agricultural Development Association and the local treated wastewater plants were done to understand the irrigation network in Nabeul.

The main instrument used in the field was chosen to be an EM38, mostly because of its quick in situ measurements. The analyses of the soil salinity data was finally done using ESAP, a software package that was chosen because of its adaptations to the EM38 used in the field.

To analyze the data collected in the field study, this master thesis also included an extensive literature study about the current situation in Tunisia and the latest findings in soil science. This was done to fully understand the basis of the problem, the prerequisites and the methods used.





## 2. Literature review - Soil salinity

In this section a general description of soil salinity and its causes and effects is firstly presented. The salt tolerance of crops is then discussed and after that some general soil salinity management practices are given. Finally, this chapter deals with soil salinity measurement and its general theory. Some methods of soil salinity measurements are described and the method used in this master thesis, according to what was described in section 1.3 above, is more thoroughly described.

### 2.1. General description of soil salinity

Salinity in soil is the inorganic solutes in the aqueous phase of the soil, that is soluble and dissolved salts like major ions (such as sodium, calcium, magnesium, potassium, bicarbonate, sulphate, chloride and nitrate), non-ionic solutes and pair-forming ions (Corwin & Lesch, 2005). The salts have many possible origins: the groundwater composition, weathering of minerals and ocean water sprayed up on the ground by the wind (USSL, 1954). Furthermore, many parameters affect the soil salinization; soil type, precipitation, evapotranspiration, irrigation water quality, irrigation practices and the groundwater level (CRUESI, 1970).

Soil salinization is a large problem in the world today. When salts, like dispersive cations, accumulate in the soil, the clay swells and the pores in the soil and the soil structure are changed. This affects the soil permeability and the water retention negatively (Keren, 2000). According to USSL (1954), a saline soil is often defined as a soil with an electrical conductivity of the soil solution extract (ECe) of 4 dS/m. According to Bouksila (2011), 5-6 million ha of arable land in the world is destroyed annually due to bad agricultural management and practices. Soil salinity is mainly a problem in semi-arid or arid areas where the rainfall is not enough to leach the salts from the soil (USSL, 1954).

Soil salinization is mainly a result of evaporation that removes the water from the soil but leaves the salts (Corwin & Lesch, 2005). The addition of water and amendments to the soil, like fertilizers or gypsum, can affect the soil salinity. Some animal manure contains salts that can increase the soil salinity (Tanji & Kielen, 2002). The dose and frequency of the irrigation water can also have an effect on soil salinity. The soil salinity is also affected by the water movement at the surface and depends on the irrigation method. Using border irrigation leads to a more homogenous soil salinity profile than using furrow irrigation (CRUESI, 1970). The irrigation methods will be further discussed below in section 3.2.

As mentioned before, addition of organic matter to soil can affect the soil salinity. At high rates of organic manure addition, the soil salinity could increase (Haynes & Naidu, 1998). However, the organic matter also has positive effects on the soil properties. The water holding capacity and the infiltration rate increases while surface crusting and runoff decreases (USSL, 1954 and Haynes & Naidu, 1998). These effects from organic matter on soil properties could lead to a higher soil leaching which could lead to a decrease of soil salinity.

The soil salt accumulation increases with increasing salinity of irrigation water (CRUESI, 1970). An experiment at a vineyard in South Africa, using 6 different salinities of irrigation water, made the observation that the soil salinity increases with an increasing salinity of the irrigation water. However, for the two highest salinity irrigation waters this trend was not visible. The given explanation is that the very saline water, more than 3.5 dS/m, is not taken up by the plants to the

same degree as with the lower salinities, so the leaching using the more saline water is larger and thus the soil salinity increase is lower when using very saline water (de Clercq, et al., 2009).

## 2.2. Crops and salinity

Soil salinity is a major abiotic factor that affects both crop production and crop quality. Most crops have a negative reaction to a too saline environment. Salinity generally has three major damaging effects on crops. Firstly, the salt can prevent the plant's uptake of several important nutrients, like phosphorous and nitrate. Secondly, the salt causes ion cytotoxicity, and thirdly, the osmotic stress caused by the salt can lead to crop damage (Chinnusamy & Zhu, 2004). The osmotic pressure in the soil solution in the root zone increases with salinity and it becomes more difficult for the plants to take up enough water. This leads to water stress and the farmer can experience a yield loss (Tanji & Kielen, 2002). Soil salinity stress can be affected by many factors. For example, a high air temperature can reduce the crop salt tolerance, thus the crop can be damaged earlier than in a cold air temperature (Tanji & Kielen, 2002).

Sensitive crops, like alfalfa and lemons, can handle soil salinity up to 4 dS m<sup>-1</sup> while tolerant crops, like sugar beet, cotton and soybean, can handle 8 dS m<sup>-1</sup>. Very tolerant crops can handle more than 12 dS m<sup>-1</sup> (USSL, 1954). A list of salt tolerance, in terms of E<sub>c</sub>, for some common crops and plants grown in Tunisia can be seen in Table 2.1. The salt tolerances are general guidelines for crop salt tolerance but they only apply when the soil salinity is approximately the same during the entire lifetime of the plant (Tanji & Kielen, 2002).

**Table 2.1. Salt tolerance data for some crops commonly grown in Tunisia and the factor that the tolerance threshold is based on is also given (Tanji & Kielen, 2002).**

<b>Crop</b>	<b>Tolerance based on</b>	<b>Threshold (dS/m)</b>
<b>Alfalfa</b>	Shoot dry weight	2.0
<b>Date palm</b>	Fruit yield	4.0
<b>Grape</b>	Shoot growth	1.5
<b>Orange</b>	Fruit yield	1.3
<b>Potato</b>	Tuber yield	1.7
<b>Sorghum</b>	Grain yield	6.8
<b>Strawberries</b>	Fruit yield	1.0
<b>Tomato</b>	Fruit yield	2.5

## 2.3. Soil salinity management

Soil salinity can be controlled. Soil salinity evolution depends on how the water is moving in the soil and to reduce the risk of soil salinization it is necessary to manage the irrigation, leaching and drainage. However, the salinity of the irrigation water cannot be too high for the cultivated crop if a sustainable agriculture is the aim. A well-planned schedule of irrigation is necessary to control soil salinity. Enough water is needed to leach the soil and to keep it moist, but overuse of water could lead to drainage problems, create a shallow groundwater and the soil salinity can increase (USSL, 1954). There are many things to consider when dealing with soil salinity (USSL, 1954);

- Do something to manage soil salinity otherwise crop failure could be the result.
- Do not use highly saline irrigation water on a soil with low infiltration and drainage rate.
- Consider the use of salt tolerate crops.

- Use an irrigation method that distribute the water evenly and allows downward movement, like border irrigation.
- Avoid water losses and seepage during transport of irrigation water.

To be able to deal with soil salinity and the problems arising with it, it is a good start to have good monitoring and control of the soil salinity. A tool to achieve this monitoring is a quick and easy soil salinity assessment, as discussed more below (de Clercq, et al., 2009).

### 2.3.1. Leaching

According to FAO (Rhoades, et al., 1992) “irrigated agriculture cannot be sustained without adequate leaching and drainage to prevent excessive salinization of the soil” (Chapter 6). Thus, without leaching there is a risk of salts accumulating in the soil. The amount of irrigated water that must be leached through the root zone to keep the soil salinity at a specified level has been defined as the leaching requirement (LR) (USSL, 1954). The leaching requirement depends on the salt concentration in the irrigated water and the maximum concentration permitted in the root zone. It is often assumed that the salt concentration in the root zone will be the same as the concentration found in the drainage water, which will make it easier to monitor the salinity in the root zone (USSL, 1954). However, the use of a drainage system is not common in developing countries.

Leaching can be accomplished by for example ponding an appropriate amount of water on the soil surface using dikes or ridges and thus establishing downward water movement through the soil. However, the most common way to leach is an addition of excess irrigation water. To establish effective leaching adequate drainage is required, because leaching requires a free passage of water through and away from the root zone. If the drainage system is inadequate the water applied for leaching might make the water table rise and then the soluble salts can return to the root zone (USSL, 1954).

A large experiment in Tunisia (1962-1969) came to some conclusions regarding the variation of soil salinity in different soils. In fine textured soil, like clay and silt, the salinity in the upper layers increases during summer due to evaporation and decreases during winter due to rainfall. However, in the deeper layers of the soil, the opposite happens. The soil salinity increases during winter due to the leaching of the rainfall. According to this experiment, leaching during winter in clayey to sandy soils gives a higher leaching efficiency due to the combination of increased rainfall and decreased evapotranspiration. However, the amount of added leaching does not affect soil salinity that much, so water could be saved by the use of a smaller amount of leaching. In sandy soils, water saving is possible because the difference in soil salinity using water saving technique, frequent leaching or seasonal leaching is small. So, in the case of a sandy soil, the winter leaching is often enough and therefore an agricultural and economical basis can be used to make the decision on the amount of irrigation water instead of using the leaching requirements. In semi-arid Tunisia it is often enough with winter leaching to reset the soil salinity to the levels before the irrigation during summer started (CRUESI, 1970).

According to FAO (1998), sandy soils consist of large particles and large pores, which do not have a great ability to hold water. As a result, sandy soils drain excessively. On the other hand, clayey soils consist of small particles and small pores, which have a greater ability to hold water. Thus, clayey soils tend to have high water holding capacity.

## 2.4. Measuring soil salinity

It is of greatest importance to conduct a soil salinity assessment to understand the extent of a soil salinity problem, which could pose as a threat to the agricultural society. By knowing the soil salinity situation, management measures can be taken that could possibly prevent a serious soil salinization. The sections below will further describe the different methods of measuring soil salinity in a field, and will help to explain the methodology used in this thesis, which was described in section 1.3 above.

### 2.4.1 Soil salinity measurement theory

The electrical conductivity (EC) and the total salt concentration in a solution are closely correlated. Therefore EC is frequently used as an expression of the total concentration of salt in soil (Rhoades, et al., 1999). The EC of a substance is a quantification of the difficulty/ease with which an electrical current can flow through it (Geonics Limited, 1980). The EC is often expressed as the apparent electrical conductivity (EC<sub>a</sub>), which is a measure of the EC through the soil via three specific pathways: through solid, liquid and solid-liquid phases. The relationship between EC<sub>a</sub> and the electrical conductivity of soil water (EC<sub>w</sub>) is described in what is commonly known as Archie's law for saturated rocks and sand soils, as

$$EC_a = a \cdot EC_w \cdot \phi^m \quad (\text{Equation 2.1})$$

where a=empirical constant, m=cementation exponent and  $\phi$  =porosity. However, several researchers have observed that Equation 2.1 is not valid to use on geological formations and soils also containing clay minerals, where the equation tends to overestimate the EC<sub>w</sub> (Hendrickx, et al., 2002). Rhoades *et al.* (1989) developed a more complex physical model that could correctly describe the relationship between EC<sub>a</sub>, EC<sub>w</sub> and volumetric soil water content under all soil conditions, as

$$EC_a = \left[ \frac{(\theta_{ss} + \theta_{ws})^2 \cdot EC_{ws} \cdot EC_{ss}}{\theta_{ss} \cdot EC_{ws} + \theta_{ws} \cdot EC_{ss}} \right] + (\theta_w - \theta_{ws}) \cdot EC_{wc} \quad (\text{Equation 2.2})$$

where  $EC_{wc}$ =specific EC in large pores,  $EC_{ss}$ =specific EC of the solid phase,  $EC_{ws}$ =specific EC in small pores,  $\theta_{ws}$ =volumetric soil water content in the small pores,  $\theta_{wc}$ =volumetric soil water content of the large pores,  $\theta_{ss}$ =volumetric solid contents in the small pores and  $\theta_w = \theta_{wc} + \theta_{ss}$  = total volumetric soil water content (Rhoades, et al., 1989). The following simplifying approximations are also valid:

$$\theta_w = \frac{P_w \cdot \rho_b}{100} \quad (\text{Equation 2.3})$$

$$\theta_{ws} = 0.639 \cdot \theta_w + 0.01 \quad (\text{Equation 2.4})$$

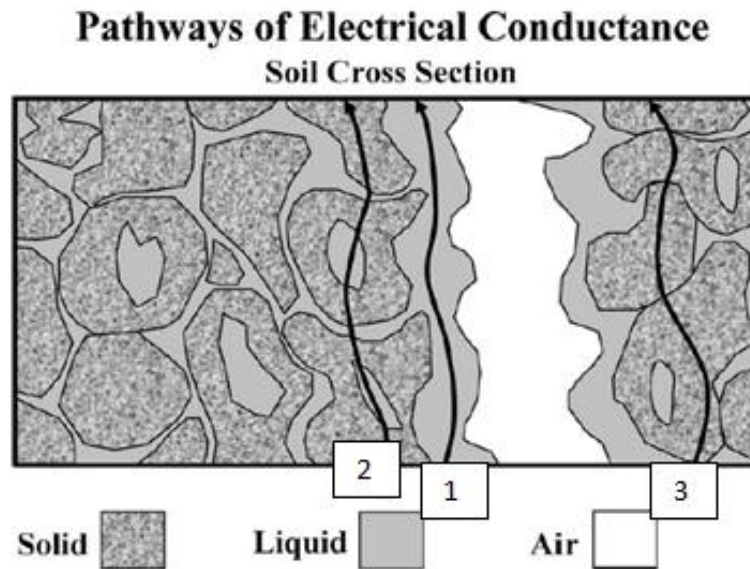
$$\theta_{ss} = \frac{\rho_b}{2.65} \quad (\text{Equation 2.5})$$

$$EC_{ss} = 0.019 \cdot S_p - 0.434 \quad (\text{Equation 2.6})$$

$$EC_w = \left[ \frac{EC_e \cdot \rho_b \cdot S_p}{100 \cdot \theta_w} \right] \quad (\text{Equation 2.7})$$

where  $P_w$ =gravimetric soil water content,  $\rho_b$ =the bulk density (mg/m<sup>3</sup>),  $S_p$ =the saturation percentage,  $EC_w$ =the EC of the soil water, assuming equilibrium (i.e.  $EC_w = EC_{sw} = EC_{wc}$ ), and  $EC_e$ =the EC of the saturation extract (dS/m) (Corwin & Lesch, 2005).

The model described with Equation 2.2 is based on three electrical conductors in the soil that are acting in parallel: (i) through the soil saturation in large pores, (ii) through alternative layers of soil particles and soil solution in small pores, and (iii) through the soil solids and the surface of the clay minerals that are rich in cations. These three pathways are visualized in Figure 2.1 below (Hendrickx, et al., 2002).



**Figure 2.1. Pathways of Electrical Conductance via three pathways: (1) is the pathway through the larger pores, (2) is the pathway through the alternative layers of soil particles and soil solution in small pores, and (3) is the pathway through the soil solids and the surface of the clay minerals that are rich in cations (modified from Rhoades *et al.* (1989)).**

Some of the model parameters in Equation 2.2-2.7 above are however difficult to estimate. Therefore Rhoades *et al.* (1990) further developed Equation 2.2 to predict the ECe from only field measured ECa, measured or estimated volumetric soil water content, bulk density and ECss. The objective was to be able to easier predict ECe, this because soil salinity has historically been defined as ECe measured in a laboratory. It has been, and continuous to be, used as a standard when measuring soil salinity and most studies regarding salt-tolerance of crops have used ECe. Therefore the soil salinity continues to be measured with ECe, even though it is hard to measure directly in the field (Corwin & Lesch, 2005).

The ECa can be influenced by several soil properties, such as soil salinity, soil water content, porosity, soil structure, temperature, clay content, mineralogy, cation exchange capacity, topography and bulk density (Friedman, 2005). The temperature dependence is mainly due to the temperature dependence of the viscosity of the water in the soil, that will affect the ionic mobility and in turn the ECa. The ECa will increase at a rate of approximately 1.9 % per degree temperature increase (Corwin, et al., 2006). According to Corwin & Lesch (2005a) the temperature will affect the ECa according to

$$EC_{25C} = f_t \cdot EC_T \quad (\text{Equation 2.8})$$

where  $EC_{25C}$  = the EC at the reference temperature 25° C,  $EC_T$  = measured EC at temperature T,  $f_t$  is the temperature conversion factor and can be described by

$$f_t = 0.4470 + 1.4034e^{\left(-\frac{T}{26.815}\right)} \quad (\text{Equation 2.9})$$

### 2.4.2. Field-scale ECa survey

An investigation about the spatial variation of soil salinity can be done by a field-scale ECa survey. The method with which the ECa should be measured might vary, but the methodology of the survey is recommended to be approximately the same. According to Corwin & Lesch (2005a) a field-scale ECa survey should include:

- (i) Site description and ECa survey design.
- (ii) ECa-data collection.
- (iii) Soil sample design based on the collection.
- (iv) Soil sample collection.
- (v) Physical and chemical analysis.
- (vi) Development of a stochastic and/or deterministic to predict ECe from measured ECa.
- (vii) Spatial statistical analysis.
- (viii) GIS database development.

Step (i) and (ii) are the initial steps that requires making an overview of the field and its background as well as determining the objectives of the study, and then performing an initial ECa data collection with an appropriate method. The data obtained from the initial ECa data collection will then be used in step (iii) to determine the soil sample design. That means, to decide at which locations soil samples should be taken for further investigation. The development of a soil sample design can be done with computer software or just by using basic statistical methods. After the soil sampling is conducted, according to the decided sample design, the soil is taken to a laboratory for physical- and chemical analysis (step (v)) to e.g. determine the soil water content, the organic matter content, ECe and the soil particle size. In step (vi) the ECa measurement are calibrated to ECe, together with the results from the laboratory analysis, with a suitable deterministic or stochastic model. This so that ECe can be estimated over the whole field from the ECa measurements. In step (vii) an investigation of which soil properties that are influencing the ECa measurement, and to which extent, can be done with basic statistical analysis and graphical displays. Finally, geographical information system (GIS) software can be used to display the spatial soil salinity pattern.

Corwin and Lesch (2005a) further states that it is of greatest importance to understand the factors influencing the within-field ECa variations to establish an efficient ECa survey. It might also be an idea to collect replicate samples at some locations to even better estimate the local-scale soil salinity variations. The study presented in this report used only the step (i) to (vi) to investigate the soil spatial variability.

#### *Sampling design*

To make an adequate soil sampling, careful planning of the entire project is needed before the sampling design is decided. Firstly, the objective of the study and the sampling, and what kind of result is wanted, should be decided. There are two different approaches that could be used when determining the sample design: the design-based approach (usually used in classical survey sampling), and the model-based approach (usually used in geostatistics). Both of the approaches take into consideration what would happen if the sampling was repeated many times in a hypothetical experiment. If neither the value patterns nor the locations of the sample sites change between the samplings there would be no temporal variation, so one of them has to vary to get a temporal variation. The difference between the two sampling design approaches is which parameter that will

vary. In the design-based approach the sampling site locations will vary and are chosen according to a random sampling scheme, while the value pattern is considered unknown but fixed. In the model-based approach the sampling sites are the same throughout the survey, while the value pattern will vary in the area according to a random model (De Gruijter, 2002). In the survey presented in this report a model-based approach called spatial response surface (SRS) algorithm was used to create a basis for the sampling design.

### **2.4.3. Methods of measuring soil salinity**

Which method to select for evaluating the soil salinity depends on the objectives of the study, the number of obtained soil samples and naturally also the time and effort wished to spend on the study. The most accurate methods usually require the most time, money and effort (Rhoades, et al., 1999). According to Corwin & Lesch (2005) there are five different methods to assess the soil salinity in the field scale: (i) visual observation, (ii) measurement of the ECe from soil samples in the laboratory (iii) in situ measurement of electrical resistivity (ER), (iv) non-invasive and in-situ measurement of electrical conductivity with electromagnetic induction (EM), and (v) in situ measurement of electrical conductivity with time domain reflectometry (TDR) or frequency domain reflectometry (FDR). The ER, EM, TDR and FDR methods all measure ECa. The measurement of ECa have developed into the most common way to assess the soil salinity, mainly because of the time and costs associated with obtaining soil solution extracts to determine ECe (Corwin & Lesch, 2005). However, as have been mentioned before, ECe still remain the standard expression for soil salinity and the in-field measured ECa is usually calibrated to ECe. It has also been shown by Corwin *et. al.* (2006) that measurements of ECa are well suited for characterizing the spatial variability of other soil parameters (Corwin, et al., 2006).

#### *Visual observation*

The method of visual observation is quick and economical. However, it also has the great disadvantage that soil salinity is detected first when crop damage has already occurred, making this method the least desirable one, since maximum crop yield is most often the desired goal (Corwin & Lesch, 2005).

#### *Soil solution extract*

The soil salinity can be determined by collecting soil samples to be analyzed in a laboratory. This method is not always practical because many samples are needed, it is destructive and only one measurement can be made on each sample (Hamed, et al., 2003). There are currently serious doubts about the possibility for mobile ECe sensors to provide representative measurements of soil water content and soil salinity. To measure soil salinity with soil solution extract might instead best be done in combination with other methods (Corwin & Lesch, 2005).

#### *Electrical resistivity (ER)*

The Electrical resistivity (ER) instrument introduces an electrical current into the soil via current electrodes at the soil surface, and the difference in the current flow potential is then measured at potential electrodes placed nearby, as can be seen in Figure 2.2. A Wenner array have the four electrodes equidistantly spaced, in a straight line at the soil surface, with the two outer electrodes serving as the current electrodes and the two inner serving as potential electrodes (Corwin & Lesch, 2005).



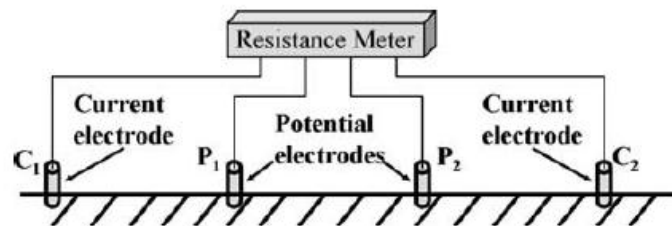


Figure 2.2. The ER method with an array of four electrodes. When the electrodes are equally spaced with the distance  $a$  it is called a Wenner array (modified from Corwin & Lesch, (2005)).

The ER method is well suited for field-scale use because the soil volume for measurement is large, which reduces the influence of possible local-scale variability. It is also a flexible method where the depth and volume of soil effecting the measurement can easily be changed by altering the spacing between the electrodes. However, a disadvantage of the ER is that it is an invasive technique and is less reliable in dry or stony soil because good contact between the soil and the electrodes is needed (Corwin & Lesch, 2005).

#### *Time domain reflectometry (TDR) and Frequency domain reflectometry (FDR)*

The Time domain reflectometry (TDR) technique is based on the time it takes for a voltage pulse to travel down a soil probe and back. This time is a function of the dielectric constant ( $\epsilon$ ) of the soil. The relationship between the  $\epsilon$  and the soil water content is almost linear and is dependent on the soil type, the bulk density, the clay content and the amount of organic matter in the soil.

The advantages of TDR include that it is a relatively non-invasive method, that it has the ability to simultaneously measure both soil water content and ECa, that it can detect small changes in ECa, that it takes continuous measurements, and that the instrument do not need to be calibrated to measure soil water content. However, TDR is a stationary instrument and cannot be used for a field-scale spatial characterization of soil water content and ECa, or to make ECa maps for larger areas (Corwin & Lesch, 2005).

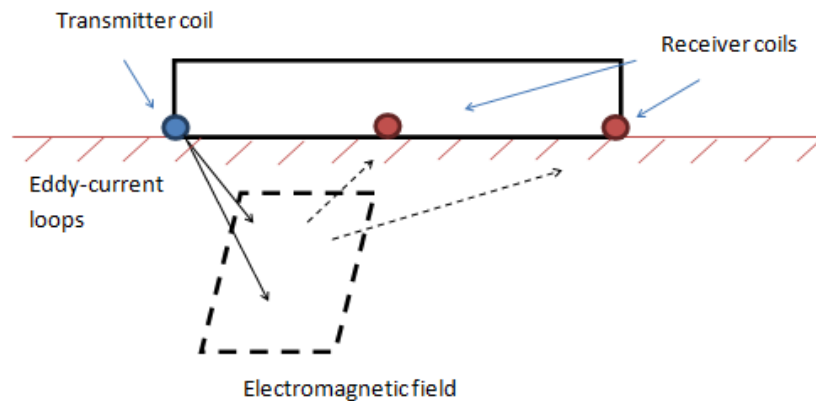
Today there are several highly promising sensors being developed that are based on the soil dielectric properties. One of these methods is the frequency domain method (FDR) that is based on the same principles as the TDR, but it uses a fixed frequency sine wave instead of a pulse to measure the impedance in the soil. A today commonly used instrument based on FDR is the Wet-2 sensor (Delta-T, UK) (Hilhorst, 2000). A WET sensor was used in this thesis.

#### *Electromagnetic induction (EM) sensor*

To use an electromagnetic induction (EM) sensor is generally considered to be one of the best methods to determine the spatial soil salinity. The measurements are preferably made at field capacity and with accompanied soil temperature measurements, because of the temperature dependence of the ECa (see Equation 3.10 and 3.11) (Bouksila, 2011). One of the most common EM sensors used for agricultural purposes is the EM38 (Geonics Ltd, Ontario, Canada) that measures the ECa at two depths simultaneously and non-invasively. It has no requirement for soil-to-instrument contact and the instrument is possible to use by both walking and trailer-mounted survey methods (Geonics Limited, 2012). In the EM38 a transmitter coil is situated at one end, where it induces eddy-current loops in the soil. The size of these loops is directly proportional to the ECa in the vicinity of



that loop. Each of these current loops generates a secondary electromagnetic field and a fraction of this field reaches a receiver coil. The sum of the electromagnetic fields that reaches the receiver coil is related to ECa (Corwin & Lesch, 2005). The EM38 has two receiver coils, 1 m and 0.5 m from the transmitter, giving data from different effective depth ranges. The range is depending on if the instrument is put in horizontal (EMh) or vertical (EMv) position. In the vertical position the effective depth is approximately 1.5 m, and in the horizontal position the effective depth is approximately 0.75 m (Geonics Limited, 2012). A schematic picture of how the EM38 works is described in Figure 2.3.



**Figure 2.3.** The EM38 with one transmitter coil transmitting eddy-current loops creating an electromagnetic field that is received by the two receiver coils.

The measurement of both EMv and EMh can give an idea of how the shape of the soil salinity profile looks like. Soils with a profile ratio (EMh/EMv) that is greater than 1 are indicated to have a net flow of salt upwards, and will thus have higher salt content at the surface. A profile ratio of less than 1 are indicated to have a net downward flow and thus a declining salt profile (Corwin & Lesch, 2005b).

#### 2.4.4. Calibration of ECa to ECe

As mentioned earlier in section 2.4.1., ECa has become the more common field-scale measurement of soil salinity and therefore a relationship between ECe and ECa is needed to relate ECa back to ECe and the crop tolerance (Corwin & Lesch, 2005). This is done by analyzing the ECe in soil samples, taken after the ECa readings (Herrero, et al., 2011). ECa is also affected by several factors, mentioned above, which makes it even more important to do the ECa measurements in combination with laboratory analysis of soil parameters to see the correlations (Rongjiang & Jingsong, 2012). There are several models and software that can be used for calibration, and which to choose will depend on the objectives of the study and the field parameters obtained. One of the traditional ways of separating these models is to divide them into deterministic and stochastic models.

##### *Deterministic models*

In a deterministic model either theoretically or empirically models can be used to estimate ECe from ECa. All deterministic models are however static. That means that all the model parameters are assumed known, and no laboratory analysis of ECe is needed. The use of a deterministic model typically requires knowledge of other soil properties such as soil water content, bulk density, saturation percentage, and temperature (Corwin & Lesch, 2003).

### *Stochastic models*

Stochastic models include geostatistical models such as spatial regression or co-kriging. The stochastic models are dynamic, and the model parameters are not known and are estimated from soil samples taken during the field survey, e.g. the soil water content, E<sub>Ce</sub>, bulk density and soil particle size. The calibration of the model parameters are done by acquiring E<sub>Ca</sub> data and soil samples from the field, and then using an appropriate stochastic model to determine the relationship between measured E<sub>Ca</sub> and the E<sub>Ce</sub> from the soil samples. Finally, by using the rest of the measured E<sub>Ca</sub> values, together with the estimated model parameters, the E<sub>Ce</sub> can be predicted at all the locations where E<sub>Ca</sub> was measured (Corwin & Lesch, 2003).

### *Kriging*

Kriging is a geostatistical method that aims to estimate a value of a soil parameter at an unobserved location, based on the weighted average of nearby observed locations within a specified area. Consider a random function  $z(s_i)$ , where  $s_i$  represent all the observed locations,  $i=1, \dots, n$ . The estimated value at the unobserved location is then defined by

$$z(s_0) = \sum_{i=1}^n \lambda_i z(s_i) \quad (\text{Equation 2.10})$$

where  $\lambda_i$  is the weight assigned to each of the observed sites. The sum of these weights is 1, so that the predictor provides an unbiased estimation (Triantafyllis, et al., 2001).

### *Job model*

According to Bouksila *et al.* (2012), because of the high spatial variability of soil moisture, a model by Job (1992) has traditionally been used in Tunisia. In this method E<sub>Ce</sub> is calculated from EM<sub>h</sub>, measured with an EM38, and the soil water content according to

$$ECe = a \cdot EMh(\theta_2) + b \quad (\text{Equation 2.11})$$

$$EMh(\theta_2) = EMh(\theta_1) + \delta(\theta_2 - \theta_1) \quad (\text{Equation 2.12})$$

where  $EMh(\theta_2)$  = the EM<sub>h</sub> expressed at the reference soil water field capacity  $\theta_2$ (%),  $EMh(\theta_1)$  = the EM reading relative to the field soil moisture  $\theta_1$ , and  $\delta$  = an empirical parameter depending mainly on soil type (Bouksila, et al., 2012).

### *Multiple linear regression model*

Another, quite common, stochastic model used to predict soil salinity is a multiple linear regression (MLR) model. For E<sub>Ca</sub> readings from EM38 a similar equation to the following is usually used

$$\ln(ECe) = \beta_0 + \beta_1(\ln(EMh)) + \beta_2(\ln(EMv)) + \beta_3x + \beta_4y \quad (\text{Equation 2.13})$$

where EM<sub>h</sub> and EM<sub>v</sub> are the EM38 readings, and x and y are trend surface parameters. The equation above is however only one out of a number of possible regression models that can be used. The goal of the regression fitting will be to find the parameters,  $\beta_0$ ,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ , and  $\beta_4$ . Once these parameters have been established the log-transformed E<sub>Ce</sub> can be predicted at every location with observed EM38 data. This method is well suited to use when one have acquired representative soil samples together with the E<sub>Ca</sub> readings (Lesch, et al., 2000). This method was used in the survey presented in this report.

### 3. Literature review - Irrigation management

Irrigation in arid and semi-arid countries is very important for a working agriculture. Without the addition of water, the crops could not grow sufficiently and the entire society, which is depending on the crop, will suffer. The farmers need to take crop water need into consideration when working with irrigation. The basics of crop water need are provided in this chapter. There are many different irrigation methods and below a short summary of them are presented.

#### 3.1. Crop water need

The photosynthesis that is taking place in the plants requires a wet surface. So, a plant with water shortage cannot convert the sun's radiation to sugar for plant growth. This leads to a standstill in the growth of the plant and if the water shortage is long, the plant could die. Water is also needed for transpiration from the plants. Transpiration is done partly to prevent the plant from overheating, which could eventually lead to crop failure (Townsend, et al., 2008). The movement of water through the plant also makes the transportation of nutrients in the plant efficient (Ward & Robinson, 2000). The amount of water needed is either covered by the rain or by a combination of rainwater and irrigation (Ehlers & Goss, 2003).

The water need of plants depends on both internal and external factors. To calculate the crop water need ( $W_{rc}$ ), which is the amount of irrigation water needed to be added, it is necessary to know the potential evapotranspiration,  $ET_p$ , of the crop.  $ET_p$  is either measured in the field or estimated, using for example the Penman-Monteith equation. The  $ET_p$  is then combined with a crop-specific coefficient,  $K_c$ , to estimate the crop water need according to Equation 3.1 (Ehlers & Goss, 2003).

$$W_{rc} = K_c \cdot ET_p \quad \text{(Equation 3.1)}$$

From Equation 4.1 above it can be seen that the larger the evapotranspiration is the larger the water need for the plant is. Thus, in arid and semi-arid regions, where the evapotranspiration is usually higher, the crop water need will also be higher.

#### 3.2. Irrigation methods

According to USSL (1954), "irrigation is the application of water to soil for the purpose of providing a favorable environment for plants" (p. 34). As mentioned earlier, irrigation is necessary in many parts of the world and several methods for irrigation exist. The goal of a good irrigation is to apply enough water that will fully wet the plant's root zone while minimizing overwatering (Allen, et al., 1998). There cannot be a soil water content that is above field capacity or soil water content below the wilting point. At wilting point the soil water cannot be extracted by plants. The optimal soil water content will be between the field capacity and the wilting point, but not too close to the wilting point to avoid plant water stress. In the laboratory, the concept of pF is most often used to estimate the field capacity and the wilting point. The soil is considered to be at field capacity when the water potential in the soil is at about -0.1 - -0.33 bar, which corresponds to a pF between 2-2.5. The pF can vary according to soil properties such as soil texture and organic matter. The permanent wilting point is when the water potential in the soil is at about -15 bar, which corresponds to pF 4.2 (Walker, 1989).

Three main types of irrigation methods exist according to FAO (1988): surface irrigation, sprinkler irrigation and drip irrigation. Surface irrigation can be divided into three kinds: basin irrigation, furrow irrigation and border irrigation. All methods have advantages and disadvantages and the

decision on which method to use needs to be based on several factors, such as the type of crop and soil, the amount of water available for irrigation and the work load of the farmer (Brouwer, et al., 1988). The selection of which method to choose depends on many factors, such as crop type, salinity of the soil, salt content of the water, soil type and availability of water. The selection is related to the soil salinity and the problems the salinity could cause. Below, a short summary of the methods mentioned above is presented.

### *Surface irrigation*

A basin irrigation system consists of basins surrounded by low banks to keep the water inside, see Figure 3.1. During irrigation the basins are flooded completely. Basin irrigation is suitable for all kinds of crops that can handle contact with water for a long time, like trees and rice. Not suitable crops are potatoes and other root vegetables. A basin irrigation system is also suitable for loamy soils to avoid water logging, except for example when growing rice when the water logging is wanted (Brouwer, et al., 1988). Basin irrigation is a good method when soil salinity is a problem (USSL, 1954).

Furrow irrigation basically uses small channels with the crops placed on top of the ridges in between, see Figure 3.2. While the water is flowing down the furrow, the water infiltrates and reaches the roots of the plants. This method is suitable for crops that cannot handle long water contact with their stem or leaves, like potatoes. However, also other types of crops, like trees and maize, can be irrigated with this method. This method works best on soils that does not consist of coarse sand since the water needs to stand in the furrow for some time to be efficient. The slope of the furrow needs to be large enough to provide good drainage but not too large, to avoid erosion of the ridges (Brouwer, et al., 1988). Furrow irrigation can lead to accumulation of salts where the water is not leached, i.e. the ridges (USSL, 1954).

Border irrigation functions similar to basin irrigation, but the basins are narrower and more like channels, see Figure 3.3. The borders only lead the water in the right direction; they do not hold the water in place (USSL, 1954). This method is mainly suitable for large, industrial or mechanized farms where the slope is enough to provide drainage (Brouwer, et al., 1988). The crops most suitable for this kind of irrigation are crops grown close together, like alfalfa or pasture crops (Brouwer, et al., 1988).

Since all the surface irrigation methods includes water being released and allowed to stand still over a large surface much water might be lost in evaporation and might infiltrate in areas with no crops; surface irrigation could have a lower irrigation efficiency than other methods.

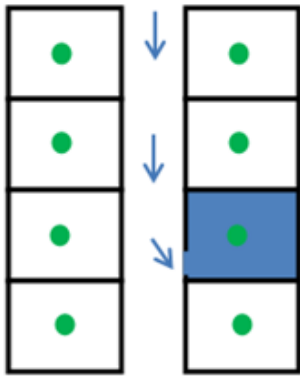


Figure 3.1. A schematic figure of the surface irrigation method basin irrigation, seen from above. The green points represent plants.



Figure 3.2. A schematic figure of the surface irrigation method furrow irrigation, seen from the side.

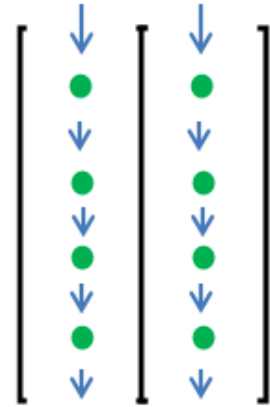


Figure 3.3. A schematic figure of the surface irrigation method border irrigation, seen from above. The green points represent plants.

### *Sprinkler irrigation*

Sprinkler irrigation is similar to a rainfall and the water is distributed by pipes and pumps. Most crops can be grown with this kind of irrigation. However, it is important to keep in mind the quality of the irrigation water when using this kind of irrigation system. The nozzles, with which the water is distributed over the crops, can be clogged if suspended solids are present in the water. This system can be adapted to almost any kind of field (Brouwer, et al., 1988). Sprinkling costs more than the other methods but is a good way to control the irrigation and to achieve higher irrigation efficiency. However, one problem that could occur with this method it that the leaching could become too small to leach the soil (USSL, 1954).

### *Drip irrigation*

A drip irrigation system usually consists of plastic tubing with holes on them to drip the water onto the soil at a low rate. The water is applied only to the root zone and it needs to be applied frequently. This method is often regarded as a way to save water, but the method in itself does not save water; the same amount of water for the plant is still needed. However, some water could be saved from a reduction in evaporation from the soil, infiltration through the soil and in surface runoff (Brouwer, et al., 1988). A disadvantage with this method is that the holes in the plastic tubes, with which the water is distributed to the crops, can be clogged if suspended solids are present in the water, as often in treated wastewater.



#### 4. Literature review - Water resources and agriculture in Tunisia

This chapter starts widely by describing the water resources and agriculture in Tunisia and the reader is given a general perception of the situation in Tunisia. The chapter continues with a description of the Cap Bon peninsula and ends with information about the situation in the city of Nabeul.

##### 4.1. Water resources

Circa half of the water resources in Tunisia is surface water, approximately 2 000 Mm<sup>3</sup>/year. However, Tunisia has mainly one permanent river, the Medjerda River, so most of the surface water resources, both the total and available, come from large dams, hillside dams and lakes (Bahri, 2002). Another large contributor to the Tunisian water resources is groundwater with approximately 2 000 Mm<sup>3</sup>/year. The reuse of water is very important in Tunisia and it is regarded as a water resource. However, compared to surface water or groundwater, the reused water is a small part of the water resources, approximately 200 Mm<sup>3</sup>/year. Below, a graph of the estimated water resources in Tunisia in 2010 can be seen in Figure 4.1 (Bahri, 2002).

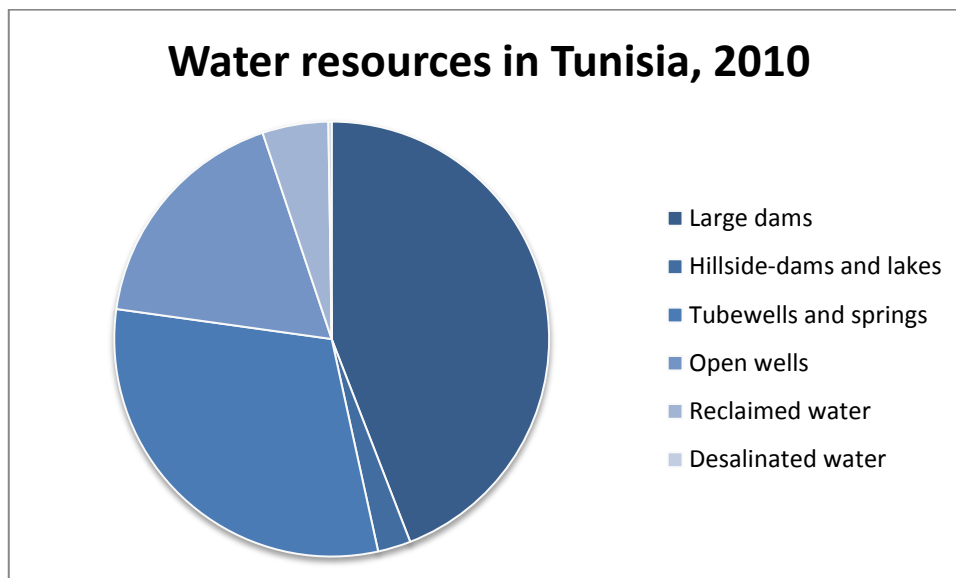


Figure 4.1. Water resources in Tunisia, 2010 (Bahri, 2002).

The water resources in Tunisia can also be seen in Table 2.1 below where possible future situations are included. The amount of water available for use is given. The amount of annual renewable water resources (ARWR) could be used as a water scarcity indicator, where less than 1 000 m<sup>3</sup>/capita means that severe water shortages may likely occur (Qadir, et al., 2010). According to Qadir et al. (2010), based on FAO data on water resources and World Resources Institute (WRI) population data, the Tunisian ARWR in 1975 was approximately 900 m<sup>3</sup>/capita and in 2009 approximately 500 m<sup>3</sup>/capita. In year 2025 the ARWR in Tunisia could be less than 500 m<sup>3</sup>/capita and this means that it is likely that greater water scarcity could happen in the country (Qadir, et al., 2010).

**Table 4.1.**The available water resources in Tunisia. Possible future scenarios are also presented. The resources include: large dams, hillside-dams, lakes, tube wells, springs, open wells, reused water and desalinated water (Bahri, 2002).

	<b>1996</b>	<b>2010</b>	<b>2020</b>	<b>2030</b>
	Available	Available	Available	Available
<b>Mm<sup>3</sup>/year</b>	2774	3300	3107	3122

According to the Intergovernmental Panel on Climate Change (IPCC) (2007), the temperature in the area around the Mediterranean will increase with between 2.2°C and 5.1°C during the 21<sup>st</sup> century. Also the precipitation will decrease with 4 % to 27 % in Tunisia and the evaporation will increase. Due to the decreasing precipitation and the increasing evaporation in the spring and summer, the soil moisture will decrease. A decrease in the soil moisture will lead to less available water for the crops. With these proposed climatic changes, the water resources in Tunisia would probably decrease even more in the future and larger problems with water scarcity could occur.

The available groundwater in Tunisia is often over-pumped (CRDA Nabeul, 2008), like in many other countries around the Mediterranean Sea, which could lead to seawater intrusion. When too much water is pumped from the groundwater aquifers, especially close to the coast, seawater can flow into the aquifers. This could lead to an increase in salinity in the aquifers and leave them less suitable for irrigation and consumption (Paniconi, et al., 2001).

The scarcity of adequate water in Tunisia has led to the reuse of treated wastewater for different purposes. These purposes include irrigation of crops, green areas in cities and golf courses.

#### **4.1.1. Treated wastewater as a resource**

In Tunisia, approximately 240 million m<sup>3</sup> of wastewater is produced every year. Nearly 97 % of that, approximately 235 million m<sup>3</sup>, is treated in public wastewater treatment plants and then most of it is released into the sea or streams (ONAS, 2010). The total amount of wastewater produced in Tunisia has increased due to many reasons, including socio-economic ones. An increase in population, urbanization, improved living conditions and economic development have contributed to a larger wastewater production (Qadir, et al., 2010).

Access to water is very important and so is the quality of the water. As mentioned above, treated wastewater has become more common as an additional water resource but the treated wastewater quality varies with many factors such as the water source quality, the industrial wastewater, the plant location and the treatment processes at the wastewater treatment plant, among others (Bahri, 2002). However, according to Bahri (2002) the average concentrations of nearly all regulated substances in the treated wastewater in Tunisia meet the Tunisian standards (which are discussed below in section 4.2.1). Bacteria and parasites could be present in the treated wastewater but if a simple wastewater treatment process, like stabilization ponds, is used this will not be a problem (Bahri, 2002).

A possible use of treated wastewater is groundwater recharge (Qadir, et al., 2010). According to Bahri (2002), groundwater recharge on a test level, in the vicinity of Nabeul, was efficient since both the water levels in the wells increased and the production around the groundwater recharge area also increased. This wastewater reuse could, in the future, lead to groundwater of good quality.



## 4.2. Agriculture

The agricultural sector is of greatest importance to the Tunisian economy and contributes on average 12 % to the Gross Domestic Product (GDP). In 2005 Tunisia had about 516 000 farms, and 75 % of these farms had an area smaller than 10 ha (ONAGRI, n.d.). There is little use in upgrading to more efficient farming and irrigation methods in small-scale farming because the more modern methods are hard to use on a small farm. Small-scale farming might thus hinder the agricultural development. This is a fact in Tunisia where the agriculture is mostly small scale and inefficient, and the land is not used to its potential ( Sveriges Ambassad Tunis, 2009). However, the agricultural production has grown substantially in the last decades and today Tunisia is self-sufficient with dairy products, fruits and vegetables (Utrikespolitiska Institutet, 2012).

Approximately 63 % of the land surface in Tunisia is potential arable land (Utrikespolitiska Institutet, 2012). The potential arable land includes already used arable land, rangeland, forest and shrublands (see Figure 4.2 below). Approximately 40 % of the use arable land is used for arboriculture; about 80 % of this is covered in olive trees (ONAGRI, n.d.).

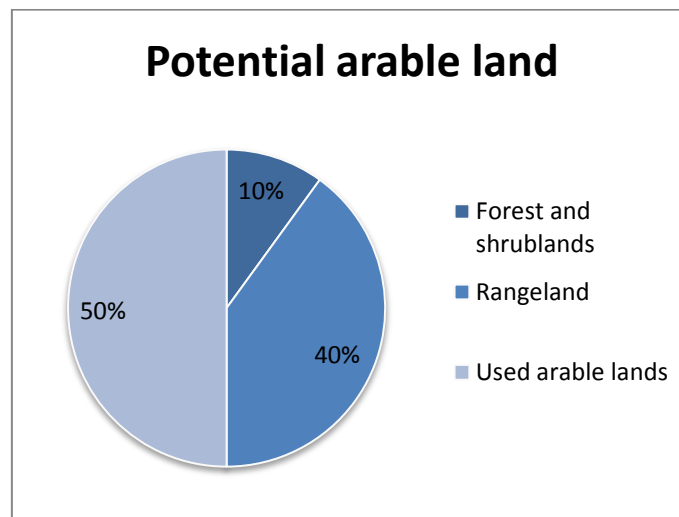


Figure 4.2. Land use for agricultural purposes in Tunisia (ONAGRI, n.d.).

The type of crop cultivated varies between the different regions. In the north the cultivated crops include wheat, barley, oats, corn and durra. In the peninsula Cap Bon the main cultivated crops are citrus fruits. Between Tunis and Bizerte there are several farms growing grapes and in the south they cultivate dates in the oases (ONAGRI, n.d.). But the most important crop in Tunisia is still olives which are grown in most parts of the country. Tunisia is one of the largest olive oil exporters in the world and olive oil corresponds to half of the exported food (Utrikespolitiska Institutet, 2012).

Irrigation is crucial in semi-arid Tunisia to be able to meet the crop water need for many crops and consequently agriculture consumes more than 80 % of the available water resources (Bouksila, 2011). Over the last 60 years the irrigated area in Tunisia has increased remarkably (Bouksila, 2011), and about 42 % of the agricultural land is adapted to use irrigation (ONAGRI, n.d.).

### 4.2.1. Irrigation with treated wastewater

Tunisia is a country well developed in reusing wastewater (Hamilton, et al., 2007 and Qadir, et al., 2010). According to Qadir *et al.* (2010) approximately 8 100 ha in Tunisia are irrigated with treated

wastewater, and Hamilton *et al.* (2007) stated that the amount of wastewater used for irrigation in Tunisia was 8.7 million m<sup>3</sup>/year in 1998. One of first wastewater reuse projects in Tunisia was started already in the 60s in the field La Soukra (Bahri, 2000).

The Tunisian restrictions for reusing water follow the WHO guidelines for wastewater reuse on health. For example, treated wastewater is not permitted to use on vegetables, that are eaten raw or cooked (Qadir, et al., 2010). It is not allowed to use untreated wastewater for irrigation for health and environmental risks (Lahlou Abid, 2005). In Table 4.2 below, the Tunisian restrictions for agricultural use of treated wastewater and the FAO guidelines for agricultural use of any irrigation water can be seen. Note that the Tunisian restrictions today do not include guidelines about fecal coliform bacteria. The FAO guidelines take long-term effects on crop production and soil conditions into consideration and the values are presented in Table 4.2 below. These are values which lead to no restriction on the usage of water (Ayers & Westcot, 1985). The WHO recommendations for the safe use of wastewater and excreta can be seen in Table 4.3 below. These standards can be reached by the use of a series of stabilization ponds and they are therefore possible to reach also in developing countries where the use of advanced wastewater treatment is limited. However, it should be noted that the WHO recommendations only take microbial quality of the water into consideration. Considering fruit trees, the fruits cannot be picked when they have fallen to the ground and the irrigation must stop two weeks before the harvest starts, to protect the consumers from infection (WHO, 2001).

**Table 4.2. The Tunisian standard for agricultural use of treated wastewater, NT 106.03, (INNORPI, 1989) and the FAO-guidelines for irrigation water quality (Ayers & Westcot, 1985). SAR is the sodium adsorption ratio and is calculated from the content of Na, Ca and Mg (Ayers & Westcot, 1985). me/l is milliequivalent per litre.**

Parameter	Tunisian restrictions	FAO guidelines
pH	6.5-8.5	6.5-8.4
Conductivity (dS/m)	7.0	0.7
Total suspended solids (mg/l)	30	
Chemical oxygen demand (mg O <sub>2</sub> /l)	90	
Biochemical oxygen demand, 5 days (mg O <sub>2</sub> /l)	30	
Nitrogen(NH <sub>3</sub> -N) (mg/l)	-	<5
Chloride (mg/l)	2000	<4 me/l at surface irrigation
Sodium (mg/l)	-	SAR<3 at surface irrigation
Fecal coliform (most probable number/100ml)	-	

**Table 4.3. The WHO recommendations for the safe use of wastewater in agriculture (WHO, 2001).**

Crop	Faecal coliform	Intestinal nematods
Crops eaten raw (and sport fields)	≤1000/100ml	≤1/litre
Cereal crops, fodder crops, industrial crops, pasture and tree crops	No limit	≤1/litre

At an investigated field in Tunisia, the bacteria contamination of the soil, from the treated wastewater, was insignificant. Citrus fruits, irrigated with treated wastewater for two years, showed

no contamination from fecal bacteria if they were not in contact with the soil (Bahri, 2002). However, at a workshop in Hyderabad, India, in 2002 it was declared that improper management of the reuse of wastewater in agriculture could be a serious threat to health and the environment (International Water Management Institute, 2002).

Irrigation using treated wastewater could mean a soil salinization risk since the average treated wastewater in Tunisia is moderately saline; the average electrical conductivity is 4.1 dS/m (Bahri, 2002). According to a study performed on wastewater treatment plants in Tunisia, the treatment processes at the wastewater treatment plants do not, in general, affect the water salinity. However, stabilization ponds are an exception. A stabilization pond can increase the salinity during warmer periods. In this survey, the average electrical conductivity (EC) in the treated effluent was between 2.4 and 8.9 dS/m (Bahri, 1998). Possible reasons for the salinity of the treated wastewater are presented in this survey; the salts could have come from seawater intrusion into the wastewater system, from a large proportion of industrial wastewater coming into the treatment plant or the plant could be located close to a salt lake (Bahri, 1998).

Some benefits from using treated wastewater for irrigation have been observed. According to Bahri (2002), tests on sorghum showed a better growth using treated wastewater. Tests on maize, alfalfa and barley showed better annual and perennial crop yields using treated wastewater for irrigation compared to irrigation with groundwater. Other tests on celery, eggplants, lettuce and maize also proved an increase in the yield due to the nutrient content in the treated wastewater (Hamilton, et al., 2007). So the treated wastewater could have a fertilizing value for some crops. The use of the treated wastewater also means less stress on the wells, which could in some coastal areas lead to less sea water intrusion. However, according to Hamilton *et al.* (2007), in some soils nitrogen leakage, from the treated wastewater, to the groundwater could occur. By using treated wastewater where it is possible, the conventional water could be saved and used for other more sensitive purposes, like tap water.

The farmers are very important for the development of wastewater reuse to save conventional water and to improve its quality. However, farmers in Tunisia are often resistant to use the treated wastewater for irrigation even if the price of the treated wastewater is much lower than the price of conventional water (Qadir, et al., 2010). Some reasons for this resistance could be the perception of the treated wastewater as dirty and unhealthy. Farmers sometimes also find that the treated wastewater affects the crop and soil in a negative way and they are, in Tunisia, not allowed to grow high-profit vegetables using this water (Lahlou Abid, 2005). So, health risks combined with economic disadvantages lead to a resistance towards the reuse of treated wastewater. However, governmental actions could lead to better understanding for irrigation with treated wastewater. In Tunisia, an increase in farmers using treated wastewater was due to a combination of a campaign by the government and an increase in water scarcity (Lahlou Abid, 2005). The wastewater reuse in Tunisia is well supported by the government which could lead to a wider acceptance and reuse of treated wastewater (Qadir, et al., 2010).

In the 1970s, a policy regarding the golf courses in Tunisia was made, to increase the use of treated wastewater for irrigation. At least eight golf courses, of the total ten (LeadingCourses, n.d.), in Tunisia are today irrigated using treated wastewater; some are using treated wastewater mixed with conventional water. According to Qadir *et al.* (2010), the total golf course area irrigated by treated

wastewater is approximately 1000 ha. The eight golf courses in Tunisia use approximately 4 million m<sup>3</sup> of treated wastewater per year which is a large part of the total amount of reused treated wastewater in Tunisia (Lahlou Abid, 2005). Other green areas in Tunisia are also irrigated using treated wastewater, approximately 420 ha (Qadir, et al., 2010).

### 4.3. Cap Bon

The province Cap Bon lies on a peninsula in northeastern Tunisia. The climate in the area is Mediterranean and the province is very important to the Tunisian economy and about 762 600 people resides here (Institut National de la Statistique - Tunisie, 2012). The water resources and the agriculture in this area are presented below.

#### 4.3.1. Water resources

In Cap Bon the main water resource is groundwater (see Figure 4.3 below). However, the demand for groundwater for irrigation is generally much higher than the actual supply, this resulting in serious problem with salt water intrusion in this area. A substantial amount of the available water resources are used for agriculture (CRDA Nabeul, 2008). With the term Water from the North it means water transported from the northern part of Tunisia, mainly the Medjerda River.

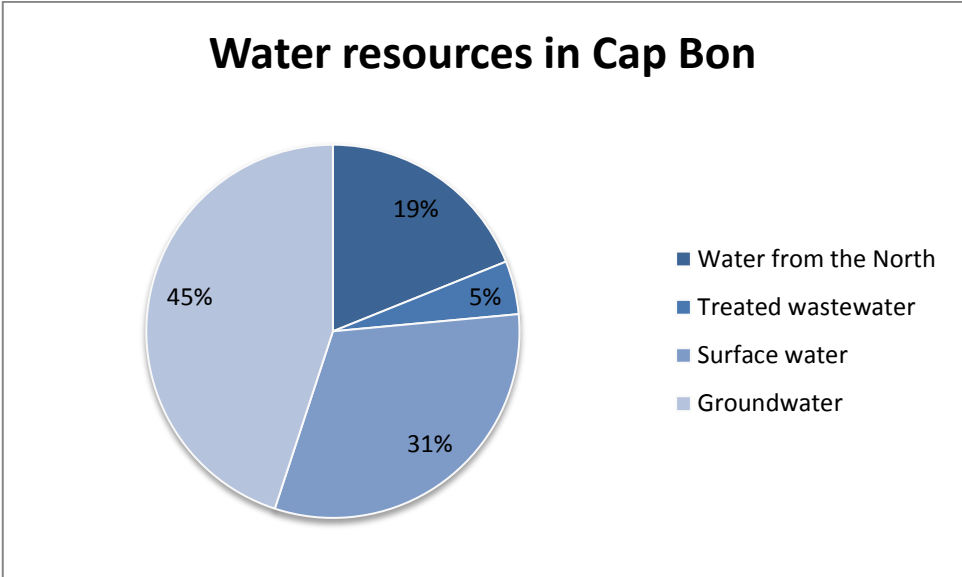


Figure 4.3. Water resources in Cap Bon (CRDA Nabeul, 2008).

#### 4.3.2 Agriculture

The province Cap Bon represents about 15 % of the total agricultural production in Tunisia. The main crops cultivated in Cap Bon are listed in Table 4.4 below, together with the extent of their respective production (CRDA Nabeul, 2008). Except for the crops mentioned in Table 4.4 below, olives, forage and pomegranate are also grown in this area.

Table 4.4. Main crops grown in Cap Bon (CRDA Nabeul, 2008).

Crop	Area (ha)	Annual production (ton)	Percentage of total production in Tunisia
Citrus	12 500	186 000	83
Vines	16 500	63 000	38.3
Tomatoes	12 000	600 000	63
Potatoes	7 500	145 000	45.3
Strawberries	460	14 000	97
Spices	1 700	1 950	90

About 66 % of the total 284 000 ha land surface in Cap Bon is used for crop cultivation. In Figure 4.4 below one can see land use in Cap Bon (CRDA Nabeul, 2008).

75 % of the citrus farms in Cap Bon are smaller than 5 ha (CRDA Nabeul, 2008). Thus the majority of the farms are small-scale and the area is not as efficient as it could be, just as mentioned above ( Sveriges Ambassad Tunis, 2009). The distribution of the citrus farm size in Cap Bon can be seen in Figure 4.5 below (CRDA Nabeul, 2008).

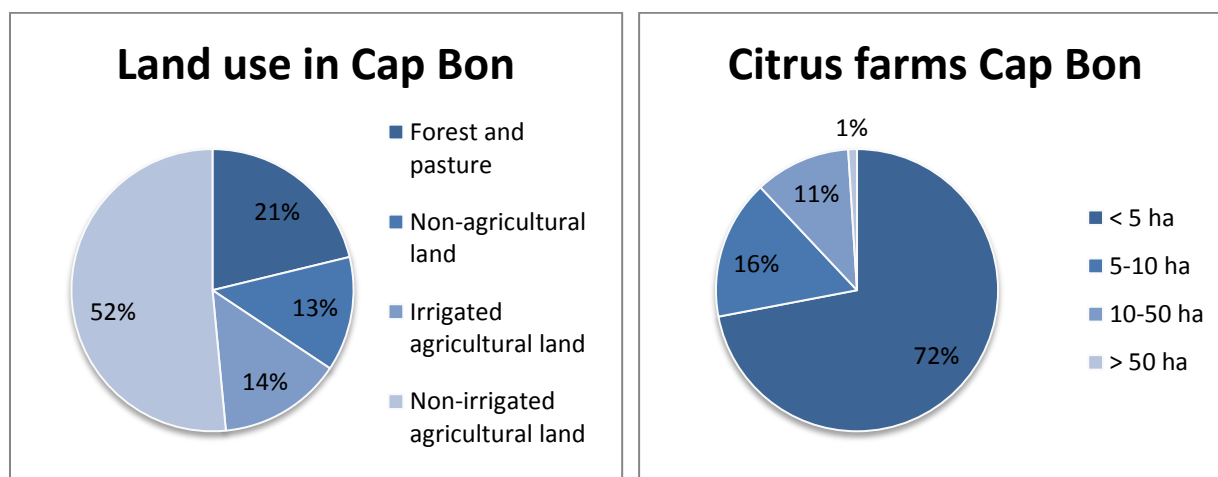


Figure 4.4. Land use in Cap Bon (CRDA Nabeul, 2008).

Figure 4.5. Citrus farms in Cap Bon (CRDA Nabeul, 2008).

Together with well water the water from the North make up about 89 % of the water supply for irrigation and only 2 % of the irrigated water comes from treated wastewater, as can be seen in Figure 4.6 below. There are currently three wastewater treatment stations in Cap Bon adapted to distribute the treated wastewater to the local irrigated districts. Two of them lie near the city of Nabeul and the third is in the north of Cap Bon near the city of Kélibia. Today about 550 ha are supplied with treated wastewater in Cap Bon (CRDA Nabeul, 2008).

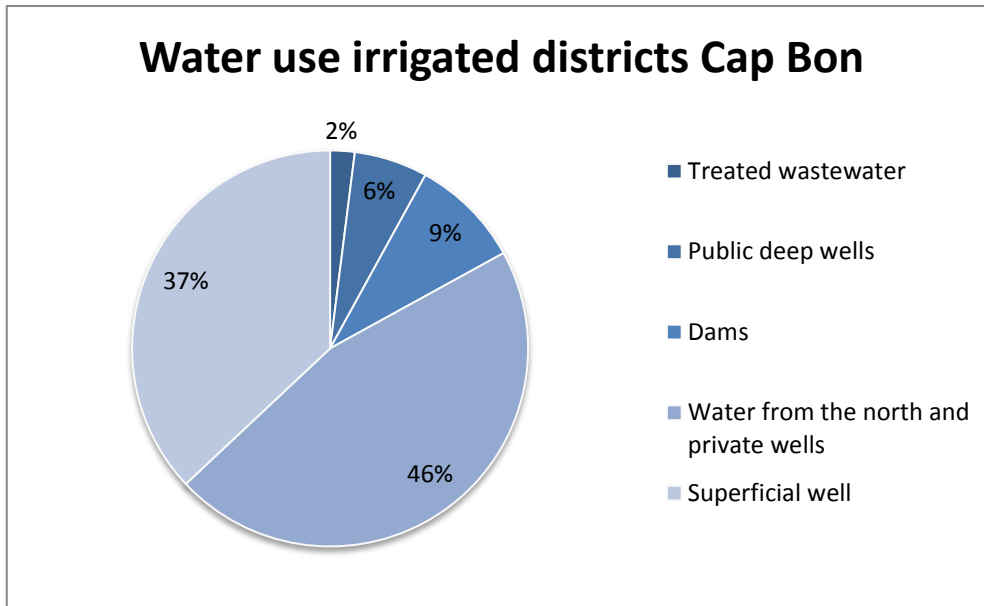


Figure 4.6. Water use of the irrigated districts in Cap Bon.

#### 4.4. Nabeul

The wastewater plant and distribution system in Nabeul and the organization of the farmer's development associations are presented below. Nabeul is the provincial capital and all the governmental institutions of the region Cap Bon are located here.

##### 4.4.1. Wastewater

The city of Nabeul is served by two wastewater treatment plants, called SE4 and SE3. The location of these two plants can be seen in Figure 4.11. The plants are located close to the sea and are therefore in the lower parts of the region. This location provides a gravitational flow from the city towards the plants and less energy is needed to pump the wastewater (Mr Mohamed Salah Glaied, CRDA, personal contact, 19-9-2012). SE4 receives water from three nearby cities, Nabeul, Beni Khiar and Dar Charbane, while SE3 receives wastewater only from Nabeul (Mr Mohamed Salah Glaied and Mr Tarak Chmingui, CRDA, personal contact, 19-9-2012). Together SE4 and SE3 receive and treat approximately 6 000 000 m<sup>3</sup>/year. 25-30 % of this is reused for irrigation and 250 000 – 300 000 m<sup>3</sup>/year, or 4-5 %, is reused for groundwater recharge. The rest of the treated water is released into a stream or the sea (Mr Mohamed Salah Glaied, CRDA, personal contact, 19-9-2012).

The two plants use primary and secondary treatment in somewhat different designs. The SE4 has separated the different steps in the process. The primary, or physical, treatment consists of four steps. The first is a grid to block larger particles and garbage, see Figure 4.7. After that the wastewater goes through a sand suction to remove sand and then through an oil and fat remover. The final physical step is combined floatation and sedimentation basins to start the removal of organic matter. According to observations, these basins do not work perfectly today, they are old and much organic matter still passes through these basins. In the primary treatment, approximately 40 % of the suspended solids and larger particles are removed. The secondary treatment is biological treatment that takes place in activated sludge basins (see Figure 4.8) and again, combined floatation and sedimentation basins. The activated sludge process removes most of the organic matter left in the wastewater. The last sedimentation and floatation basin in SE4 is broken and therefore the treated wastewater, which is collected in an open reservoir, still contains some suspended solids, see



Figure 4.9. The sludge that is produced in the entire process is either being processed in a digester, to dry the sludge and to produce gas, or returned into the activated sludge process to keep the microorganisms active. After the sludge leaves the digester it is transported to a sludge press (Mr Mohamed Salah Glaied and Mr Tarak Chmingui, CRDA, personal contact, 19-9-2012). The SE3 has a more compact design where one large basin contains both activated sludge and sedimentation and floatation, see Figure 4.10.



Figure 4.7. The physical treatment at SE4. This is the grid to block larger particles.



Figure 4.8. The biological treatment process at SE4.



Figure 4.9. The last sedimentation and floatation is broken and the treated water contains suspended solids at SE4.



Figure 4.10. The more compact design of SE3.

The SE4 is the larger of the two and has a capacity of 9 585 m<sup>3</sup>/day (ONAS, 2011). This capacity was adapted to handle the wastewater from 81 400 inhabitants, which was the population in 1979 when the plant was built. However, today the population in this area has increased and the SE4 plant receives wastewater from approximately 150 000 inhabitants (Mr Mohamed Salah Glaied and Mr Tarak Chmingui, CRDA, personal contact, 19-9-2012). This means that the plant sometimes needs to treat more than twice of the capacity. The flow through the plant is measured every day and the maximum in September 2012 was approximately 18 000 m<sup>3</sup>. The SE3 plant was built in 1981 with a capacity of 3 500 m<sup>3</sup>/day (ONAS, 2011) and today this plant often handles a flow of more than twice its capacity. This heavy load to the plant affects the quality of the treated wastewater and this can be

seen in the reservoirs where the water is collected and stored. Large amounts of particles can be seen in the open storage basin.

The two plants were built several years ago and the old age is visible, both in the general appearance of the plants and the quality of the treated wastewater. The plants are not properly maintained due to lack of funding and due to plans of building a new wastewater treatment plant close to SE4. In the end of 2012 a new plant should start to be constructed which will include also a tertiary treatment. According to Mr Mrabet Slim (personal communication, 2012), the principal biochemist of ONAS in Nabeul, the new plant will have a capacity of 18 000 m<sup>3</sup>/day and a maximum capacity of 24 000 m<sup>3</sup>/day and it will utilize new technology and be completely automatic. The plant will use less energy and the quality of the treated wastewater will be better. An improved wastewater quality could lead to fewer restrictions for the farmers on which crop to grow and maybe make it possible to use other irrigations methods.

*Distribution of treated wastewater*

The treated wastewater is led from the wastewater plant to reservoirs close to the plants. The plants are under the supervision of the Department of Environment. However, when the water reaches the reservoirs, the water is under the supervision of the Regional Department for Agricultural Development (CRDA) (Mr Mohamed Salah Glaied, CRDA, personal contact, 19-9-2012).

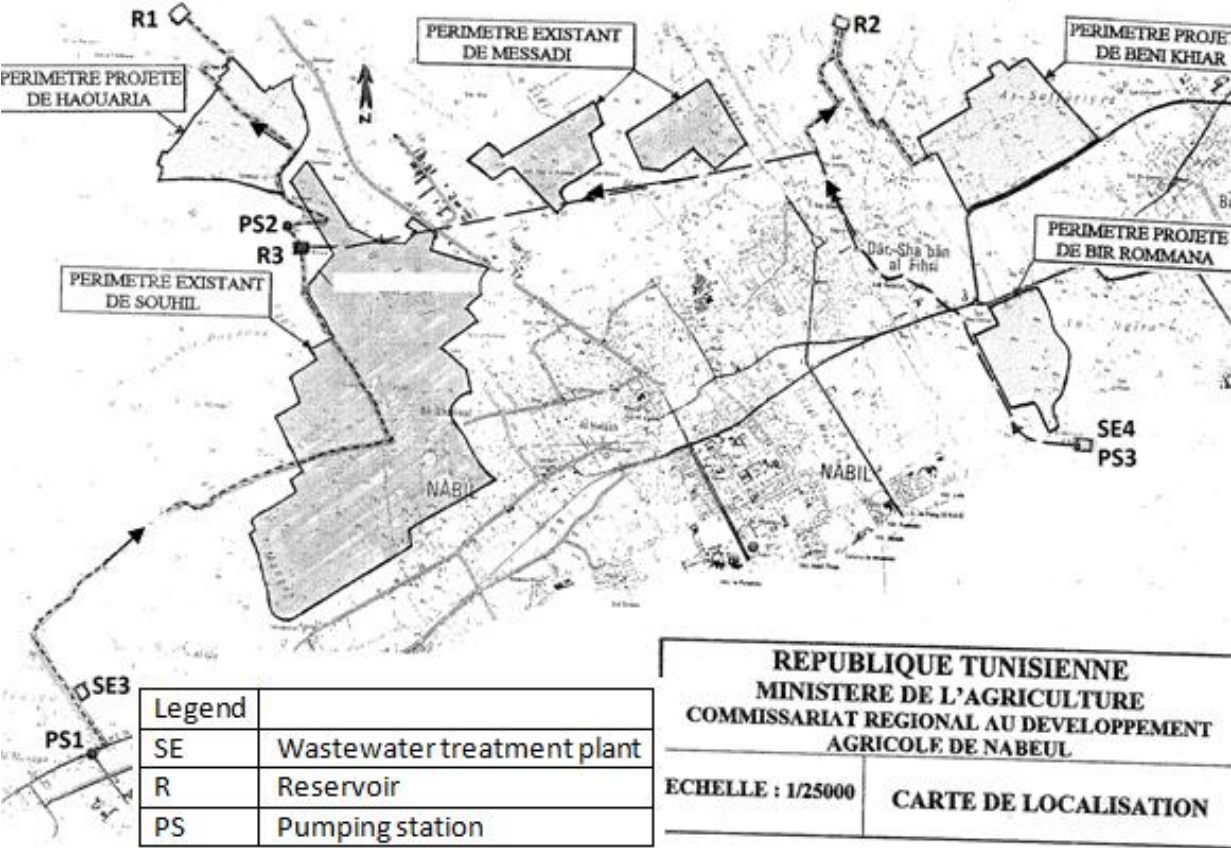


Figure 4.11. The distribution system of the wastewater around the city of Nabeul. Arrows indicate the direction of the flow of water (modified from CRDA, 2012).

From the reservoirs the water is pumped to the distribution system. The treated wastewater is delivered to 7 irrigation districts, see Figure 4.11. At SE4, the pumping is done by 3 pumps with an



original capacity of 400 m<sup>3</sup>/h/pump at a pumping station, PS3, close to the wastewater treatment plant. However, the pumps are now old and can only work at a capacity of 250 m<sup>3</sup>/h/pump (Mr Mohamed Salah Glaied, CRDA, personal contact, 19-9-2012). The reservoir at SE4 has a capacity of 500 m<sup>3</sup>. From the pumping station PS3 the water is transported to another reservoir at a higher altitude, R2, or to the nearby irrigation district of Bir Romana. The reservoir R2 is located at 61 meters above sea level and from here the water is distributed to the fields Charki and Messadi 2 by gravity. The capacity of R2 is approximately 2000 m<sup>3</sup>. R2 can also provide another reservoir, R3, with some water if there is enough water in R2 (Mr Mohamed Salah Glaied, CRDA, personal contact, 19-9-2012).



Figure 4.12. The reservoir R3 receiving water from the two wastewater plants.



Figure 4.13. The water at the pumping station PS1 is not of good quality due to the large amounts of wastewater being received to SE3.

The plant SE3 has a pumping station located nearby, PS1 (see Figure 4.13) and this pumping station provides reservoir R3 with water. During the transportation it also pumps to the irrigation district Souhil, since this district is located on the way to the reservoir R3. R3 is located at 50 meters above sea level and provides the Souhil and Massadi 1 districts with irrigation water, see Figure 4.12. The capacity of R3 is approximately 4500 m<sup>3</sup>. Water is also pumped from the station PS2 towards another reservoir, R1, to provide the irrigation district of Haouaria with treated wastewater. The capacity of R1 is approximately 2000 m<sup>3</sup> (Mr Mohamed Salah Glaied, CRDA, personal contact, 19-9-2012).

#### *Water quality of the wastewater*

The quality of the treated wastewater coming from the two wastewater treatment plants for five months, May to September 2012, can be seen in Table 4.5 below. The water samples were taken at the pumping stations nearby the wastewater treatment plants. The values that exceed the Tunisian restrictions are marked bold. The physiochemical and microbial analyses are performed by INRGREF, Tunis. No analyses are performed during the time when no irrigation takes place, i.e. spring and winter.

Table 4.5. The treated wastewater quality from SE3 and SE4, 2012. The values that are bold are the values that exceed the Tunisian standards. TSS means Total Suspended Solids, COD means Chemical Oxygen Demand, BOD5 means Biochemical Oxygen Demand, 5 days and MPN means Most Probable Number. The laboratory analyses are done at INRGRF, Tunis.

	22 <sup>nd</sup> of May		26 <sup>th</sup> of June		26 <sup>th</sup> of July		29 <sup>th</sup> of August		18 <sup>th</sup> of September	
Parameter	SE3	SE4	SE3	SE4	SE3	SE4	SE3	SE4	SE3	SE4
Temperature (°C)	22.6	21.8	27.7	26.9	29.6	28	31.4	28.6	29.5	28.1
pH	7.5	7.9	7.5	7.6	8.1	7.8	7.6	8.1	7.7	8.0
Conductivity (dS/m)	3.11	3.15	3.14	2.96	2.9	2.8	2.9	3.3	3.1	2.9
TSS (mg/l)	<b>50</b>	<b>80</b>	<b>120</b>	<b>400</b>	<b>200</b>	<b>140</b>	<b>162</b>	<b>235</b>	<b>60</b>	<b>60</b>
COD (mg O <sub>2</sub> /l)	<b>92.3</b>	<b>166</b>	75.2	<b>205</b>	<b>297</b>	<b>310</b>	<b>160.5</b>	<b>165</b>	<b>106</b>	<b>94.4</b>
BOD5 (mg O <sub>2</sub> /l)	<b>40</b>	<b>63</b>	<b>67</b>	<b>165</b>	<b>96</b>	<b>67</b>	<b>59</b>	<b>76</b>	<b>62</b>	<b>38</b>
NH <sub>3</sub> -N (mg/l)	41.95	69.57	41.4	47.6	29.98	36.41	24.5	34.6	24.5	34.8
Na (mg/l)	617	596.9	485.6	449.6	731.2 1	669.9 3	731.2	706.7	580.1	547.4
K (mg/l)	36.8	49	-	-	42.25	57.16	-	-	69.6	47.2
Cl (mg/l)	591.7	500	512.5	537.5	537.5	425	575	550	725	550
Fecal coliform (MPN/100 ml)	1.1·10 <sup>7</sup>	1.1·10 <sup>7</sup>	7.5·10 <sup>6</sup>	1.1·10 <sup>8</sup>	9.3·10 <sup>5</sup>	1.1·10 <sup>8</sup>	4.3·10 <sup>6</sup>	4.3·10 <sup>6</sup>	9.3·10 <sup>6</sup>	2.3·10 <sup>8</sup>

From Table 4.5 it is clear that the two wastewater treatment plants cannot deal with the amount of wastewater needed to be cleaned since the influent to the plants often exceeds the capacity. Some substances do not reach the restrictions however, the conductivity never exceeds 3.5 mS/cm and the average conductivity for both SE3 and SE4 is approximately 3 mS/cm. This seems low compared to the average EC in Tunisian treated wastewater mentioned above. As a comparison the tap water measured in October 2012 in Nabeul have an EC of 1.5 dS/m.

The treated wastewater that is distributed to the Souhil irrigated district, from the reservoir B3, is a mix of water from SE3 and SE4. The water quality in this reservoir can be seen in Table 4.6 below. The values that exceed the Tunisian restrictions are marked bold. In July and August, the reservoir was empty the day for the sampling and no sample was collected.

Table 4.6. The treated wastewater quality, 2012, in the reservoir supplying Souhil irrigation district with irrigation water. Values come from INRGREF, Tunis. The values that are bold are the values that exceed the Tunisian standards.

Parameter	22th of May	26 <sup>th</sup> of June	18 <sup>th</sup> of September
Temperature (°C)	22.4	27.8	28.8
pH	7.8	7.5	7.8
Conductivity (dS/m)	3.23	3.09	3.0
Total suspended solids (mg/l)	30	<b>600</b>	<b>100</b>
Chemical oxygen demand (mg O <sub>2</sub> /l)	80.4	<b>379</b>	<b>106.7</b>
Biochemical oxygen demand, 5 days (mg O <sub>2</sub> /l)	<b>33</b>	<b>217</b>	<b>41</b>
NH <sub>3</sub> -N (mg/l)	80.11	32.8	31
Na (mg/l)	563.4	449.6	518.8
K (mg/l)	42.9	-	42.2
Cl (mg/l)	575	675	600
Fecal coliforms (most probable number/100 ml)	>1.1*10 <sup>7</sup>	2.8*10 <sup>6</sup>	4.3*10 <sup>6</sup>

The average conductivity for the water distributed to Souhil irrigation district is approximately 3.1 dS/cm and it never exceeds 3.3 dS/cm. However, note that the BOD<sub>5</sub>, COD and TSS often exceed the Tunisian standards.

#### 4.4.2. Agriculture Development Association (GDA)

GDA (Groupement de Développement Agricole) is an organization under CRDA in Nabeul and is run mainly by its members, the farmers in the local agricultural districts. The purpose of the GDA is firstly to share the available water between its members and develop and maintain the irrigation water distribution network. Other responsibilities of the GDA include the prevention and treatment of pests and insects, organizing workshops and conferences for the farmers in educational purposes and to act as a bridge between the farmers and the CRDA (Mrs Sonia Mahmoud, GDA, personal contact, 26-09-2012).

In the province of Cap Bon there are in total 41 GDAs to represent and organize the local farmers. Around the city of Nabeul there are two GDAs representing the seven irrigated districts (Mr Isam Jedidi, CRDA, personal contact, 21-09-2012). The first GDA is commonly known as the Souhil GDA and represents the three irrigated districts of Souhil, Haouaria and Messadi 1, see Figure 4.11, with a total area of 403 ha of agricultural land irrigated with treated wastewater. The other GDA in Nabeul represents the irrigated districts Messadi 2, Beni Khiair and Bir Rommana, that together have an area of 141 ha that is irrigated with treated wastewater (Mrs Sonia Mahmoud, personal contact, 26-09-2012).

The Souhil irrigated district was constructed in 1982 and today there are 205 farmers that use the treated wastewater supplied by the GDA, and they can thus be regarded as members. However, the irrigated districts holds more farmers, but some chose to not use the water supplied by the GDA, for

different reasons, and use other water resources (Mrs Sonia Mahmoud, personal contact, 26-09-2012).

*Organizational structure of Souhil GDA*

The Souhil GDA is run by its members/the farmers, an administrative committee and a technical committee. The hierarchical structure of the Souhil GDA is described below in Figure 4.14.

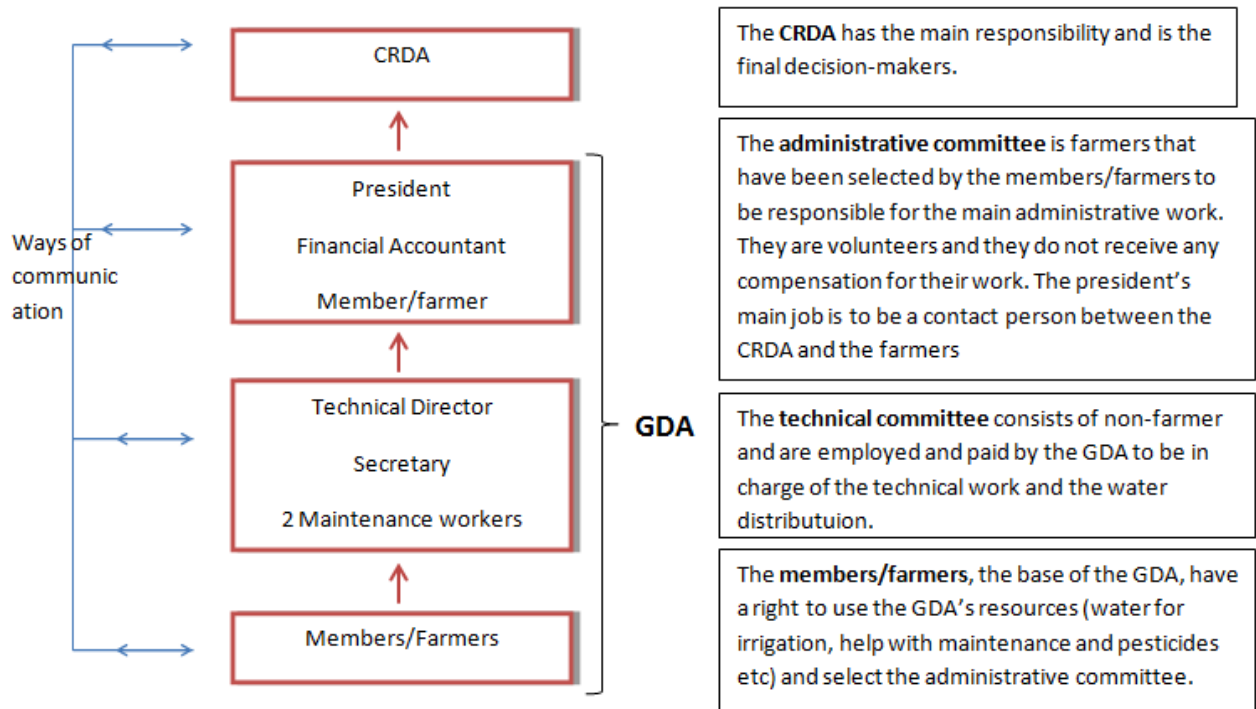


Figure 4.14. The structure of Souhil GDA.

*Irrigation in Souhil district*

The CRDA distributes the treated wastewater to the GDA without any financial compensation and the GDA then sells the water to the farmer for a small amount. The charge the GDA take for the irrigation water is to cover the salaries for the technical committee and the maintenance costs. The price is 30 millimes/m<sup>3</sup> (1 millime=1/1000 Tunisian Dinars, 1 Tunisian Dinar=4.2 SEK on current date), the total cost for the farmer is thus dependent on the water flow and the time used for irrigation (see Table 4.7 for details) (Mrs Sonia Mahmoud, personal contact, 26-09-2012).

Table 4.7. Hourly price for the irrigation water (Mrs Sonia Mahmoud, personal contact, 26-09-2012). DT means Tunisian Dinars.

Flow (m <sup>3</sup> /h)	Price (DT/h)
35	1.05
45	1.35
60	1.8
90	2.7

The amount of water a farmer can receive depends firstly on the amount of available wastewater, and secondly on the crop water need for the each specific crop. However, the demand for irrigation water can often not be fulfilled, especially during the warm summer months. This is a major problem for the farmers and can greatly affect the production (Mr Mohamed Salah Glaied, Mr Samir Gabsi and Mr Tarak Chmingui, personal contact, 19-09-2012). Furthermore, since 2009 there has been a sizable decline in the available treated wastewater, partly due to some technical problems at the wastewater treatment plants that have not been fully repaired. The demand within the Souhil GDA is approximately 10 000 m<sup>3</sup>/day during the irrigation season, but unfortunately this demand is very rarely fulfilled (Mrs Sonia Mahmoud, personal contact, 26-09-2012).



## 5. Method

The field study for this master thesis has consisted of four parts; a field experiment, soil laboratory analyses, data analysis and a farmer survey. The four parts have all been done to achieve the objectives presented above. Each part is described in detail in this chapter. Most soil laboratory analyses used are standard methods and more detailed descriptions of the methods are provided in the references given.

### 5.1. Field experiment

Four campaigns of ECa readings, using the EM38, and soil samples were collected; one campaign representing the initial conditions, two campaigns after irrigations and one after rainfall. Also, WET-sensor readings were taken during each campaign. Both EM38 and soil sampling were performed on the same day for the two last campaigns. However, due to time issues, the first two campaigns were conducted over two days. The data collections were performed 2 or 3 days after the irrigation or rainfall event to try to keep the soil water content close to field capacity. For a more detailed description of the campaigns and the activity on Field H see Table 5.1 below.

Table 5.1. The activities and collecting campaigns on Field H.

Month	Date	Activity	Campaign
September	12	Measurement with EM38	Initial conditions
	13	Soil sampling	
	16	Irrigation	
	17	Irrigation	
	20	Measurement with EM38 and soil sampling	After one irrigation event
	23	<i>Rain, 23 mm</i>	
October	7	Irrigation	
	8	Irrigation	
	10	Measurement with EM38	After two irrigation events
	11	Soil sampling	
		<i>Rain, 57.5 mm</i>	
November	1	Measurement with EM38 and soil sampling	After rain

#### 5.1.1. Site description

The field experiments were conducted in the irrigated district of Souhil close to the city of Nabeul in the Cap Bon province during September, October and the beginning of November 2012. One field was chosen and given the reference Field H. The location of the field, related to the city of Nabeul, can be seen in Figure 5.1.

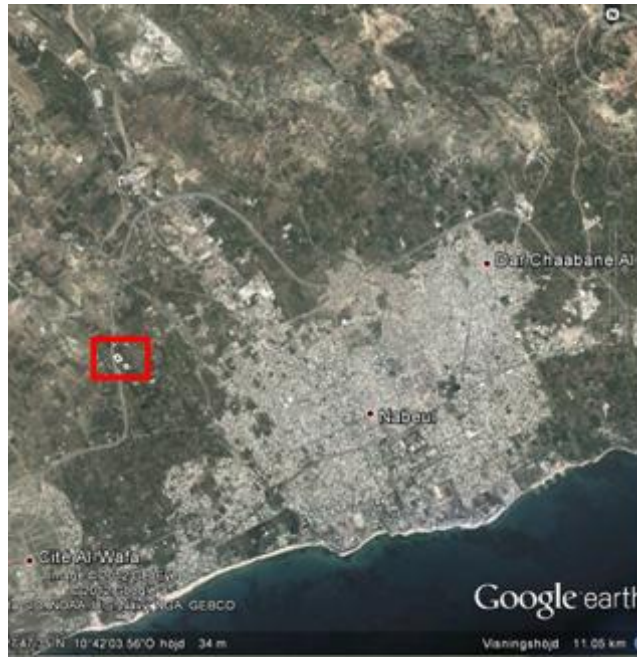


Figure 5.1. The location of the field related to Nabeul. The red square marks the field (modified from Google Earth, 2012).

The average temperature in the area is 26°C during summer and 15°C during winter. The annual rainfall is approximately 455 mm (based on measurements from 1982-2007) and the estimated evapotranspiration, using Penman-Monteith model (Allen, et al., 1988), is 1200 mm/year (based on measurements from a ten year period). The climatic data comes from a nearby located weather station, the Oued Souhil station.

The surface of Field H is slightly larger than the marked area in Figure 5.2, but to keep the experimental field more easily spatially analyzed, a rectangular part of the field was chosen. The experimental field measures 50 times 70 m. The field has a slight inclination towards the south. Field H holds citrus and olive trees where the distance between the olive trees is approximately 8 m and between the citrus trees approximately 4 m. There is in total 146 trees on field H, 104 citrus trees and 42 olives. Some trees are very young and small while other trees are older and larger. At some points a tree has been removed or was excluded in this experiment since they were regarded too small. The general location of the trees can be seen in Figure 5.2. The upper right corner tree, H1, is located at N 36°27'37.5", E 10°42'6.0". For a schematic description of the location of the olive and citrus trees, see Appendix I. According to the farmer, the groundwater level is below 5 m in this field.





Figure 5.2. The general location of the trees at Field H. The red and white points represent the chosen soil sample points and the EM38 readings respectively (Google Earth, 2012).

The field is irrigated using basin irrigation. The basin irrigation in Field H can be seen in Figure 5.3 – Figure 5.6. Only the citrus trees are irrigated since the olive trees can survive with the water provided from rain. However, some of the pipes used for the irrigation have leaks and accidentally irrigated some of the olive trees. The field is irrigated during the summer and early fall. In one agricultural year, from September 2011 to October 2012, the field was irrigated 6 times. Field H is irrigated for 16 h each time and the valves should provide irrigation water at 60m<sup>3</sup>/h. However, the farmer experiences a lower flow, approximately 40m<sup>3</sup>/h. Each irrigation event adds 640 m<sup>3</sup> to the field. Thus, the approximate total amount of irrigation water added to the field every agricultural year is 3 800 m<sup>3</sup> or 10 900 m<sup>3</sup>/ha. Table 5.2 below gives an overview of the inputs and outputs of water and salts to Field H during this field study. The calculations for the given values can be seen in Appendix II.

Table 5.2. Overview of the input and output to Field H.

September (13-30 September)				October (1-31 October)			
Rain (mm)	Evaporation (mm)	Irrigation (m <sup>3</sup> )	Added salt (kg)	Rain (mm)	Evaporation (mm)	Irrigation (m <sup>3</sup> )	Added salt (kg)
32	69.3	640	1286	57.5	86.49	640	1286
<b>Total amount of added water</b>			219 mm	<b>Total amount of added water</b>			227 mm

During the irrigation plastic tubing is used to lead the irrigation water via channels between the basins from the northwestern part of the field towards the southeastern parts. The tubes are located in the northwestern part of the field and they are often broken and irrigation water is leaking out in the basins of the trees located close to the plastic tubing.



Figure 5.3. Basin irrigation in Field H. The channel and the plastic tube delivering water to the basins.



Figure 5.4. Basin irrigation in Field H. Water entering the basin.



Figure 5.5. Basin irrigation in Field H. Note the leaking tube to the left of the tree.



Figure 5.6. Reeds growing under an olive tree in Field H after irrigation.

### 5.1.2. Soil salinity measurement with EM38

Using an EM38 (Geonics Ltd, Ontario) ground conductivity meter, ECa readings were taken at 146 points, close to the trees. The readings were taken inside the irrigation basin for each tree. At each point, both a vertical, EMv, and a horizontal, EMh, coil values were read. Each reading was repeated three times in different directions to provide an average value. Before the readings, the EM38 was calibrated according to the manual. During the readings, no metals or electronic devices were allowed close to the equipment because the instrument is affected by the high EC of metals. Figure 5.7 displays ECa measurements being taken using an EM38.

### 5.1.3. Soil sampling

The first campaign included soil sampling at 7 points, H44, H49, H54, H71, H104, H112 and H121, see Figure 5.2. All of these trees are citrus trees and were chosen since the olive trees are not irrigated. The rest of the campaigns also included H60; an olive tree to be used as a reference point since this point is not irrigated. The selection of these points was made by looking at a sample design made by ESAP-RSSD, generated from the EM38 readings, and by looking at the field and adjusting the

selection according to knowledge about the ECa readings, from the first campaign, distribution from maps generated by ESAP-Saltmapper.

The sampling depths were 0-0.3, 0.3-0.6, 0.6-0.9, 0.9-1.2 and 1.2-1.5 m. For each depth, all soil collected using a hand auger was put in a bucket, and a small and well mixed sample was put into a glass bottle with a lid, to preserve the soil moisture for soil water content calculations. The rest of the soil from each depth was put into marked plastic bags for transport to the soil laboratory. Figure 5.8 and Figure 5.9 display soil samples being taken using a hand auger.

#### *WET sensor*

A WET sensor (Delta T Devices Ltd, UK) was used at the middle of the three first soil depths, see Figure 5.10. The two deepest sample depths were too deep; it was not possible to insert the WET sensor by hand. The temperature, the volumetric soil water content, the pore water conductivity and the bulk conductivity were measured using the WET sensor. The temperature was measured to convert the EM38 readings to a reference temperature of 25°C, according to Equation 3.10. The rest of the measured parameters were used as control. The reason for using the WET sensor is to be able to check the soil salinity variations during the field work and soil water content data during data analysis.

#### **5.1.4. Bulk density**

The bulk density was measured according to the Agricultural Handbook No 60 from USDA (1954) in order to convert the gravimetric soil water content to volumetric. The aim was to measure bulk density at five depths, 0-0.1, 0.1-0.3, 0.3-0.6, 0.6-0.9 and 0.9-1.2 m, for all the points where soil samples were taken. However, due to time issues, this was not possible and only three points for the field were chosen in the end. Two profiles at each point were made and an average calculated for each depth. Figure 5.11 and Figure 5.12 below displays a bulk density sample being collected.

The bulk density points in Field H were chosen according to a visual estimation of the soil particle size distribution and the ECa distribution. The field could approximately be divided into three areas: one with higher ECa values, one with lower and one with the middle range values. This was done after the second EM38 campaign, after the first irrigation in this field study. One point was chosen within each area to provide a bulk density for all the soil sample points within the respective areas. So H49, H104 and H121 were chosen and the representation of these points can be seen in Table 5.3 below. In Field H, a clay layer around 1 m below the surface caused some problems. Thus, only one bulk density sample was collected from the depth 0.9-1.2 m. This bulk density was used for the deepest section in the entire field.

**Table 5.3. The representation of the bulk density over Field H.**

<b>Bulk density point</b>	<b>Representative soil sample point</b>
<b>H104</b>	H54, H104
<b>H49</b>	H49, H60, H112
<b>H121</b>	H44, H71, H121





Figure 5.7. EM38 measurements being taken.



Figure 5.8. Field work.



Figure 5.9. Soil sampling.



Figure 5.10. The WET-sensor.



Figure 5.11. Bulk density sampling.



Figure 5.12. A bulk density sample.



## 5.2. Soil laboratory analyses

All of the laboratory analyses require the soil to have been dried in an oven, for 24 hours at 105 °C or during at least two or three days at 40°C. This was done in paper bags, or in wooden trays for the very clayey soil samples, see Figure 5.13 below. After the drying, the samples needed to be crushed and sieved through a 2 mm sieve to be ready for analysis, see Figure 5.14 below. The laboratory soil analyses that were performed for each campaign can be seen in Table 5.4.

Table 5.4. The laboratory analyses performed on the different campaigns.

Campaign	Laboratory soil analyses performed
Initial conditions	Soil particle size, soil salinity extract and pH, pF
After one irrigation	Soil salinity extract, pH, pF
After second irrigation	Soil salinity extract, pH, pF
After rainfall	Soil salinity extract, pH, pF



Figure 5.13. Soil samples being dried in an oven.



Figure 5.14. The 2 mm soil particles after crushing sieving.

### 5.2.1. Soil salinity extract

The E<sub>c</sub> is measured using a conductivity meter on the soil salinity extract. The laboratory follows the Agricultural Handbook No 60 from USDA (1954) to obtain the soil extract. However, some adjustments regarding the amount of soil and time have been done. The first step is to mix 200 grams of dry soil, 2 mm, with enough water to reach saturation of the soil, this means to create a paste. Stirring is done using a spatula, see Figure 5.15. The amount of added water is based using visual estimation so the result of this analysis could vary depending on the laboratory staff conducting the analysis. The paste should be well-mixed, smooth and shiny. If not, more water is added and the total amount of water added is noted. The jar with the paste is then closed and left for 24 hours. The second step is the extraction of the added water. The paste is put in a funnel placed above a filter and vacuum is connected to extract the water containing the dissolved salts, see Figure 5.16. The solution is collected in a tube and the volume is measured. This solution is then used for conductivity measurements.



Figure 5.15. The preparation of the soil salinity extract paste.



Figure 5.16. The extraction of soil salinity extract using vacuum.

### 5.2.2. Soil pH

A pH-meter is used for measuring the pH in soil. However, the soil must be prepared by mixing 20 g soil, 2 mm, with 50 ml of distilled water. This mixture is agitated and then it is left for 2 h. After this, the pH is measured with the pH-meter. The method comes from the Agricultural Handbook No 60 from USDA (1954).

### 5.2.3. Soil particle size

Soil can be categorized according to the size of the soil particles. The soil texture affects the physical, hydrodynamic and chemical soil properties, like the soil water content. The classification according to USDA can be seen in Table 5.5 below.

Table 5.5. The soil particle classification to USDA (Gee & Or, n.d.)

Classification	Soil particle size diameter
Sand	50-2000 $\mu\text{m}$
Silt	2-50 $\mu\text{m}$
Clay	<2 $\mu\text{m}$

The method used to decide the soil particle size was the pipette-Robinson method. This method is based on Stoke's law about sedimentation (Pansu & Gautheyrou, 2006). The method is described in detail in the Handbook of Soil Analysis by Pansu and Gautheyrou (2006). In this method it is necessary to prepare the dry soil, 2 mm, in two steps. The first step is the cold attack to destroy the organic matter in the soil. 20.0 grams of soil is mixed with 20 ml hydrogen peroxide (30 %) in an Erlenmeyer flask and this will create a chemical reaction. This solution should then wait for 24 hours in a fume cupboard. The result of the cold attack can be seen in Figure 5.17. The next step is the hot attack to break all the bonds between the particles. 200 ml of distilled water is added to the soil solution from the first step and brought to boiling for 2 hours. After this, 10 ml of 50 g/l sodium hexametaphosphate is added to the flask. This is done to neutralize the surface of the soil particles so they will not aggregate again. The solution is left for rotation agitation for 4 hours, see Figure 5.18.

After the agitation the solution is added to a glass cylinder, 1000 ml, and distilled water is added until the total amount of solution is 1000 ml, see Figure 5.19. The temperature is measured to determine the time of sedimentation according to the Agricultural Handbook No 60 (1954). The first soil particle size to be determined is clay plus silt. A sample is taken, using the Robinson pipette, at 10 cm down in the glass cylinder after a certain time; the time is the time it takes for the particles to settle and is determined using a table, from Handbook of Soil Analysis (Pansu & Gautheyrou, 2006), and the temperature in the room (see Figure 5.20). This step is then repeated for the clay with another time of sedimentation. At the INRGREF laboratory in Tunis, the sedimentation time for clay was set to 6 hours and then the depth of sampling is modified according to the time. The rest of the soil is washed until only sand remains and then sieved, after drying, to divide the sand into coarse sand, fine sand and coarse loam. All of the samples are dried and weighed. A blank sample should also be made to be able to disregard the effects of the reagents (Pansu & Gautheyrou, 2006).

When all samples are dried and weighed, the calculations of the percentages of the three different soil particle sizes can start. The Equations 5.3-5.5 come from the Handbook of Soil Analysis (Pansu & Gautheyrou, 2006).

$$Clay = \frac{(mass_{clay} - mass_{blank}) \cdot 1000 \cdot 100}{volume_{sample} \cdot mass_{dry\ sample} \cdot moisture\ correction\ coefficient} \quad (\text{Equation 5.3})$$

$$Silt = \frac{(mass_{clay+silt} - mass_{clay}) \cdot 1000 \cdot 100}{volume_{sample} \cdot mass_{dry\ sample} \cdot moisture\ correction\ coefficient} \quad (\text{Equation 5.4})$$

$$Total\ sands = \frac{100 \cdot mass_{total\ sand\ after\ drying}}{m_{soil\ sample} \cdot moisture\ correction\ coefficient} \quad (\text{Equation 5.5})$$



Figure 5.17. The cold attack of the soil particle size analysis



Figure 5.18. Agitation of soil samples to prepare pipette-Robinson analysis.

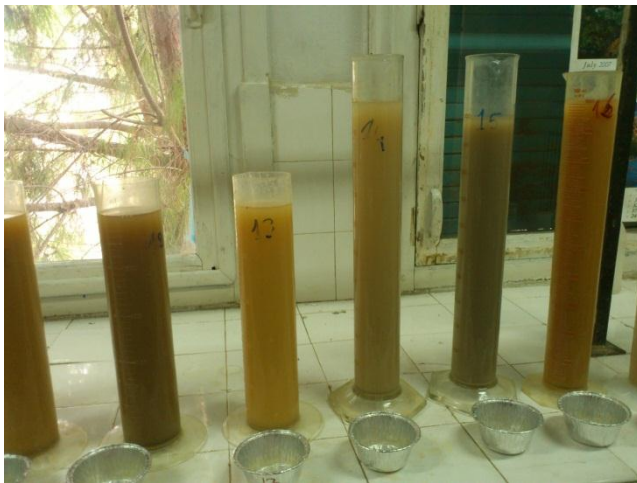


Figure 5.19. The sedimentation of particles.



Figure 5.20. A sample being taken using a Robinson pipette.

#### 5.2.4. pF and irrigation efficiency

To estimate the farmer's irrigation efficiency, the soil moistures measured in the field were compared to the soil water content at field capacity (at pF 2.7) and the wilting point (at pF 4.2). Preferably the soil moisture should be measured before and after irrigation. But since the EM38 reading should be done at soil moisture close to field capacity the soil water content were measured a few days after an irrigation event or rainfall.

The pF at 2.7 and 4.2 is decided using a pressure chamber; see Methods of Soil Analysis part 4 for a detailed description of the method (Dane & Hopmans, 2002). pF 4.2 represent the wilting point. pF for the field capacity is usually between 2 and 2.5 (as was discussed in section 3.2), but in the laboratory of the Tunisian Soil Department, Tunis, the standard is 2.7 due to practical reasons. Dry soil, 2 mm, is put in small open cylinders that are allowed to sit in water for 24 hours. During that time the soil will absorb the maximum amount of water. After 24 hours in water, the cylinders are put in two pressure chambers, one for pF 2.7 and one for pF 4.2. The cylinders sit in the pressure chambers for 24 hours so all excess water, that cannot be hold by the soil, is drained from the soil.



After this, the wet soil is weighed and out into an oven for another 24 hours. Here the soil will dry and all remaining water will evaporate. After the 24 hours, the dry soil is weighed and the difference between the wet and dry soil is calculated. The gravimetric soil water content is calculated for different pressures and displayed in a graph with soil water retention, in mm, on the y-axis and the soil depth, in m, on the x-axis. To get the volumetric soil water content, the gravimetric soil water content is multiplied with the bulk density.

### 5.3. Data analysis

Before performing the analysis of the data from the fields and the lab, the data was examined to identify possible outliers and/or faults in the measurements. Then the analysis was carried out using basic statistical methods and finally by using ESAP to evaluate the spatial soil salinity variability across the field.

The data was foremost analyzed for three depths; 0-0.3 m, 0-0.9 m and 0-1.5 m. This to provide information about the top layer, the root zone and the total depth the EM38 can reach. The top layer is important to analyze since it is here the water and salts are entering and changes should be most clear. The root zone is important since this is the zone that is affecting the plants. Another possible analysis would be to map the salinity in all the depths for which soil samples were taken, these results are presented in Appendix VII. However, these results will not be analyzed further within this master thesis due to time limitations.

The aim of this thesis is to investigate the effect of irrigation, and by removing plots that are not irrigated, i.e. the olive tree plots, this effect will be more clear. Therefore the plots containing olives were removed from the rest of the data. The field is then assumed to be irrigated over the entire surface. Both the EM38 readings and the soil samples from the olive tree H60 were excluded from the analysis.

#### 5.3.1. Data treatment

Because of some errors, due to instruments or to personal faults, some values were missing or clearly deviated from the pattern the other values displayed. To determine whether a value deviated from the pattern or not, the values from the same point, but from different campaigns, were compared. The values from the WET-sensor were sometimes used to verify the pattern for the soil water content. If a value was missing or deviated from the pattern different techniques were used, depending on the parameter and the situation:

- *Linear regression.* If the other campaigns had shown a more or less linear decreasing or increasing pattern with depth, the missing or deviating value was estimated using a linear regression between the value before and after.

- *Average.* If the other campaigns did not show a significant pattern, or the values did not differ too much between the depths, the missing or deviating value was assigned the average of the values from the depth before and after.

- *Copied from other depth.* If the missing or deviating value came from the deepest or second deepest sample it was sometimes assigned the value from the sample above or below. This is based on that clay was present in the deeper soils to a larger extent, and that some of the soil parameters will show the same value in the entire clay layer.

### 5.3.2. EM38 calibration and salinity mapping using ESAP

The ESAP software was used to calibrate the EM38 readings to ECe and map it. ESAP is statistical software consisting of five different programs, developed by the USDA, which is especially adapted to the EM38 instrument and to estimate and display the spatial variability of soil parameters, such as soil salinity. In this thesis three of the ESAP programs were used: ESAP-RSSD, ESAP-Calibrate and ESAP-SaltMapper. For further explanation, more detailed descriptions and tutorials see the ESAP 95 User Manual (Lesch, et al., 2000).

#### *ESAP-RSSD*

The measurements from the EM38 are, together with the coordinates of the measurements, input to the ESAP-RSSD. The coordinates are only fictive local coordinates and were established only to display the locations of the different measurements, and the distance between them.

The raw EM38 measurements were first analyzed using basic statistical methods, and the distribution of the raw data is checked by examining the histograms. If the histograms did not display a bell shape (typical for a normal distribution) the data might be log-normally distributed and a log-transformation was needed (Lesch, et al., 1995). A normal distribution is a prerequisite to perform some of the basic statistical methods performed in this thesis (Nielsen & Wendroth, 2003). After it has been arranged so the raw data is normally distributed the raw data is checked for outliers. Outliers are defined as values with a standard deviation higher than 4.5. The raw data was then decorrelated according to

$$z_1 = a_1(s_1 - \text{mean}[s_1]) + a_2(s_2 - \text{mean}[s_2]) \quad (\text{Equation 5.6})$$

$$z_2 = a_3(s_1 - \text{mean}[s_1]) + a_4(s_2 - \text{mean}[s_2]) \quad (\text{Equation 5.7})$$

where,  $a_1$ ,  $a_2$ ,  $a_3$  and  $a_4$  are determined by the principal components analysis. A principal components analysis is a method of transformation to reduce the number of dimensions of the data (Härdle & Simar, 2007).  $s_1$  and  $s_2$  are the raw EM38 data. The local coordinates (u and v) are scaled according to

$$x = \frac{(u - \min[u])}{k} \quad (\text{Equation 5.8})$$

$$y = \frac{(v - \min[v])}{k} \quad (\text{Equation 5.9})$$

$$\text{where } k = \text{the greater of } (\max[u] - \min[u]) \text{ or } (\max[v] - \min[v]). \quad (\text{Equation 5.10})$$

The decorrelation and scaling showed in Equation 5.6-5.10 help make sure that the techniques used by the regression modeling algorithm in ESAP-Calibrate remain stable (Lesch, et al., 2000).

The final step in the ESAP-RSSD is to establish a sampling design for the soil sampling. This can be done by letting ESAP design an optimal sampling design based on the EM38 measurements, or by manually selecting the sample sites. As have been mentioned before, the sites used for soil sampling in this thesis were selected based on the design made by ESAP, but with some alterations.

#### *ESAP-Calibrate*

The input data to ESAP-Calibrate are the soil parameters measured in the lab or in the field. What parameters that are needed depend on the objective of the study and on the model that is to be used to predict the soil parameters. In general a deterministic model requires less information about

the soil parameters in the field (see also 2.4.4.). However, for this thesis a stochastic model was used, which requires the following soil parameter at each sampling depth: ECe, soil water content, clay content and bulk density (Lesch, et al., 2000).

The main objective of the ESAP-Calibrate is to find the best possible model that describes the relationship between the measured EMh and EMv, and the ECe (see e.g. Equation 3.17). This relationship can then be used to predict the ECe on all the sites where the EM38 have been used. ESAP can auto-select the best possible model or one can manually select the model. In this thesis the following model had the best fit

$$\ln(ECe) = b_0 + b_1(z_1) + b_2(z_2) + b_3(x) \quad (\text{Equation 5.11})$$

where  $z_1$ ,  $x$  and  $y$  is described in Equation 5.6, 5.8 and 5.9.

#### *ESAP-SaltMapper*

The ESAP-SaltMapper is a tool to create maps to display the spatial variability of a soil parameter, e.g. the soil salinity or EM38 measurements. This is done from the predictions made in ESAP-Calibrate, or from the decorrelated EM38 values from ESAP-RSSD. An interpolation is then made between these points to do a complete map of the chosen soil parameter. The spatial variability can be displayed for each of the sampling depths, as well as for a bulk average.

#### **5.3.3. Model accuracy and validation**

The accuracy of the models retrieved from ESAP-Calibrate is checked by looking at the  $R^2$  value, root mean square error (RMSE) and the estimated coefficient of variation (Est-CV). A high  $R^2$  value, a low RMSE and a low Est-CV indicates a good fit of the model.

The chosen models were validated by performing a so called jack-knifed prediction. Jack-knifing is a technique in which each known value is removed, one at a time, and the model is estimated based on the remaining values. The predicted value, based on this model, is then compared with, and plotted against, the true value, and so on until all known values have been removed. The resulting graph should display point close to a 1:1 line originating from origo (Lesch, et al., 2000). According to Amezketa (2006), this method of validation is a realistic way to look at the prediction accuracy of the model.

Another way to check the accuracy of the models were to look at the PRESS score. The PRESS score is the sum of the jack-knifed errors and is obtained by taking the difference between the observed values and the jack-knife prediction value, square it and then add them together. A low PRESS score indicates a good and accurate model (Lesch, et al., 2000).

#### **5.4. Farmer survey**

A farmer survey was performed to obtain general information about the farmer practices and constraints in the irrigation district of Souhil. This information is collected to increase the understanding of the problem of soil salinity and water scarcity, and to provide inspiration for ideas of possible solutions if needed.

### 5.4.1. Selection of farmers and implementation

The total amount of farmers within the Souhil irrigation district is 205 (Mrs Sonia Mahmoud, GDA, personal contact, 26-09-2012). The aim of the survey was to interview approximately 10 % of the farmers in Souhil to get information about their agricultural practices. A division of the farmers into four groups based on the size of their field was made and the size intervals for the selection are presented in Table 5.6 below. This division was made based on a dated list of the members of the GDA. The limit 0.2 ha was chosen since this is the minimum amount of land needed to sustain a farm (Fehti Bouksila, personal contact, 26-09-2012).

Table 5.6. The intervals for the selection of farmers for the farmer survey.

Interval	Percentage of farmers within limit	Number of chosen farmers
0-0.2	0.11 %	2
0.2-0.7	0.52 %	7
0.7-1.2	0.18 %	8
≥1.2	0.17 %	5

The staff of GDA in Nabeul helped with the selection according to the size of the fields of the farmers and to get the locations of the farmers' field evenly distributed across the Souhil district. Sometimes the original selection of farmers had to be modified to fit the intervals since the size of their fields was not updated in the file of GDA and the farmers often had much larger fields than registered at GDA. In the end 22 farmers had been interviewed according to this selection. However, since the list of farmers was not updated, all the farmers are not exactly distributed according to Table 5.6 and the selection in this survey might not be representative.

The farmer survey was conducted, when possible, at the fields of the farmers. However, in some cases when the farmers could not be found in their field, they were interviewed on the street in the city of Nabeul where they were found by the staff of GDA Nabeul. The interviews were conducted in Arabic, in some cases in French, and the field supervisor of this master thesis translated the answers of the farmers to English. A copy of the survey can be found in Appendix VIII. The farmers interviewed in the farmer survey all have their fields located within the irrigation district Souhil. The location of the farmers chosen for the survey can be seen in Figure 5.21 below.



Figure 5.21. The location of the selected farmers for the farmer survey. The white border represents the Souhil irrigation district (Google Earth, 2012).

## 6. Results and discussion

The results of this master thesis include a short presentation of the soil texture of Field H, a basic soil property assessment, a salinity assessment during four campaigns at Field H and the results from the farmer survey.

### 6.1. Soil texture

The soil particle size was only analyzed only in one occasion; in the first campaign. This since it will not change within the time frame of this field study. The average distribution of the soil texture with depth can be seen below in figure Figure 6.1. The division of the different soil textures has been done according to USDA (see Table 5.5).

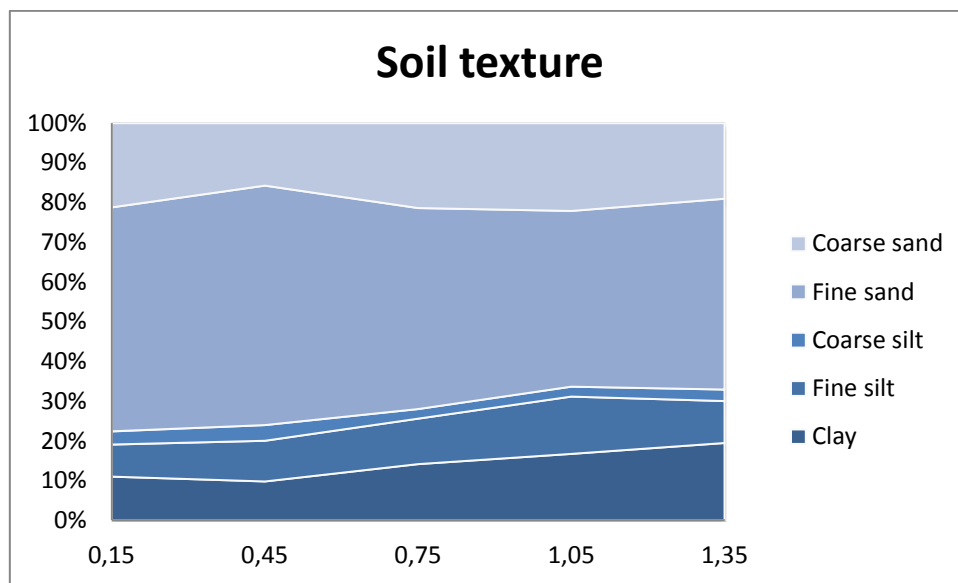


Figure 6.1. The average soil texture with depth across Field H.

As have been mentioned before, the clay content can greatly affect the soil salinity, so that high soil salinity content could be related, partly, to high clay content, and vice versa. The spatial variation in clay content can be seen below in Figure 6.3. The basic statistics for clay content, at each depth can be seen in Appendix VI. The clay content differs significantly across the field, which is also evident when looking in Figure 6.3. The profiles for clay content can be seen in Figure 6.2 below. From visual observation in the field and by looking at the clay content profiles, a clay layer around the depth 1.0-1.3 m was observed.

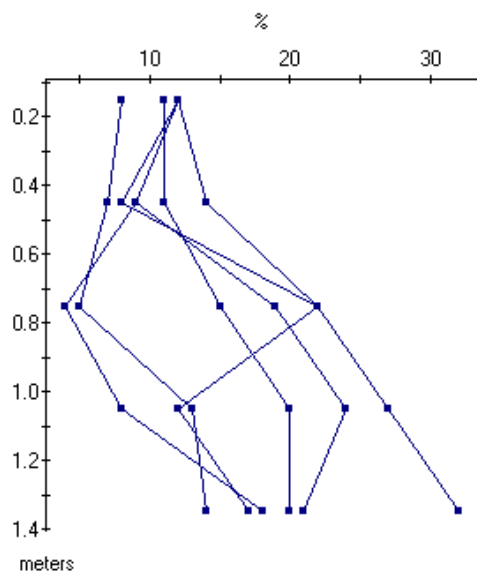


Figure 6.2. The profile data for clay content.

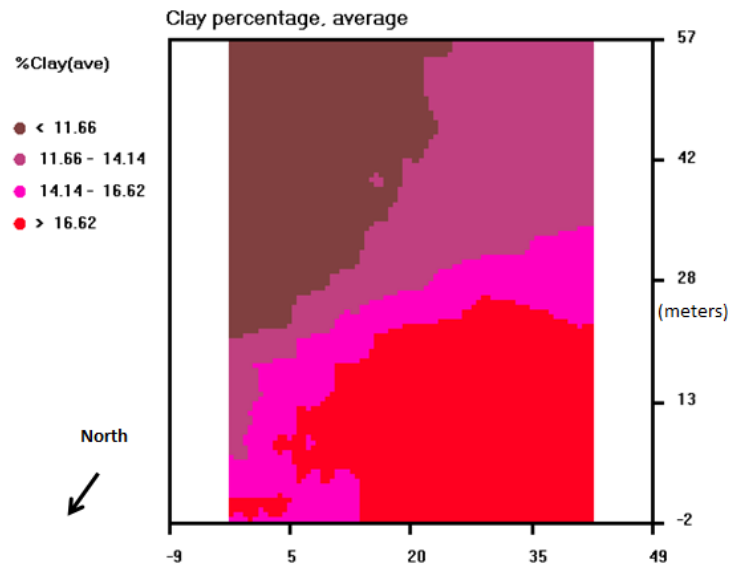


Figure 6.3. The spatial variation in average clay content over the field (0-1.5 m depth). Note that the coordinate system is fictive with origin in the northern corner.

The predictions used in the interpolation, to create the map in Figure 6.3, were estimated using a model from the auto-select option in ESAP-Calibrate with a  $R^2$  value of 0.91. This model depends on the EM38 readings over the field and the clay content from the soil sample analyses.

## 6.2. Soil salinity

The salinity assessment is presented below with soil salinity maps, over the three different average depths and basic statistics for the four campaigns, together with a basic statistical overview of the soil properties possibly affecting the soil salinity.

### 6.2.1. Initial conditions

#### *Soil properties*

When analyzing the soil properties, and their correlation to the E<sub>Ce</sub>, it was observed that the values from the point H121 differed remarkably for the other values. Therefore, it was decided to remove the result from H121 from the modeling in this campaign (this is further validated when looking at the soil salinity profile in Figure 6.6 below). The laboratory analysis also showed that field H had an average pH of approximately 8.4, with a standard deviation of 0.4.

The water content profiles in the soil at initial conditions can be seen in Figure 6.4, and a map over the average water content can be seen in Figure 6.5. The model used to map the average soil water content was chosen with the auto-select option with an  $R^2$  value of 0.81. This model depends on the EM38 readings over the field and the water content from the soil sample analyses. Basic statistics for water content can be seen in Appendix VI.

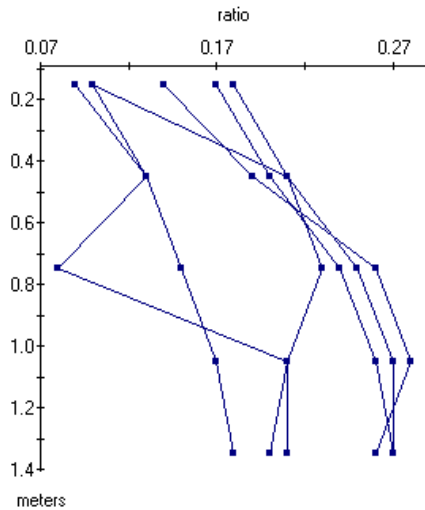


Figure 6.4. The volumetric soil water content profiles, initial conditions.

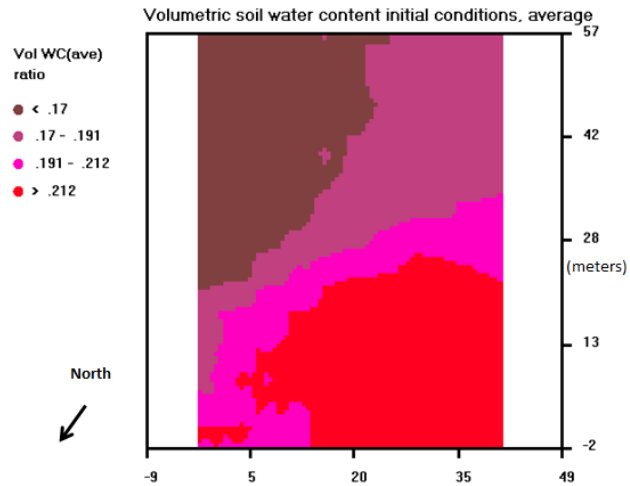


Figure 6.5. The average (0-1.5 m depth) spatial variation of soil water content over the field, initial conditions. Note that the coordinate system is fictive with origin in the northern corner.

### Spatial variation of ECa

When visualizing the EMh and EMv readings in a histogram the data appeared skewed, and therefore the data was log transformed to be more normally distributed. The histogram, before and after the log transformation, can be seen in Appendix IV. Basic statistics of the EMh and EMv readings can be seen below in Table 6.1. To get an overview and an indication of the soil salinity situation in the field, EM38 readings have been interpolated to a surface and this can be seen in Appendix V. One outlier was detected in the data and it was removed.

Table 6.1. The basic statistics of the EMh and EMv readings (dS/m) and the correlation between the two.

	N	Average	Std	Min	Max	Corr
<b>EMh</b>	104	0.381	0.114	0.23	0.65	0.9521
<b>EMv</b>	104	0.514	0.141	0.32	0.90	

### Soil salinity profiles

The soil salinity (ECe) profiles for the initial conditions can be seen in Figure 6.6 below. The point H121 is marked red since it differs remarkably from the rest of the points. This point was removed from the data because of the large difference. Some basic statistics for the ECe data can be seen in Appendix VI.



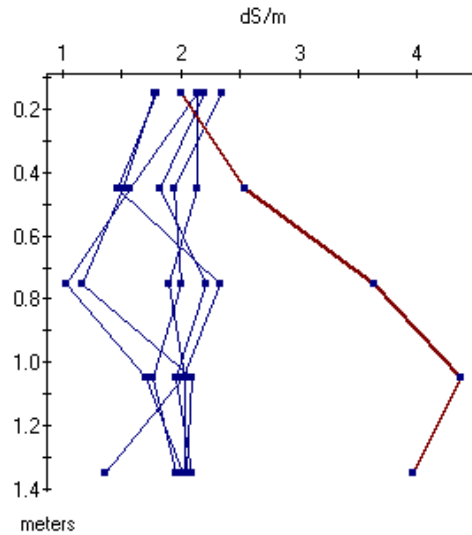


Figure 6.6. The raw soil salinity profiles for the initial conditions. The point H121 is marked red.

#### Model and model coefficients

As mentioned above, the point H121 was removed from the data set since it differed remarkably, and this proved to be a necessary measure to take since the  $R^2$  values increased remarkably when H121 was removed ( $R^2$  changed from 0.439, 0.299 and 0.381 to 0.886, 0.957 and 0.949). A model for each of the three depths has been developed. The coefficients for the models, see Equation 5.11, for this campaign can be seen in Table 6.2 below. The PRESS scores are generally low and this indicate good accuracy of the models.

Table 6.2. The model coefficients and the PRESS score for each soil depth.

Depth	b0	b1	b2	b3	PRESS score
0-0.3 m	1.022	0.126	0.095	-0.987	0.536
0-0.9 m	0.830	0.179	0.061	-0.742	0.341
0-1.5 m	0.752	0.080	-0.028	-0.366	0.045

The  $R^2$ -values, the estimated coefficient of variation and the root mean square error of the model for each depth can be seen in Table 6.3 below. The  $R^2$  values are generally high which indicates a good fit. The low estimated coefficients of variation and root mean square errors also indicate a good model for the three depths.

Table 6.3.  $R^2$ -values, estimated coefficient of variation and root mean square error for the model at the different soil depths.

Depth (m)	$R^2$	Est-CV (%)	RMSE
0-0.3	0.886	6.14	0.061
0-0.9	0.957	4.84	0.048
0-1.5	0.949	3.26	0.033

To validate the model jack-knifed predictions were plotted against the observed values, see Figure 6.7 below. Since majority of the points are located close to the line, the validation implies that the model can be considered adequate for the data.

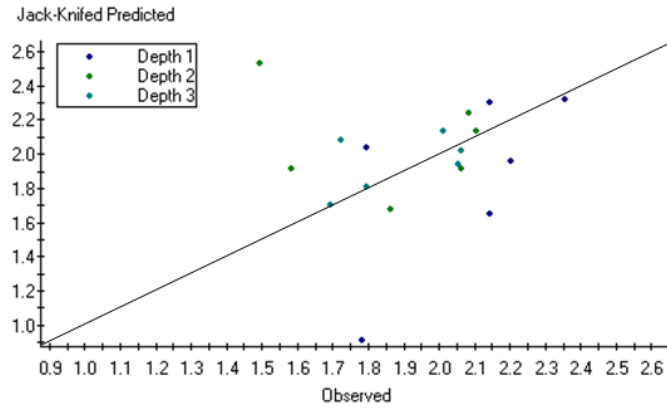


Figure 6.7. The jack-knifed predictions plotted against the observed predictions. This displays a good accuracy of the model. Depth 1 represents 0-0.3 m, depth 2 represents 0-0.9 m and depth 3 represents 0-1.5 m.

*Soil salinity maps*

With the model parameters in Table 6.2 the soil salinity (ECe) for all points could be predicted, with measured EM38 values. The spatial distribution of soil salinity, for each depth, based on these predictions can be seen below in Figure 6.8-Figure 6.10. In the figures it can be seen that the highest salinity is generally in the northern part of the field. Note that the bright red indicates the highest concentration.

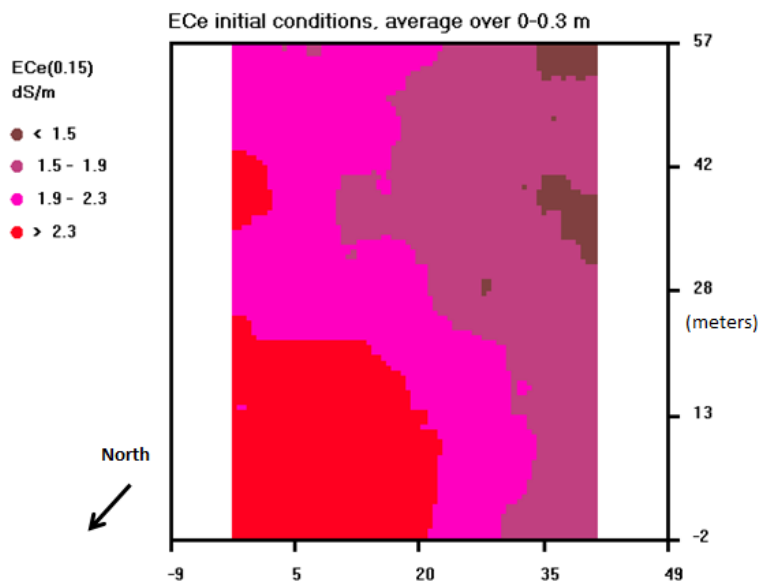


Figure 6.8. The spatial distribution of soil salinity at the depth 0-0.3 m. The bright red indicates the highest salinity.

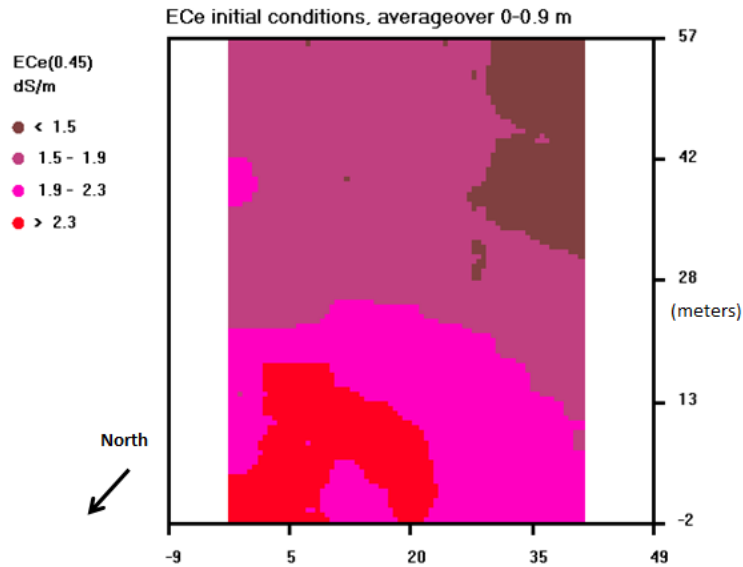


Figure 6.9. The spatial distribution of soil salinity for the depth 0-0.9 m which is approximately equivalent to the root zone. The bright red indicates the highest salinity.

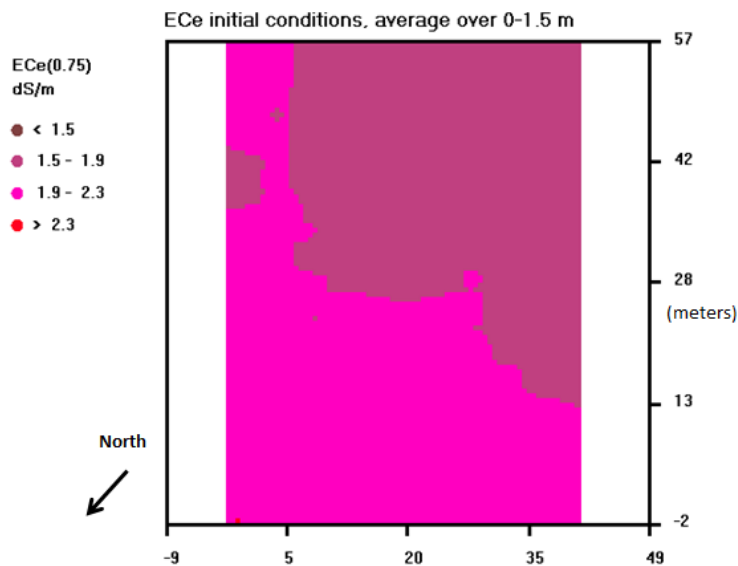


Figure 6.10. The spatial distribution of soil salinity for the depth 0-1.5 m.

### Discussion

From this first campaign of measurements, a relation between clay and soil water content can be suspected. The areas with higher content of clay correspond roughly to the areas with higher soil water content. It can also be noted that both the clay content and soil water content increased with depth. It is not a surprise that these two parameters agree with each other. With more clay in the soil, more water is being held. So, when there is an increase in clay content, like in this case, water will be held in this layer.

It is clear that removing the point H121 was a necessary decision when looking at the soil salinity profile, Figure 6.6, since the point deviated remarkably. Something could have happened with this point. Since the salinity at this point is so much higher, it is possible that this point received much

more irrigation water previously during the year. However, the opposite is also possible; the point could have received too little water to leach the soil.

For all of the three depths, the salinity is higher in the north corner. It was expected that higher soil salinity would somewhat correspond to higher clay content and soil water content. However, this does not seem to be exactly the case for this campaign. One possible reason for the higher salinity in the north corner, in all the depths, could be that some pipes with irrigation water has been leaking in this area of the field during the entire agricultural year and this is affecting the initial conditions of this field study. Another possible reason could be the opposite; that this area received less irrigation water. It was observed that the farmer started irrigating in the western part of the field and finished in the eastern parts. This could possibly affect the soil salinity in the field. The amount of water the farmer have to irrigate the field is limited and it is therefore likely that by the end of the irrigation event there is little water left for the eastern part. If too little water is added less leaching will occur in this area and the salts will be left in the soil. Overall the farmer practice can greatly affect the soil salinity and the amount of water added to each irrigation basin is based on a visual estimation. It is thus very likely that each basin receives a different amount of irrigation water, even though it might be difficult to know the exact reason for this.

In Figure 6.8 - Figure 6.10 it is indicated that the initial conditions display the highest salinity in the first depth, a slightly lower salinity in the second depth and an even lower salinity in the third depth. The second depth takes the data from the first depth into account and the third depth takes both the other depths into account. For this campaign this means that there has to be a decrease in the salinity at 0.3-0.6 m depth to make the average over the second depth lower than in the first depth. The same reasoning can be used for the third depth; where there has to be a decrease in the salinity between 0.9-1.5 m to make the average here even lower than in the second depth.

Another conclusion to draw from this first campaign is that it is likely that the initial conditions of this field study are affected very much by the irrigation, farmer practices and climate during the earlier parts of the agricultural year.

### **6.2.2. After one irrigation event**

About two days after irrigation the data sampling was performed. The irrigation meant the addition of about 640 m<sup>3</sup> of irrigation water and 1286 kg of salt (see Table 5.2). Also, during the time between this and the previous campaign it rained 9 mm, which is too little to be considered to have any significant impact on the soil salinity. Also, the soil sampling and EM38 readings were conducted close to the citrus tree trunks, which is underneath the tree leaves. The tree leaves could reduce the impact of smaller rainfalls.

#### *Soil properties*

The laboratory analysis showed that Field H had an average pH of approximately 9.2, with a standard deviation of 0.4, after one irrigation event. The distribution of the soil water content can be seen in Appendix VI. The soil water content has changed since the last campaign and the water content profiles can be seen in below Figure 6.11. It seems like the water content is higher around 1 m depth than at the surface. The spatial distribution of the soil water content can be seen in Figure 6.12 below. The map is based on a model based on soil sample analyses and EM38 readings from the second campaign. The R<sup>2</sup> value for this model is 0.73 and is considered to be good.

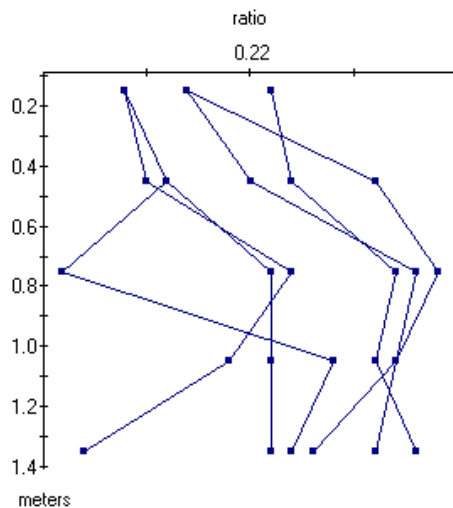


Figure 6.11. The volumetric soil water content profiles, after one irrigation event.

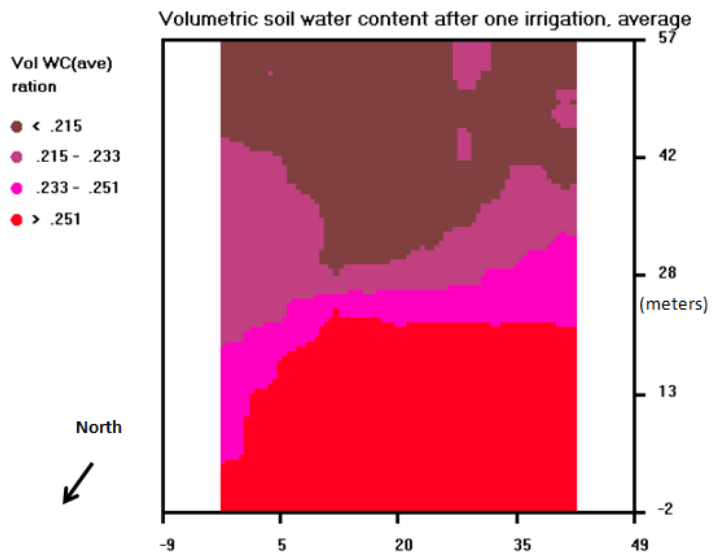


Figure 6.12. The spatial distribution of the average soil water content, after one irrigation event.

### *Spatial variation of ECa*

When visualizing the EMh and EMv readings, from the second campaign, in a histogram the data appeared skewed. The data therefore log-transformed to be more normally distributed and the histograms, before and after the log transformation, can be seen in Appendix IV. The basic statistics of the EMh and EMv readings can be seen below in Table 6.4. The spatial distribution of the decorrelated and interpolated EM38 readings can be seen in Appendix V. 1 outlier was detected and removed from the data in this campaign.

Table 6.4. Basic statistics for the EM38 readings (dS/m) for the second campaign, representing the conditions after one irrigation event.

	N	Average	Std	Min	Max	Corr
<b>EMh</b>	104	0.402	0.123	0.230	0.700	0.9694
<b>EMv</b>	104	0.511	0.144	0.230	0.900	

### *Soil salinity profiles*

The soil salinity profiles can be seen below in Figure 6.13. The data does not display any specific pattern, but most of the points display increasing soil salinity with depth. Basic statistics regarding the ECe data can be found in Appendix VI.

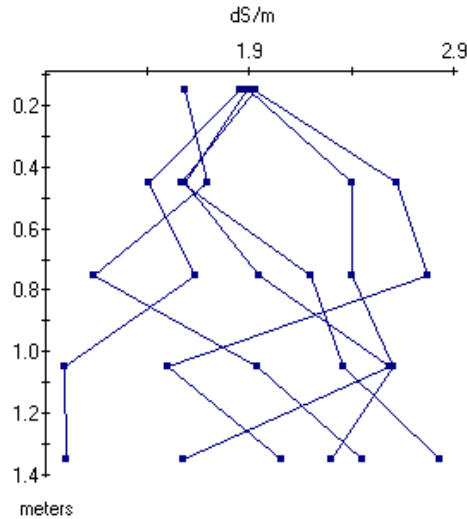


Figure 6.13. The soil salinity profiles, after one irrigation event. Note that H54 is not included.

#### Model and model coefficients

To achieve sufficiently high  $R^2$  values, the point H54 had to be excluded from the modeling. When this point was present, all  $R^2$  values were too low to indicate an accurate model. By removing H54 the  $R^2$  values changed from 0.391, 0.546 and 0.429 to 0.809, 0.593 and 0.411.

The model coefficients, see Equation 5.11 above, can be seen in Table 6.5 below. The PRESS score can also be seen in this table and they are generally low and indicate a good model fitting.

Table 6.5. The model parameters and the PRESS score for each depth after one irrigation event.

Depth	b0	b1	b2	b3	PRESS score
0-0.3 m	0.583	0.025	-0.095	0.127	0.462
0-0.9 m	0.377	0.066	0.109	0.613	6.864
0-1.5 m	0.562	0.042	0.009	0.216	3.046

The  $R^2$ -values, estimated coefficient of variance and the root mean square error of the model for each depth can be seen in Table 6.6 below. The shallowest depth has a high  $R^2$  value indicating that the model is satisfactory for this depth. For the other two depths, the  $R^2$  values are lower and indicate that the models are not satisfactory for these two depths. The estimated coefficients of variation and RMSE agree with the above statements about the models performances. Therefore the second and third depths are not displayed in maps.

Table 6.6. The  $R^2$  values, estimated coefficient of variation and root mean square error of the model for each soil depth.

Depth (m)	$R^2$	Est-CV (%)	RMSE
0-0.3	0.809	5.10	0.051
0-0.9	0.593	18.81	0.187
0-1.5	0.411	13.03	0.130

The validation, using the jack-knifed predictions, can be seen below in Figure 6.14. It is very difficult to see how the points close to the origin are located due to two very high values. This means that the validation cannot be an indicator for the model performance.

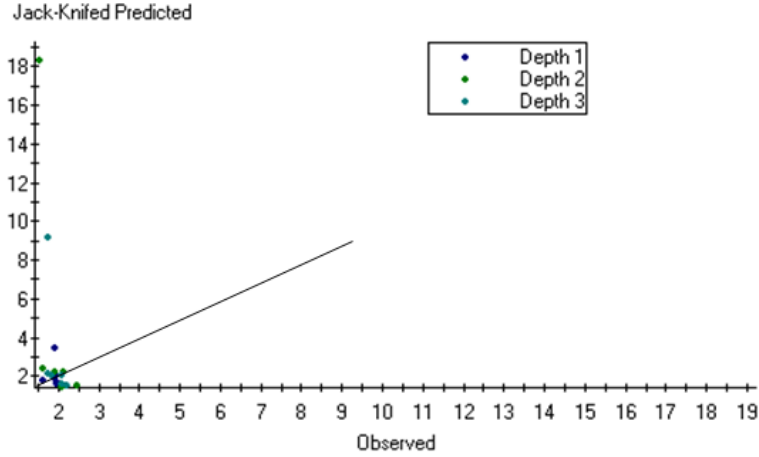


Figure 6.14. The jack-knifed predictions plotted against the observed values. Depth 1 corresponds to 0-0.3 m, depth 2 corresponds to 0-0.9 m and depth 3 corresponds to 0-1.5 m. The ECe values are all back transformed.

*Soil salinity maps*

The soil salinity maps for the upper depth can be seen in Figure 6.15 below. The map is based on the model parameters presented in Table 6.5 above and on the EM38 readings from the second campaign. The first and shallowest depth displays a pattern with the salinity increasing from the east to the west. This is also the way the irrigation is conducted; from the east to the west.

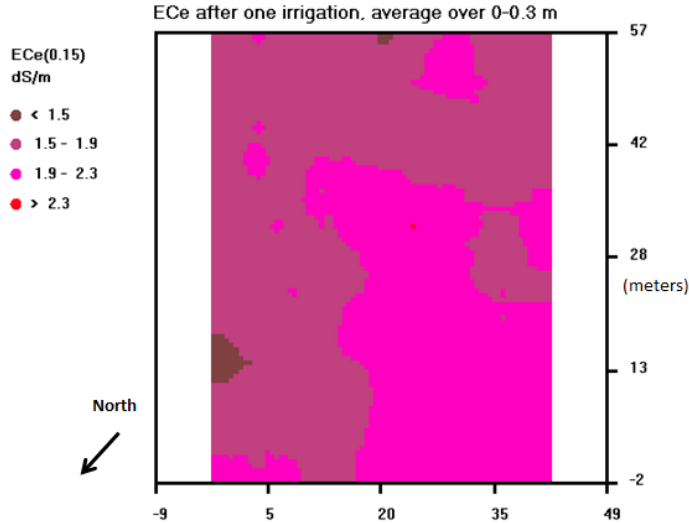


Figure 6.15. The spatial distribution of soil salinity, after the first irrigation.

*Discussion*

The removal of the point H54 improved the model performance. However, there was no indication in the ECe data that this point deviated. Also, when looking at the correlations between ECe and clay and water content, this point alone was not responsible for the low correlations. Instead, the indication that this point deviated could be seen in the validation, and then after removing his point the model improved. So, it was considered to be a necessary decision to remove H54.

The models performances for this campaign are generally low which indicates that the soil salinity maps might not be representative for the actual soil salinity. These models are the best possible ones for this campaign. However, this campaign could be excluded from the analysis of changes between the different campaigns since the third campaign also deals with the conditions after irrigation; it is more likely to see any changes between the first and third campaign.

Also in this campaign, the soil water content agrees with the clay content. As mentioned before, this is not a surprise. It is interesting to note the increase in soil water content around 1 m depth. This could be the irrigation water that has moved down the soil. It can also be seen that the general water content has increased since the last campaign. This was expected since irrigation water was added.

A possible reason for the soil salinity to be higher in the southern and western parts of the field could be the small inclination of the field. More irrigation water may be accidentally directed towards the south of the field and more salts could be accumulated here. In the western and northern parts of the field, the pipes directing the irrigation water is often placed and the pipes are not always good. More often than not, the pipes are broken and irrigation water leaks. Therefore, it is likely that the western parts of the field receives more irrigation water and therefore more salts. The western part also has higher clay content and this could affect the soil salinity. The salts could get stuck on the very fine clay particles and accumulate there. The soil salinity distribution could also be due to, as was discussed above, the order in which the field is irrigated. Most likely the higher salt content is due to a combination of these parameters.

It is difficult to make any conclusion about the soil salinity changes after only one irrigation event. It seems like the salinity in the upper layer, 0 - 0.3 m, has decreased. This could be due to leaching by the added irrigation water and that added salts in the irrigation water have been transported further down.

### **6.2.3. After two irrigation events**

About two days after irrigation the data sampling was performed. The irrigation meant the addition of about 640 m<sup>3</sup> of irrigation water and 1286 kg of salt (see Table 5.2). This making the total addition during this field study: 2572 kg of salt and 1280 m<sup>3</sup> of water. Also, during the time between this and the previous campaign it rained 23 mm in one day, which is regarded to be a rainfall of such a substantial amount that it might have an impact on the soil salinity and water content field.

#### *Soil properties*

When looking at the data and the correlations between E<sub>c</sub> and water and clay content, it was seen that the point H121 deviated from the data. It was decided to remove this point from the data.

The laboratory analysis showed that Field H had an average pH of approximately 8.9, with a standard deviation of 0.5, after the second irrigation.

The profiles and spatial distribution of the water content after the second irrigation can be seen in Figure 6.16 and Figure 6.17 respectively. The model used to retrieve the map has an R<sup>2</sup> value of 0.85. Basic statistics for the water content can be seen in Appendix VI. Generally, the water content increases with depth and is higher in the northwest corner.



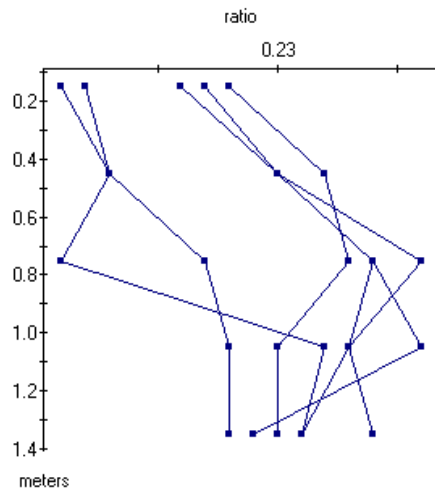


Figure 6.16. The volumetric water content profiles, after the second irrigation.

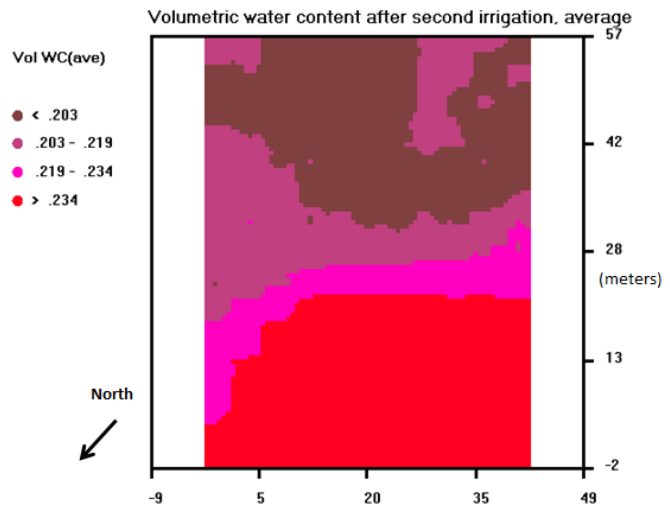


Figure 6.17. The spatial variation of the average soil water content, over depth, over the field, after the second irrigation. Note that the coordinate system is fictive with (0,0) in the northern corner

### Spatial variation of ECa

When visualizing the EMh and EMv readings in histograms, the data appeared skewed. The data was therefore log-transformed to be more normally distributed and the histograms, before and after the transformation, can be seen in Appendix IV. Some basic statistic for the EMh and EMv data can be seen in Table 6.7 below. The spatial distribution of the EM38 readings can be seen Appendix V. No outliers were found in this data.

Table 6.7. The basic statistic for the EM38 readings (dS/m) for the third campaign representing the conditions after two irrigation events.

	N	Average	Std	Min	Max	Corr
<b>EMh</b>	104	0.424	0.119	0.23	0.70	0.9632
<b>EMv</b>	104	0.534	0.139	0.30	0.91	

### Soil salinity profiles

The soil salinity profiles after the second irrigation can be seen in Figure 6.18 below. The point H121 is marked red since it differs remarkably from the rest of the points. This point was removed from the data. Basic statistics for the ECe data can be seen in Appendix VI.

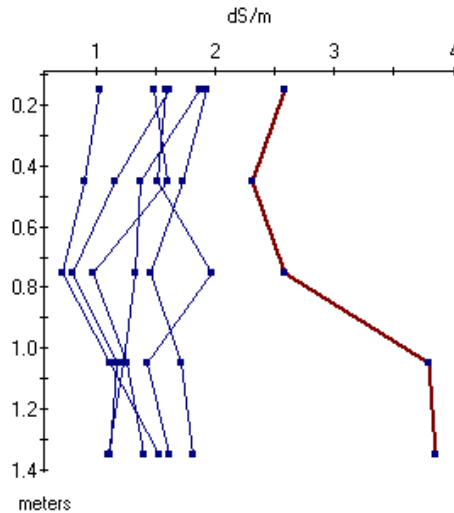


Figure 6.18. The soil salinity profiles, after the second irrigation. Note the profile marked red; this is point H121 which deviates remarkably from the rest.

#### Model and model coefficients

The point H121 was removed from the data and this improved the  $R^2$  values of the models remarkably. The coefficients for the models, see Equation 5.11, can be seen in Table 6.8 below. One model for each of the three depths was developed and the PRESS scores are generally low.

Table 6.8. The model coefficients and the PRESS score for each depth.

Depth	b0	b1	b2	b3	PRESS score
0-0.3	-0.751	-0.057	0.679	2.897	0.132
0-0.9 m	-0.635	0.046	0.612	2.170	0.119
0-1.5 m	-0.191	0.058	0.394	1.066	0.128

The  $R^2$  values, the estimated coefficient of variation and the root mean square error can be seen in Table 6.9 below. The  $R^2$  values are generally very high and this indicates a good fitting of the model to the data. Also the estimated coefficient of variation and the root mean square error indicates satisfactory models.

Table 6.9.  $R^2$ -values, estimated coefficient of variation and root mean square error for the model at the different depths.

Depth (m)	R-square	Est-CV (%)	RMSE
0-0.3	0.979	5.25	0.052
0-0.9	0.970	6.91	0.069
0-1.5	0.967	5.29	0.053

To validate the model, jack-knifed predictions were plotted against observed values, see Figure 6.19 below. The majority of the points are located close to the 1:1 line which indicates that the models are good for this campaign.

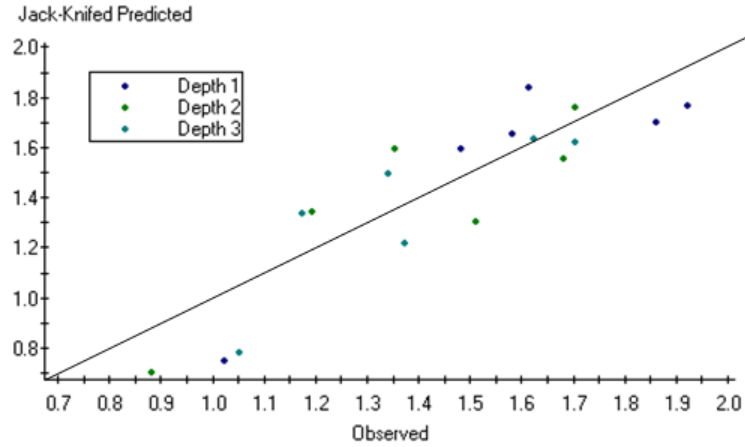


Figure 6.19. The jack-knifed predictions plotted against the observed predictions. This displays a validation that cannot be an indicator for the model performance. Depth 1 represents 0-0.3 m, depth 2 represents 0-0.9 m and depth 3 represents 0-1.5 m.

*Soil salinity maps*

With the model coefficients from Table 6.8 above the soil salinity (ECe) for all points on the field could be predicted using the EM38 readings. The spatial distribution for all three depths can be seen in Figure 6.20 - Figure 6.22 below.

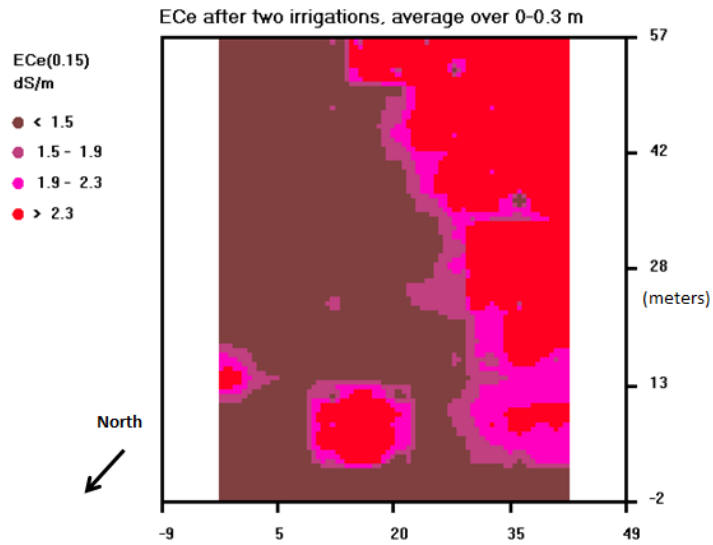


Figure 6.20. The spatial distribution of soil salinity for the depth 0-0.3 m, after two irrigation events. The bright red indicates the highest salinity.

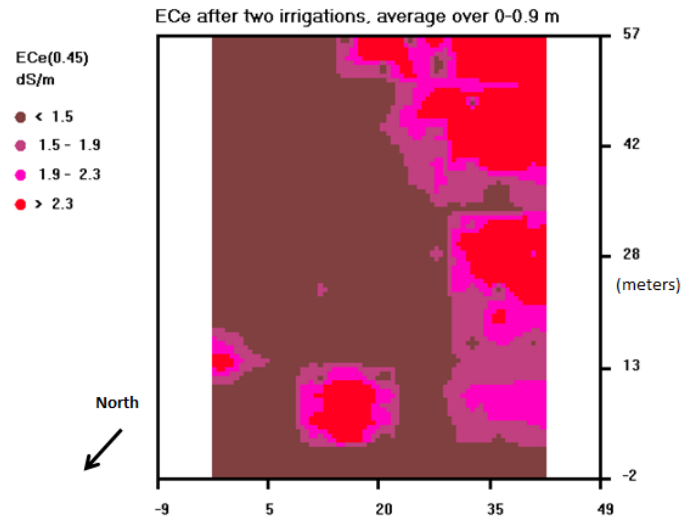


Figure 6.21. The spatial distribution of soil salinity for the depth 0-0.9 m, after two irrigation events. The bright red indicates the highest salinity.

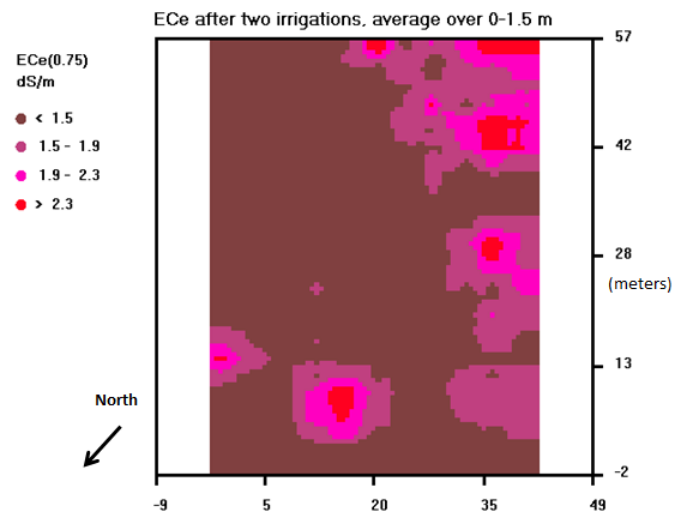


Figure 6.22. The spatial distribution of soil salinity for the depth 0-1.5 m, after the second irrigation. The bright red indicates the highest salinity.

### Discussion

By removing the point H121, the  $R^2$  values increased and the model fit was improved, proving this to be a good decision. This point also deviated in the first campaign, the initial conditions. Like mentioned before, this point could have received more or less irrigation water. Since this deviation happened twice, it is likely a valid assumption. It could be due to the location of the point; it is located in the lowest part of the field.

Also in this campaign, the soil water content agrees with the clay content in the soil. The area with the highest clay content is also the area with the highest soil water content.

The higher soil salinity does not, for any of the depths, completely agree with higher water content. This adds to the previous statement that a relationship between soil salinity and soil water content is difficult to find in this thesis. This can be further concluded by looking at the generally low  $R^2$  values for the correlations between ECe and soil water content in Appendix VI.

The soil salinity is higher in southern parts of the field at all three depths. This could be due to the inclination of the field; the irrigation water could be accidentally lead to this area due to gravity. Between the maps one can generally see a small decrease in the salinity with depth. Using the same reasoning as in section 6.1.1., this indicates that the salinity is decreasing with depth, which could be due to leaching. The highest salinity can be observed in the upper depth, which indicates that the added salt from the irrigation water has not reached further than this at the time of sampling.

An increase in soil salinity was expected due to the addition of saline irrigation water. However, a clear increase is conspicuously absent from the results. An increase in soil salinity in the southern parts of the field can be observed. Between the irrigation events there was a large rainfall that could have leached the soil of salts and generally decreased the soil salinity over the field. The increase in the southern part after two irrigation events is then due to field inclination explained above.

#### **6.2.4. After rainfall**

After some time of rain the data sampling was performed on a dry day. Since the campaign for the initial condition there had totally rained 89.5 mm (310 m<sup>3</sup>) and since the previous campaign it had rained 57.5 mm (200 m<sup>3</sup>) over 0.35 ha.

##### *Soil properties*

The ECe data for point H121 deviated once again from the rest of the data and the point was removed to improve the model fitting.

The clay content and distribution is regarded the same as the initial conditions. The laboratory analysis of the soil showed that the soil at Field H has a pH of 9.0 with the standard deviation of 0.2.

The water content profiles for this campaign can be seen in Figure 6.23 below. The spatial distribution of the water content can be seen in Figure 6.24 below. The map was created using a model with an R<sup>2</sup> value of 0.89.

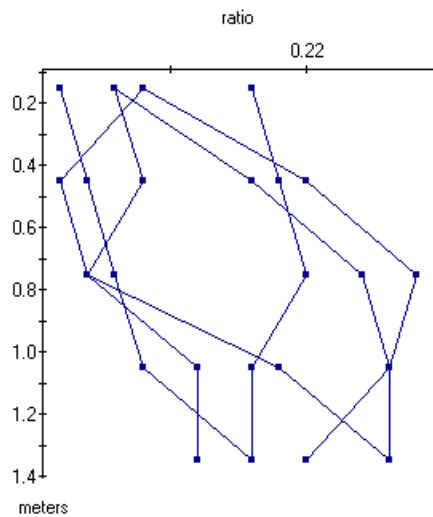


Figure 6.23. The volumetric water content profiles, after rainfall.

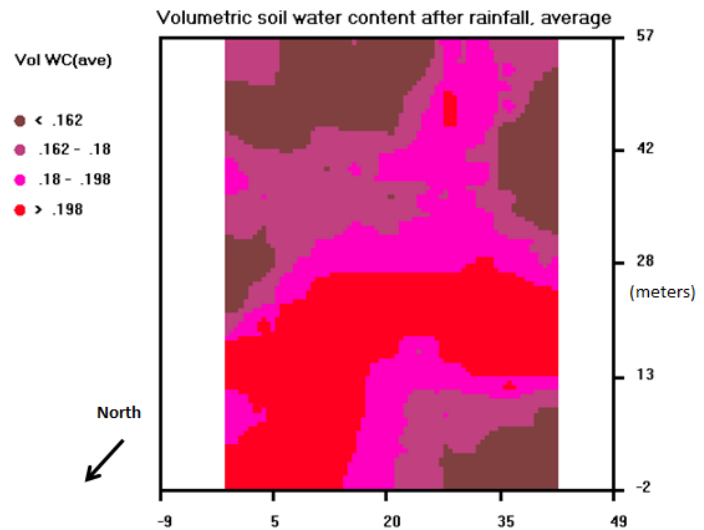


Figure 6.24. The spatial distribution of the volumetric water content, after rainfall.

*Spatial variation of ECa*

When visualizing the EMh and EMv readings for the campaign after rainfall, the histograms appeared skewed. Therefore a log transformation was conducted to make the data more normally distributed. The histogram, before and after the transformation can be seen in Appendix IV. The spatial distributions of the EM38 readings can be seen in Appendix V. Basic statistics for the EMh and EMv readings can be seen in Table 6.10 below. 2 outliers were found and removed from the data.

Table 6.10. Basic statistics for the fourth campaign representing the conditions after rainfall.

	N	Average	Std	Min	Max	Corr
<b>EMh</b>	104	0.344	0.103	0.22	0.58	0.9625
<b>EMv</b>	104	0.482	0.134	0.27	0.82	

*Soil salinity profiles*

The soil salinity profiles for this campaign representing the conditions after rainfall can be seen in Figure 6.25 below. The point H121 is marked red since it differs remarkably. Basic statistic for ECe data can be seen in Appendix VI.

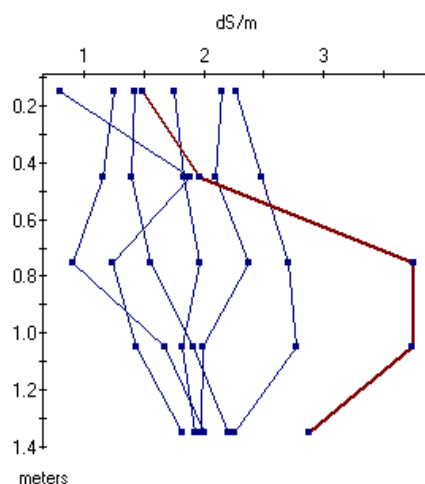


Figure 6.25. The soil salinity profiles, after rainfall. Note the profile marked red; H121 is deviating remarkably from the rest of the profiles.

#### Model and model coefficients

H121 was once again removed to improve the model fit and the resulting model coefficients can be seen in Table 6.11 below where the PRESS scores are also presented. The PRESS scores are generally low and this implies a good model. The removal of H121 resulted in the  $R^2$  value changing from 0.810, 0.676 and 0.465 to 0.897, 0.950 and 0.976.

Table 6.11. The model coefficients for the fourth campaign, after rainfall.

Depth	b0	b1	b2	b3	PRESS score
0-0.3 m	0.270	0.334	0.115	-0.003	0.578
0-0.9 m	0.282	0.240	0.148	0.321	0.570
0-1.5 m	0.495	0.184	0.113	-0.014	0.172

The model performance is further evaluated by looking at the  $R^2$  values, the estimated coefficient of variation and the root mean square error, which can be seen in Table 6.12. The  $R^2$  values for this campaign are very high and the root mean square errors are low. This indicates good model performance.

Table 6.12. The  $R^2$  values, the estimated coefficients of variation and the mean root square error for the models in the fourth campaign, after rainfall.

Depth (m)	R-square	Est-CV (%)	RMSE
0-0.3	0.897	19.95	0.198
0-0.9	0.950	11.14	0.111
0-1.5	0.976	5.59	0.056

To validate the model calibration, the jack-knifed predictions were plotted against the observed values, see Figure 6.26 below. The majority of the points are located close to a 1:1 line and therefore are the models considered good for this campaign.

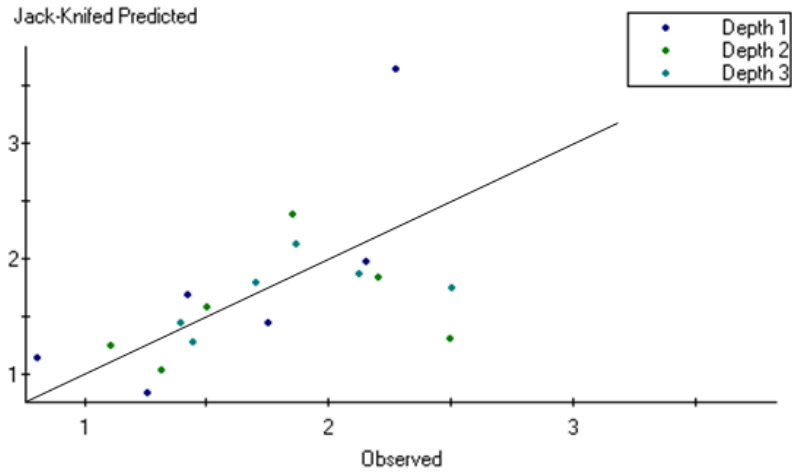


Figure 6.26. The jack-knifed predictions plotted against the observed values.

### Soil salinity maps

Using the model coefficients and the specified MLR model seen above, the spatial distribution of the soil salinity for the three depths can be predicted using the EM38 readings. The result can be seen in Figure 6.27 - Figure 6.29. Note that the bright red color indicates the highest soil salinity.

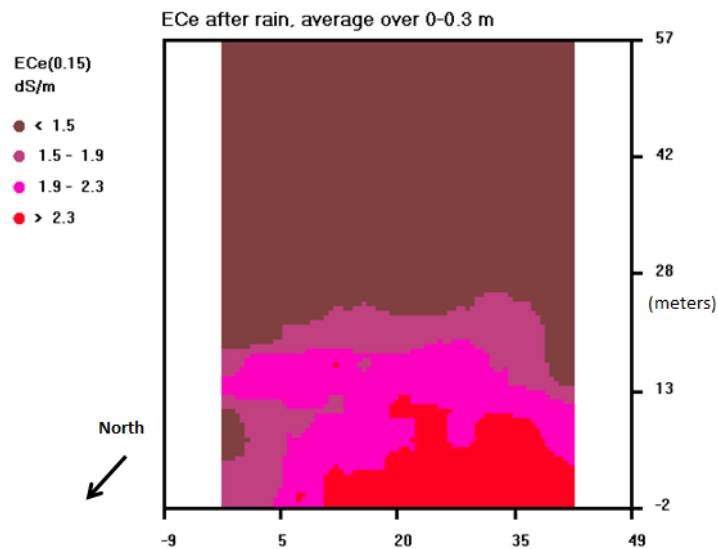


Figure 6.27. The spatial distribution of soil salinity for the depth 0-0.3 m, after rainfall. The bright red indicates the highest salinity.



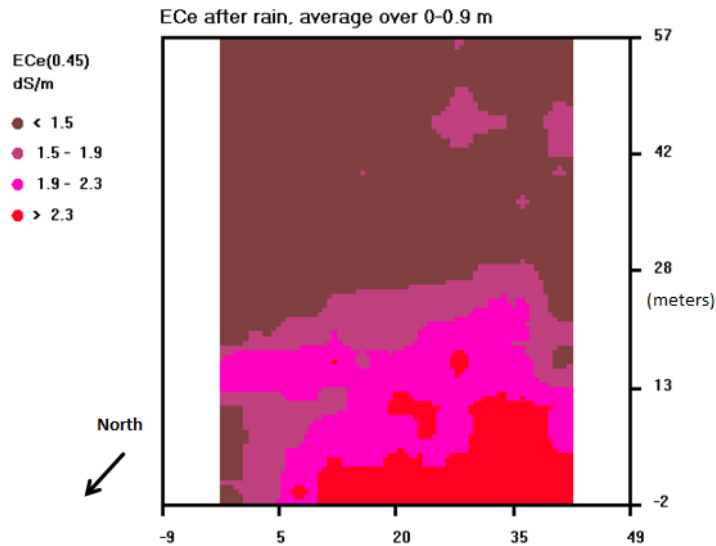


Figure 6.28. The spatial distribution of soil salinity for the depth 0-0.9 m, after rainfall. The bright red indicates the highest salinity.

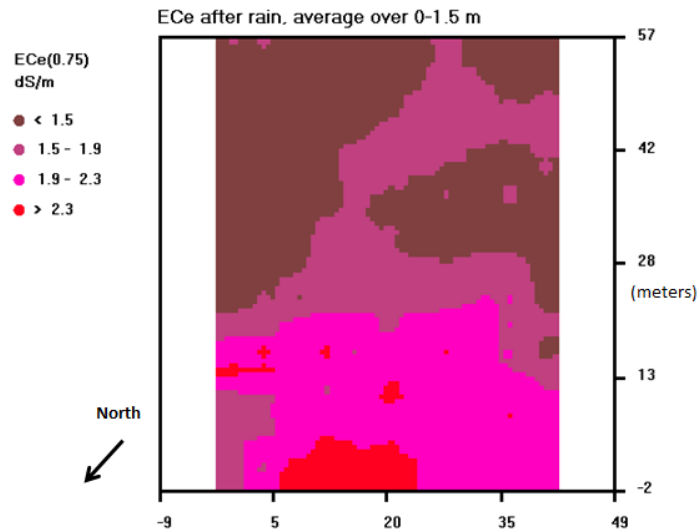


Figure 6.29. The spatial distribution of soil salinity for the depth 0-1.5 m, after rainfall. The bright red indicates the highest salinity.

### Discussion

Once again the point H121 deviated and had to be removed. This improved the model performance remarkably. Possible reasons for the fact that this point is deviating for three out of four campaigns have been discussed in the discussion of the previous campaign.

The soil salinity is highest in the north eastern part of the field and possible reasons, like leaking pipes, for this have been discussed in the discussions for the previous campaigns.

Generally, the soil salinity has decreased compared to the last campaign for the first and second depths. This was expected since no salt has been added; no irrigation took place. Possibly, a small increase can be seen in the average over the entire depth which could indicate a larger increase in the deeper parts, 0.9-1.5 m, like discussed in the previous discussion. The increase in the deeper parts could be explained by leaching; the rainwater leached the salts further down in the soil.

However, the leaching was not enough to leach the entire soil and the salt could be held here in the clay layer.

### 6.3. Crop water need and irrigation efficiency

Based on Equation 3.1, the real crop water need for this field was calculated for each month, see Table 6.13. For information about the calculations see Appendix III.

Table 6.13. The real crop water need on Field H.

Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
15.28	31.97	51.70	66.10	159.41	191.50	220.98	197.55	94.83	31.40	37.46	0.00

In Table 6.14 below the summary statistics of the field capacity at pF 2.7 ( $\theta_{FC}$ ) and the wilting point at pF 4.2 ( $\theta_{WP}$ ) over the entire field and sampling depth can be seen. For information about the calculations see Appendix III.

Table 6.14. Summary statistics of the water content at field capacity ( $\theta_{FC}$ ) and wilting point ( $\theta_{WP}$ ).

	$\theta_{FC}$	$\theta_{WP}$
	% by volume	
<b>Average</b>	18.3	11.5
<b>Min</b>	9.1	5.1
<b>Max</b>	27.6	19.1
<b>Std</b>	3.7	2.8
<b>CV-%</b>	20	24

As can be seen in Table 5.2 the total amount of added water in September was about 220 mm and in October it was about 230 mm. According to Table 6.13 the total real crop water need for the citrus trees was about 94.8 and 31.4 mm in September and October, respectively. This means that both during September and October more water was added to the field than was needed to fulfill the crop water need. The extra added water cannot only have been added to secure a leaching of salts in the field; the amount is too large. The irrigation efficiency in the field will further be investigated by looking at the observed soil water content in relation to the field capacity and wilting point. In Figure 6.30-Figure 6.32 below the field have been divided in three areas; the north-western, the central and the south-eastern part. The north-western part is represented by the representative points H104 and H54, the central part by H49 and H112, and the south-eastern part by H44, H71 and H121 (for locations of the points on the field see map in Figure 5.2). This division was based on the observed soil parameters.

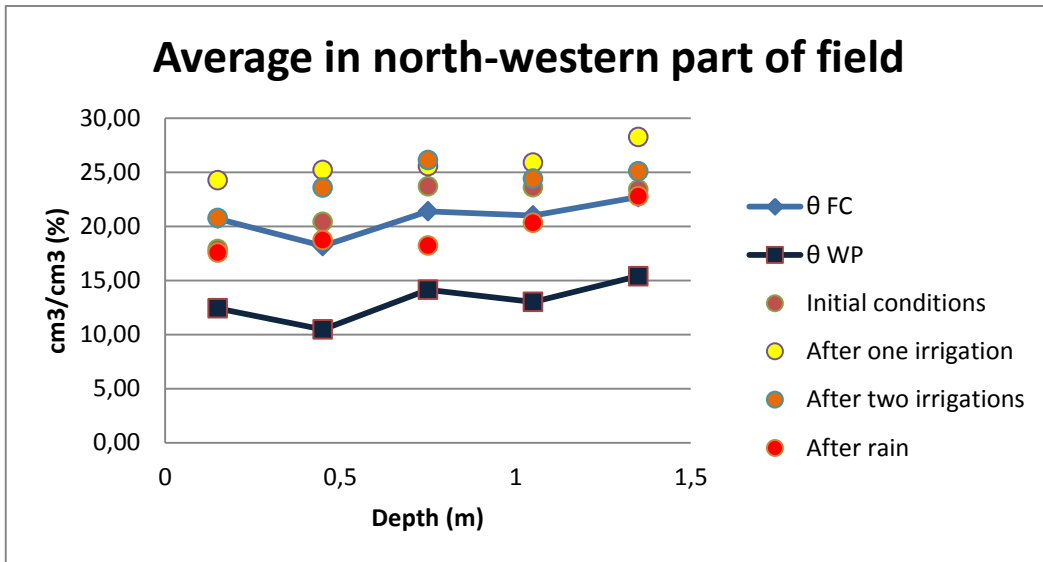


Figure 6.30. The average field capacity, wilting point and observed soil water content in the north-western part of the field.

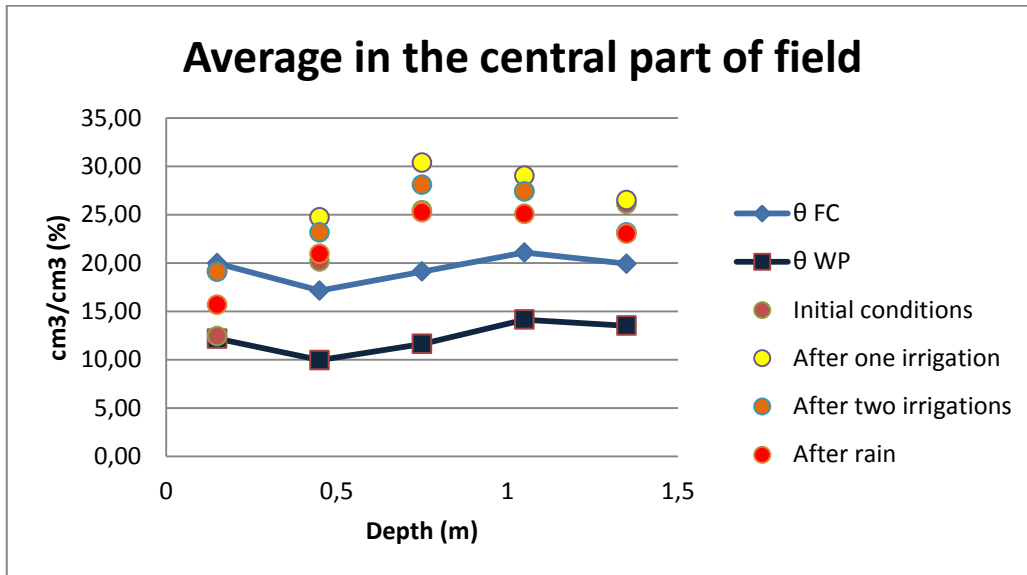


Figure 6.31. The average field capacity, wilting point and observed soil water content in the central part of the field.

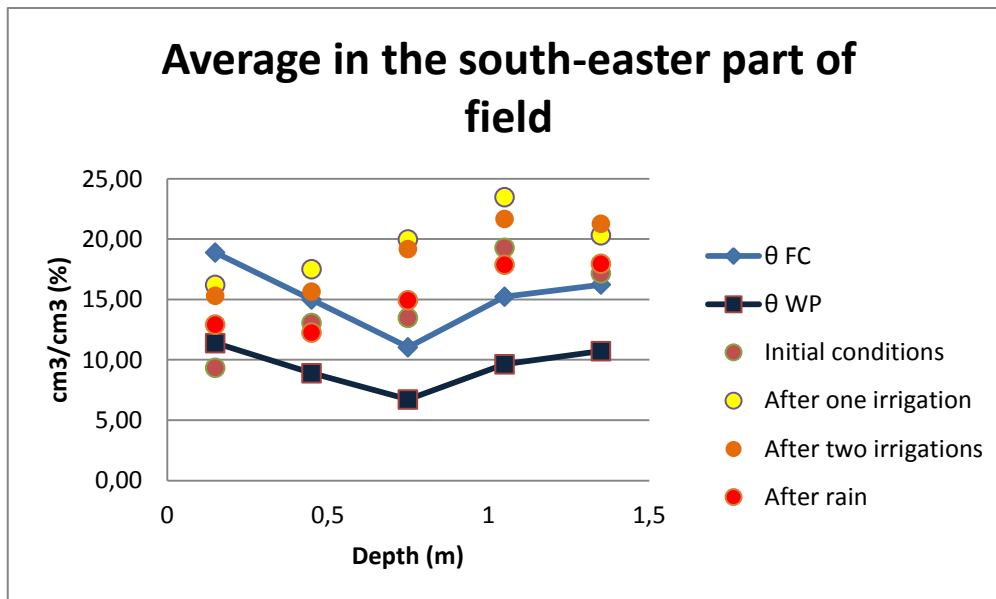


Figure 6.32. The average field capacity, wilting point and observed soil water content in the south-eastern part of the field.

By looking at Figure 6.31-Figure 6.33 it is evident that the observed soil water content, except in the upper most layer, exceeds the field capacity, which should not be possible. The field capacity might be false due to that the laboratory in Tunis used pF 2.7 as a standard instead of 2.5 that should be used according to theory (see i.e. section 3.2) or that the pF analyses were not done on undisturbed samples, therefore the calculated field capacity is not to be trusted. Hence, no clear indications of the irrigation efficiency can be seen in Figure 6.31-Figure 6.33. However, as mentioned above, the calculated crop water need indicated that the farmer added too much water to the field. In Figure 6.31-Figure 6.33 it can also be observed that in general an increase in soil water content and wilting point are related to a deeper soil depth. Generally also an increase in clay content could be seen in the deeper layers, meaning that the soil water content and wilting point are higher at higher clay content. This further means that the observed maximums seen in Table 6.14 are from the deeper layers with higher clay content.

#### 6.4. Farmer survey

22 farmers were interviewed with an average age of 56 years and the age distribution can be seen below in Figure 6.33. Agriculture is the main activity for 18 of the farmers, and 3 of them also had a secondary activity. Most often the secondary activity involved managing a shop of some sort. Furthermore, only 23 % of the farmers had gone through secondary school or a higher education. Most of the farmers own their own land, and about 64 % have inherited it from their father. However, about 18 % of the farmer rent their land from another farmer. Farmers who own his own land usually seemed to have another sense of responsibility to carry on the work on the farm even though the farm might not always provide a substantial income. Also, an owner was generally more open to suggestions of using other techniques or to make changes in the land to further increase the production, while a renter did not feel he had the choice to make changes since it was not his land.

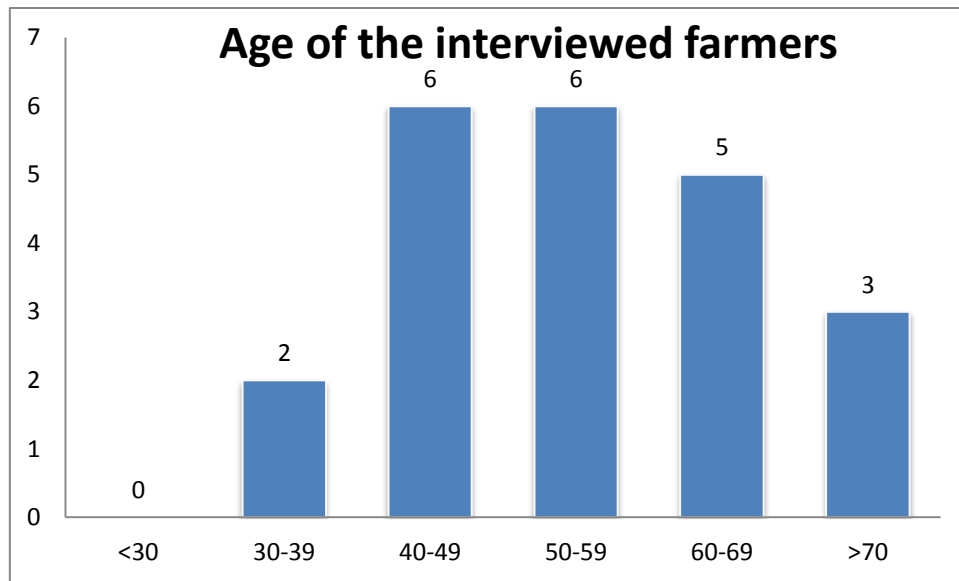


Figure 6.33. The age distribution of the interviewed farmers.

The average net agricultural area was 1.4 ha, the minimum 0.15 ha, the maximum 8.5 ha and the standard deviation 2.2 ha. All but 2 of the farmers have land with mostly sandy soil. 82 % of the farmers have a deep groundwater, more than 10 m, and only 1 farmer has a shallow groundwater table, less than 5 m. All the farmers cultivate irrigated crops and 4 also have rainfall crops. The irrigated crops include citrus fruits, bitter oranges, pomegranate and different types of forage. Olives is usually a rainfall crop, but some farmers irrigate also this crop. 77 % of the farmer grows more than 1 crop. To see the distribution of the crops grown see Table 6.15 below.

Table 6.15. The crops grown by the interviewed farmers.

Crop	Citrus	Bitter orange	Pomegranate	Olives	Forage
Number of farmers	13	18	4	5	6

All farmers use organic matter on their fields. Other fertilizers like Ammonitre (a Tunisian fertilizer with nitrogen), phosphate and potassium are less commonly used. The main reason for using these fertilizers was to increase production; 64 % of the farmers gave this as a reason. It was usually tradition that regulated the use of fertilizer; 68 % of the farmers used a traditional method, i.e. the method used by their parents. The rest used visual estimation to regulate the addition of fertilizers. Many farmers (59 %) also used insecticides to protect their crops, but only 14 % also used pesticides. During some periods the pesticides and insecticides were given to the farmers for free from the government. This is however not the case today and many farmer thought it too expensive to buy it themselves.

95 % of the farmers have their own well, but more than half of them believe the well water is too saline and therefore they do not use it for irrigation. However, when there is treated wastewater shortages some farmers, 36 %, still use it. For all but 1 farmer, the treated wastewater is the main water source for irrigation. None of the farmers know the crop water need for their crops. 82 % estimate the irrigation frequency visually while 18 % use a traditional irrigation frequency. Most of

the farmers use basin irrigation for their tree crops, and most farmers growing forage use furrow irrigation.

1 farmer has not made any observations regarding the treated wastewater quality. However, 32 % think the quality is average, 27 % thinks the quality is bad, 23 % thinks the quality is good and 14 % says it is better than nothings (see Figure 6.34 below). Up to 59 % of the farmers noticed an increase in production using the treated wastewater, while 18 % experienced a problem with production or quality. 1 farmer actually experienced both; the farmer noticed an increase in production but the quality of the fruit produced was worse when using treated wastewater. 23 % noticed soil degradation from the treated wastewater, 9 % noticed other problems and 14 % experienced no problems. Only 2 of the 22 farmers feel the need to plough due to the degradation effects on the soil from the treated wastewater. 86 % experiences some problems with the treated wastewater but only 9 % associated these problems with soil salinity. Some farmers seemed to regard the treated wastewater as “dirty water” and disliked it just because it was wastewater and questioned why they could not use conventional water. The biggest issue farmers had with the treated wastewater seemed to be that they could not grow high profit vegetables with this water, which could possibly mean a larger income for the farmers.

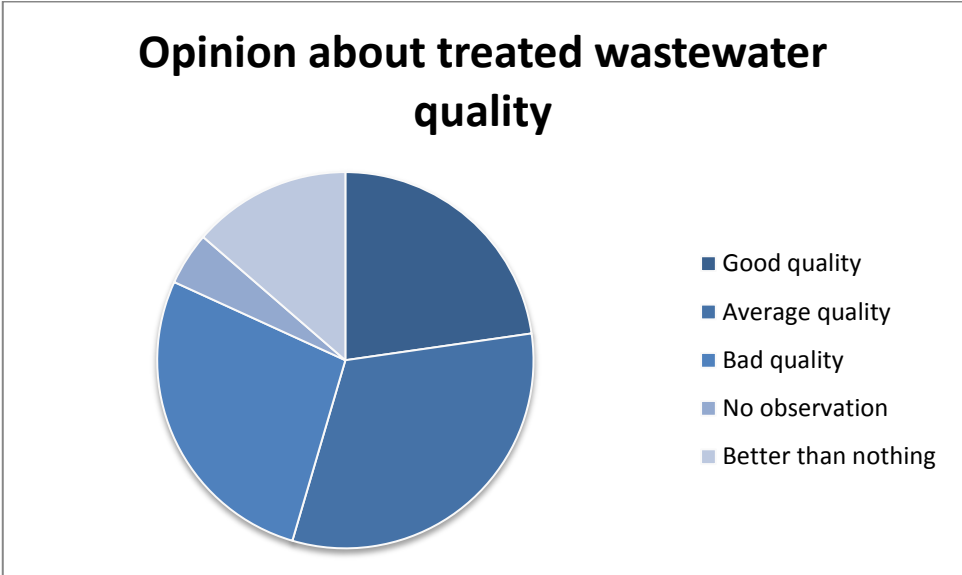


Figure 6.34. The interviewed farmers’ opinion about the treated wastewater used for irrigation.

## 7. General discussion and conclusion

The soil salinity assessment done in this thesis can only be considered a qualitative one and the result can only be seen as an indication of an increase or decrease in the soil salinity over this particular field. Firstly, the result is based on assumptions and models, which could have a significant impact on the soil salinity predictions, as discussed in the following section. Secondly, the time frame for this thesis is too short and the data collected during the field study represents only a fraction of the agricultural year. Nothing can be said about the variation over the year, the variation between years or the impact on the soil salinity after several years of irrigation with treated wastewater. Thirdly, this is a field study and not a controlled laboratory experiment. However, the indications can be a help when deciding the objectives and limitations on future studies in this area.

### 7.1 Methodology – EM38 and ESAP

One of the objectives of this master thesis was to use the EM38 instrument together with the computer software ESAP to map the salinity across Field H. The EM38 was proven to be an easy to handle instrument that has many advantages in a field survey. The EM38 gives quick in situ measurements which are easy to redo and the instrument is easy to move between measurement points. Some disadvantages might include its sensitivity to metals, which sometimes were found in the field and thus could have affected the measurements.

The ESAP software is relatively easy software to use, and it comes with an extensive manual. However, it seems to be a sometimes arbitrary software that does not work on all computers, without any clear reason. Also, many of the help files are not available and the output files cannot be viewed from the programs themselves. But once one has got acquainted with ESAP it is not hard to find one's way around these obstacles. Another important feature of ESAP is its ability to map other soil properties, such as clay content and soil water content. All in all, ESAP is well adapted to be used together with the EM38, and soil samples, and the method of using them together is a relatively quick and easy one. Generally, ESAP is a time-saving tool.

### 7.2. Models and models' performances

The most important way to evaluate the models' performances in this thesis has been the  $R^2$  values. By looking at these values it has been decided which basic model to use, and also, in some cases, if any maps generated by the models should be excluded from the analysis. The limit for a good or bad  $R^2$  value was decided to be 0.60 and most of the models reach this value by far. Only the models for two depths in the second campaign did not reach this limit and they were therefore excluded. The reason for excluding these was that these maps are not good representatives of the reality. The aim of modeling is often to see the reality and using a model with a very low model performance might therefore not be suitable. Since, in this thesis, the third campaign also represents an irrigation event, it is possible to exclude these maps without affecting the results too much.

Each of the campaigns includes three models and all the coefficients in these models are different. Any differences between the maps, produced from predictions made by these models, could be due to the differences in the models. However, since the model performance of all models, included in the analysis, are mostly satisfactory, the maps are considered to represent the reality, which means that they can be compared with reasonable certainty.

Some of the data used in this thesis have been modified. By looking at the raw data, likely errors have been encountered and corrected using one of the methods mentioned above. So, any unreasonable data should have been excluded from the analysis, which should improve the accuracy of the models in this thesis. All the EM38 data have been corrected according to the temperature in the soil, as it should be. However, the temperature is an average over the entire field and the entire sampling depth, which could make some of the corrections a little less accurate. Even if the temperature did not differ so much over the field, many small errors could add up to a large one. All the EM38 data was also log transformed to make the data more normally distributed; this is needed since ESAP is using statistical methods that require normal distributions. However, by looking at the histograms in Appendix IV it can be noted that the histograms after the log transformation did not perfectly display the typical bell-shape. So, the data might not be normally distributed after all even after a log transformation, which in turn raises the question whether ESAP can work properly using the data or not. To answer this question is very hard and in this thesis it is assumed that this does not affect the models visibly.

In each campaign one point was removed and removing one out of seven points means that quite a large part of the data is removed. So, the models are based on a smaller amount of data and that could also affect the accuracy of the models. Altogether, many assumptions were made in this thesis which could affect the results. However, due to the good model performance and the fact that the assumptions are regarded as reasonable, all models and results are considered accurate.

### 7.3. Soil salinity

According to theory it was expected that the salinity would display an increase after one irrigation event, an even clearer increase after two irrigation events and then a decrease after rainfall. When comparing Figure 6.8-Figure 6.10 with Figure 6.15 and Figure 6.20-Figure 6.22, as well as Figure 6.20-Figure 6.22 with Figure 6.27-Figure 6.29, it is not evident that this is the case and it seems difficult to quantify a general decrease or increase. In some areas of the field the salinity has in fact increased after two irrigation events, but in other areas it has instead decreased. As has been discussed above (for example in section 6.2.1), the most visual increase in soil salinity in the south part of the field might be due to the natural inclination of the field, irrigation practice or to lateral flow in the soil. However, when looking at the general soil salinity over the entire field it seems like the soil salinity has actually decreased from the initial conditions to after two irrigation events. This might indicate that the amount of added water during irrigation helped leach the soil of salts in addition to adding more salts. Or there might be other factors, such as the large rainfall on one day between the irrigation events, that have affected the decrease. Over the short time frame for this thesis it is difficult to know the main reason for this decrease with any great certainty. It should also be noted that two irrigation events does not represent the majority of the irrigation events over one agricultural year, and an increase or decrease seen from only these events might be based on extreme values. To see whether the agriculture is sustainable or not, it is necessary to perform soil salinity assessments over a much longer period, i.e. several years.

To be able to identify any affects from the Tunisian winter rains on the soil salinity, a sampling should have been done even later in the season to cover more rainfall events. Between the campaign representing the condition after two irrigation events and the last campaign it rained 57.5 mm. In this part of Tunisia it annually rains about 455 mm, and most of it falls during the winter months, which means that the rains observed between these campaigns represent only about 13% of the



total annual rainfall and any results from this campaign will only be due to a fraction of the total annual rainfall. Comparing Figure 6.20-Figure 6.22 with Figure 6.27-Figure 6.29 it seems like the 57.5 mm rain have resulted in a general decrease in the soil salinity at 0-0.3 m depth, but in the deeper soils it is more difficult to see any clear change in salinity. An indication might thus be seen that the rain has leached the salts in the upper most soil. The salts leached from the upper most soil should have been transported to the underlying soil, however since the salinity in 0-0.9 m has not increased significantly one can draw the conclusion that some leaching has occurred also between 0-3 and 0.9 m. In the deepest soil salinity map, 0-1.5 m, one might see a small increase in the salinity, indicating that some of the leached salts have accumulated between 0.9-1.5 m. The accumulation might be due to the clay layer here, or that not enough water was added to leach the salts further down. All in all, one can see an indication that even this somewhat small rain have resulted in leaching enough to remove salts from the important root zone. It is also important to note that some of the older trees in the field had a larger canopy cover, which can function as an umbrella, than the younger ones and this could affect the amount of rain that falls close to the tree and can infiltrate in the soil, where the EM38 measurements and soil samples were taken. The full extent of the effect on the soil salinity the trees canopy cover might have is hard to predict, but most likely the canopy cover will hinder the rain from reaching the soil and leaching out the salts. This means that for some trees only a fraction of the 57.5 mm rain reached the ground and could leach the soil.

As mentioned previously in this report, 4 dS/m is generally the definition of saline soil. For the field observed in this thesis the measured soil salinity never exceeds 3 dS/m (see Appendix VI) and thus by definition the soil of this field cannot be regarded as saline. However, according to Table 2.1 the salt tolerance for citrus trees is around 1.3 dS/m, see Table 2.1, and the fruit yield might be affected already at this fairly low salinity value. In Figure 6.8-Figure 6.10, Figure 6.15, Figure 6.20-Figure 6.22 and Figure 6.27-Figure 6.29 it is apparent that there is a substantial part of the field, even though it might be different parts, which has salinity above 1.5 ds/m. So even if the soil in the field cannot be regarded as saline, the observed salinity values can still have a significant negative effect on the citrus trees in the field. However, some of these negative effects could be overcome by the positive effects from the added nutrients in the treated wastewater.

In general the indications seen in this thesis does not perfectly agree with the theory. Some possible reasons for that have already been discussed elaborately above, but there are also other possible sources of errors. Firstly, the EC<sub>a</sub> measured with EM38 should be done close to field capacity, which was probably not the case for most of the campaigns since it is difficult to know exactly when the field is at field capacity. Secondly, in this field, EC<sub>a</sub> is more dependent on the soil water content than EC<sub>e</sub>. The soil salinity maps presented in this thesis is done with predicted EC<sub>e</sub> based on a linear relationship between measured EC<sub>a</sub> and EC<sub>e</sub>, which means that an increase in EC<sub>a</sub> should mean an increase in EC<sub>e</sub>. This was however not always observed, and this difference in EC<sub>a</sub> variation can be due to a difference in the soil water content between the campaigns. Finally, sometimes deviating and strange measured EC<sub>e</sub> values were observed. These values could for example be due to that the laboratory measurement of EC<sub>e</sub> is based on visual observation, and if different people performed the measurement there might be a difference in the results. It could also be due to very local variations around these points. It should also be noted that the groundwater level in the field is relatively low, and it seems very unlikely that any salt would be transported in the soil layers with the groundwater. Any increasing salinity content could thus not be explained by groundwater moving upwards.

An attempt to evaluate the irrigation efficiency was done by comparing the observed soil water content and the calculated field capacity and wilting point (see Figure 6.31-Figure 6.32), and by looking at the crop water need. Because of doubt about the credibility of the field capacity no indications of the irrigation efficiency could be drawn from Figure 6.31-Figure 6.33. However, by looking at the calculate crop water need it was concluded that the farmer added more water than needed during the irrigation events. This excess of water could lead to a significant leaching of the soil, which could explain the observed general decrease in soil salinity after the two irrigation events. A significant leaching can also lead to groundwater contamination when salts, nutrients and fertilizers are transported down to the groundwater.

It has been discussed previously that removing the olive trees from the data might give a clearer indication of the effects of irrigation with treated wastewater. The removal will assume that the whole field is irrigated and make a more even interpolation over the field. This removal could thus have the effect that the resulting average soil salinity in the field is overestimated; a larger area have been subjected to salt addition. However, since the main objective of this thesis have involved trying to find an indication associated with the worse possible scenario the decision to remove the olive trees is regarded as a necessary measure.

#### **7.4. Farmer practices**

Many farmers see the effects of soil salinity on their crop but do not connect it to salinity in the irrigation water. However, very few of the farmers do anything, knowingly, to manage soil salinity. All farmers add organic matter to the soil, which could have a good effect on the soil structure and thus the water and salt transfer. Possible reasons for the farmers not doing anything could be that the winter rainfall leach their sandy soil from salts or that they lack information about soil salinity. In this thesis it has been discussed that the few smaller rainfalls observed has had a positive effect on soil salinity; the rainfall leached the soil from some of the salts added by two irrigation events using treated wastewater. So, the farmers might be right in trusting the winter rainfall. However, during the irrigation season the farmers should aim to add enough water to leach the soil and avoid soil salinity during this period. It will rain more during the winter in Tunisia than it did during this field study and if a few smaller rainfalls could leach salts from two irrigation events; imagine what more rainfall could do. However, if the winter leaching is not enough, salt will accumulate from irrigation using saline treated wastewater every year and after some years the soil salinity could have reached very high levels if no measures are being taken. If the winter leaching is not enough, this kind of agriculture is not sustainable and could probably lead to soil degradation, which will affect the farmers and their lives remarkably. It is sustainable to reuse treated wastewater but if the negative effects from it overcome the positive effects, the sustainability of reusing water has to be questioned. However, irrigation using treated wastewater has been used in Souhil for more than 20 years and the soil salinity is, according to this thesis, not that high; it never exceeds 4 dS/m, as mentioned before. In the field observed in this thesis no well water, which has a higher salinity than the treated wastewater, was used. As have been discussed before some farmers in the area use the well water as a complement to the treated wastewater when there is a water shortage. When well water is used it is very likely that the soil salinity will be higher than what have been observed in this thesis, maybe even over 4 dS/m.

The lack of information about soil salinity among the farmers in the Souhil irrigation district might not come as a surprise. The farmers often lack any higher education and they often use tradition to

make their agricultural decisions. The Souhil GDA has great opportunities to spread information since they organize workshops. If the GDA could organize workshops and spread information about soil salinity and simple solutions to the problems connected to it, the farmer's knowledge would increase. One simple thing the GDA could spread information about is the use of fertilizers like organic matter. As mentioned before, organic matter could have positive effects on soil salinity and the soil degradation it is causing. However, if too much is added, the soil salinity could increase. GDA should spread information and recommendations about the right amount to apply to a tree or any other crop.

Even if the Tunisian government took actions to increase the understanding and use of treated wastewater for irrigation, some farmers still perceive the water as dirty. To change this perception, lots of information has to be spread and people need to be educated. It is not easy to change people's view on things. However, many farmers experience benefits from using treated wastewater and this could be used as a carrot; larger production could be an incentive for other farmers to use treated wastewater if the right information is spread. Another thing that seems to be a problem for the farmers is the fact that they cannot grow high profit crops, such as vegetables, using treated wastewater. The farmers in Souhil irrigation district can only choose between using treated wastewater and using the very saline well water. If they choose the well water, the crops and soil might be destroyed due to the very high salinity of the water and if they choose the treated wastewater, they cannot make the highest profit.

No modern techniques are used in Souhil irrigation district; it is often tradition that decides what to do with the field. This statement points to an agriculture with the capacity to update and making things more efficient. However, this might not be a good idea because of the size of the fields. For example, modern machines cannot enter the fields to plough and a modern irrigation method might not be possible due to the quality of treated wastewater. The farms might be compelled to use inefficient techniques and, as mentioned above, small farms might be inefficient. The smaller size of the farms also affects the farmers' mentality and willingness to do investments and possible improvements; there might not be much economical gain in doing an investment or improvement on these small farms.

The average farmer interviewed was of a relatively high age and used a lot of traditional methods. The traditional methods might not have changed in several decades and might not be adapted to the current conditions. This might for example have the result that too much fertilizer is added to the field, which can leach down to the groundwater and pollute it. It might also have the effect that too much or too little water is added during irrigation. Too little means that little leaching of salt will occur and the salt might accumulate in the root zone and effect the crops. Too much water might instead leach the soil from nutrients that can pollute the groundwater. The relatively high age of the farmers also raises the question; who will take care of the farms in a few years when the current farmer is gone? Overall it might be important that more and younger people get involved in the agricultural sector to secure its future development and that the farming practices ensure a sustainable agriculture.

As was mentioned above there are plans on building a new, larger and more modern treated wastewater plant in Nabeul. This new plant could greatly improve the quality of the treated wastewater used for irrigation. A better quality on the water might improve the opportunity for

other irrigation methods, such as drip irrigation. It is also possible that better quality in the future will partly lift the restrictions on what to grow with the treated wastewater and the farmers will have a larger say in what they want to cultivate.

Since the interviews were conducted in Arabic and the authors of this thesis do not master Arabic, the supervisor translated the interviews. However, many things could get lost in translation, or even added. Also, the aim of the interview might not have been clear to the farmers being interviewed. Many of them seem to think that if they gave the worst possible answers, they would receive help directly. They did not have the understanding that the goal was research and not investigating if there was a need to give help or not. So, some answers could be misleading. It is important to think about this when analyzing the interviews and to take into consideration that only 10 % of the farmers in this small irrigation district have been interviewed.

## 7.5. Future recommendations

From the results discussed above, it has been evident that a longer and more comprehensive study needs to be done in order to establish any effects from irrigation with saline treated waste water in this area. Therefore, it is recommended that the results from this thesis should foremost be seen as a first investigation that is to be used as the base for further studies in the same field. For these future studies it is suggested that additional representative points are chosen for soil sampling and laboratory analysis to get a better representative of the field, that the laboratory analyses is started earlier in to see if there are some irregularities with the data or faults in the laboratory, and that a closer analysis of the amendments the farmer put in the field is done to find other possible sources of salt. Also, as have been discussed above, there are possible developments within the local GDA that could greatly diminish the negative effects from soil salinity and benefit the farming community.

## 7.6. Main conclusions

To sum up, some main conclusions can be drawn from the discussion above:

- The models need to be compared with care. However, they are in this thesis considered to be representative of the reality.
- Rainfall can affect the soil salinity.
- Local conditions, such as soil properties, irrigation practice, inclination of the field and the state of the irrigation pipes, can affect the soil salinity.
- The farmer adds more water to the field than required by the crops.
- The soil at the studied field is not saline. However, the fruit trees grown there might still be at risk due to their low salt tolerance.
- Further study is needed to be able to draw any conclusions about the sustainability of the agriculture at this field.
- The observed soil salinity variations, from this study, did not always agree with the theory.
- The farmers in the area might lack information and knowledge about soil salinity management and crop water need. The farmers usually use traditional agricultural practices.
- The Souhil GDA, could play an important role in spreading information and knowledge.
- The farmers experience problems connected to soil salinity but also other problems, like the perception of treated wastewater and the limitations in crops to grow using treated wastewater.

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




































































































































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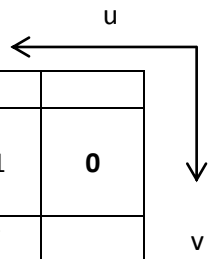
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# I. Appendix - Map over Field H

 Citrus tree  
 Olive tree

40	36	32	28	24	20	16	12	8	4	0	
	 H133		 H106		 H83		 H55	 H27	 H26	 H1	<b>0</b>
 H134	 H132	 H107	 H105	 H84	 H82	 H56	 H54	 H28		 H2	<b>4</b>
 H135	 H131	 H108	 H104	 H85	 H81	 H57	 H53	 H29	 H25	 H3	<b>8</b>
 H136	 H130	 H109		 H86	 H80	 H58	 H52	 H30		 H4	<b>12</b>
 H137	 H129	 H110	 H103	 H87	 H79	 H59	 H51	 H31	 H24	 H5	<b>16</b>
 H138	 H128	 H111		 H88	 H78	 H60	 H50	 H32	 H23		<b>20</b>
 H139	 H127	 H112	 H102		 H77		 H49	 H33	 H22	 H6	<b>24</b>
 H140	 H126	 H113	 H101		 H76	 H61	 H48	 H34	 H21	 H7	<b>28</b>
 H141		 H114	 H100	 H89	 H75	 H62	 H47	 H35	 H20	 H8	<b>32</b>
 H142	 H125	 H115	 H99	 H90	 H74	 H63	 H46	 H36	 H19	 H9	<b>36</b>
 H143	 H124	 H116	 H98		 H73	 H64	 H45	 H37	 H18	 H10	<b>40</b>
 H144	 H123	 H117	 H97	 H91	 H72	 H65	 H44	 H38	 H17	 H11	<b>44</b>
 H145	 H122	 H118	 H96		 H71	 H66	 H43		 H16	 H12	<b>48</b>
 H146	 H121	 H119	 H95	 H92	 H70	 H67	 H42	 H39	 H15	 H13	<b>52</b>
	 H120		 H94	 H93	 H69	 H68	 H41	 H40	 H14		<b>56</b>



## II. Appendix – Salt and water balance

Below follows the calculations made to determine the values in Table 5.1.

*Rain:*

Table II.1. Observed rainfall from the Qued Souhil weather station during the study period.

	September		October	
	Date	Rain	Date	Rain
	13	9.0	11	1.0
	23	23.0	12	19.0
			13	9.5
			15	7.5
			24	15.0
			30	3.0
			31	2.5
<b>Total</b>		<b>32</b>		<b>57.5</b>

*Evaporation:* Based on the average observed evaporation (mm/day), from the Qued Souhil weather station, over a 10 year period for respective month. The daily average for September is 3.85 mm and for October 2.79 mm.

September: Total evaporation = 3.85 (mm/day) · 18 (days) = 69.3 mm

October: Total evaporation = 2.79 (mm/day) · 31 (days) = 86.49 mm

*Irrigation:* The amount of irrigated water is the estimated amount added in each irrigation event observed by the farmer himself (see section 5.1.1.). Each irrigation event adds about 640 m<sup>3</sup> to the field, and there was one irrigation event in each of the months.

*Added salt:* The salt concentration in the added irrigation water is from the quality assessment done by INRGREF on the water in the reservoir supplying the Souhil irrigation district, on the 18<sup>th</sup> of September 2012 (see Table 2.6), which was 3.0 dS/m. According to the Department of Environmental and Resource Management in Queensland, Australia (2011) a solution with an electrical conductivity of 1 dS/m contains 670 mg/l of salt.

September and October: Total amount of added salt: 3 (ds/m) · 670 (mg/l) · 640 (m<sup>3</sup>) ≈ 1286 kg

(Department of Environmental and Resource Management in Queensland, 2011)

### III. Appendix - Real crop water need

#### *Real crop water need*

The monthly net crop water need was calculated according to Equation 3.1, with the specific crop water coefficient,  $K_c = 0.7$  (Allen, et al., 1998). It was then estimated that about 80% of the monthly rainfall would infiltrate and reach the roots. Finally the monthly real crop water need was calculated according to

$$W_{RC,real} = (W_{RC} - 0.8 \cdot P) \cdot I_{eff}$$

where  $W_{RC}$  = net crop water need,  $P$  = the monthly precipitation (mm) and  $I_{eff}$  = irrigation efficiency. The irrigation efficiency was decided to 0.6 (Brouwer, et al., 1989). The monthly evapotranspiration (calculated with Penman- Monteith) and precipitation observed at the Oued Souhil weather station, that were used in the calculations, can be seen in Table III.1 below.

**Table III.1. Monthly precipitation and evapotranspiration over a ten year period in Nabeul.**

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Precip	32.0	27.5	32.5	37.0	1.0	0.0	0.0	0.0	32.0	55.0	28.5	65.0
Evap	49.7	58.8	81.5	98.9	137.8	164.1	189.4	169.3	117.9	89.8	64.7	39.5

## IV. Appendix – Histograms EM38 measurements

*Initial conditions*

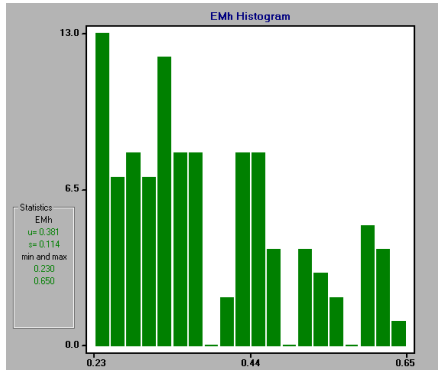


Figure IV.1. Histogram over raw EMh, from citrus trees, under initial conditions.

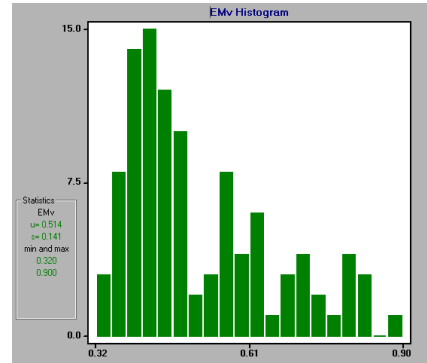


Figure IV.2. Histogram over raw EMv, from citrus trees, under initial conditions.

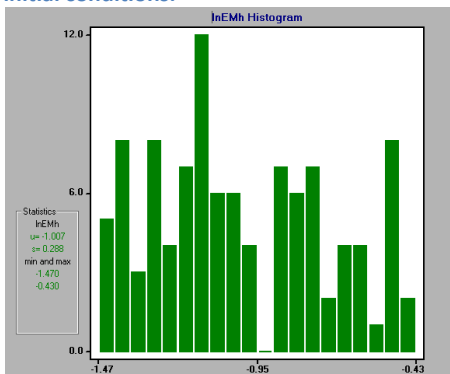


Figure IV.3. Histogram over log-transformed EMh, from citrus trees, under initial conditions.

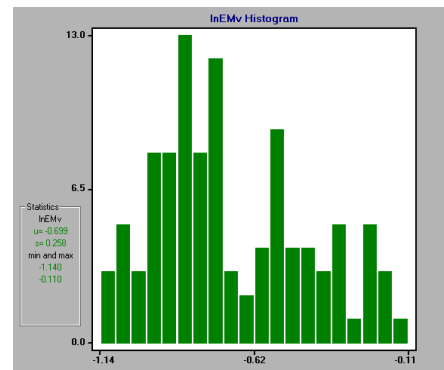


Figure IV.4. Histogram over log-transformed EMv, from citrus trees, under initial conditions.

*After one irrigation event*

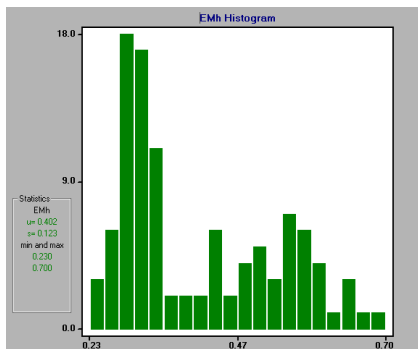


Figure IV.5. Histogram over raw EMh, from citrus trees, after one irrigation event.

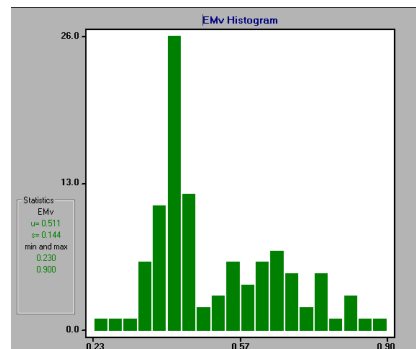


Figure IV.6. Histogram over raw EMv, from citrus trees, after one irrigation event.

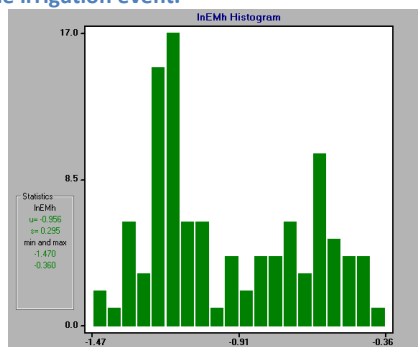


Figure IV.7. Histogram over log-transformed EMh, from citrus trees, after one irrigation event.

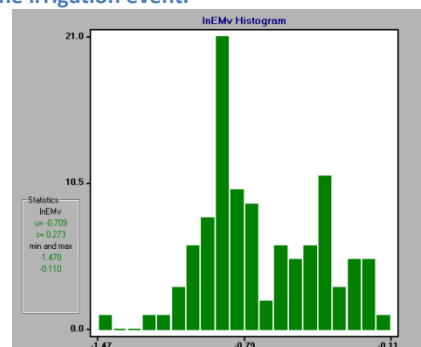


Figure IV.8. Histogram over log-transformed EMv, from citrus trees, after one irrigation event.

After two irrigation events

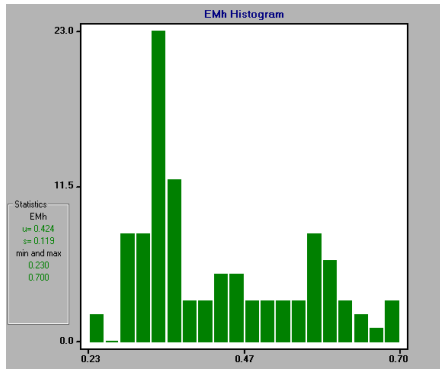


Figure IV.9. Histogram over raw EMh, from citrus trees, after two irrigation events.

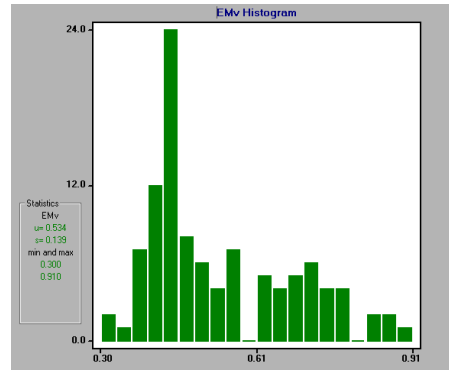


Figure IV.10. Histogram over raw EMv, from citrus trees, after two irrigation events.

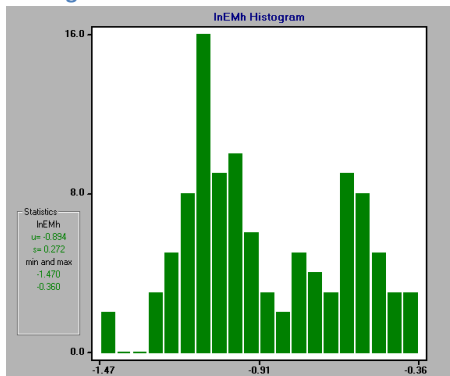


Figure IV.11. Histogram over log-transformed EMh, from citrus trees, after two irrigation events.

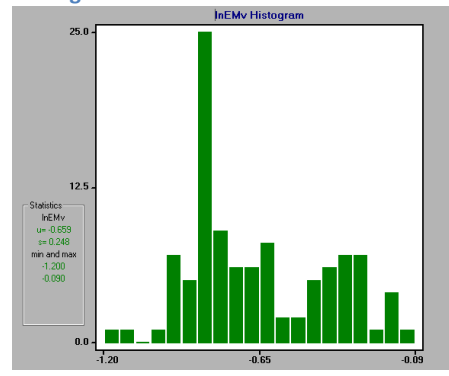


Figure IV.12. Histogram over log-transformed EMv, from citrus trees, after two irrigation events.

After rainfall

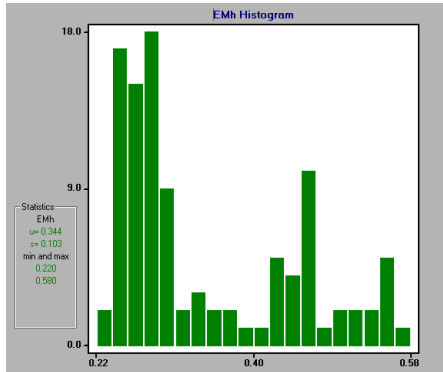


Figure IV.13. Histogram over raw EMh, from citrus trees, after rainfall.

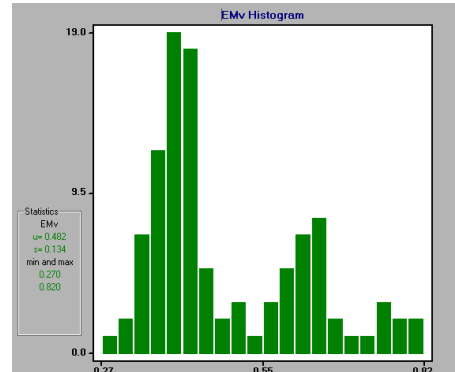


Figure IV.14. Histogram over raw EMv, from citrus trees, after rainfall.

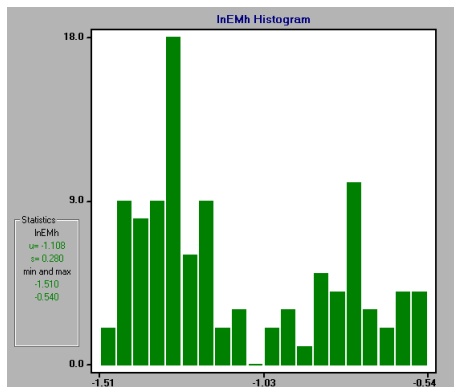


Figure IV.15. Histogram over log-transformed EMh, from citrus trees, after rainfall.

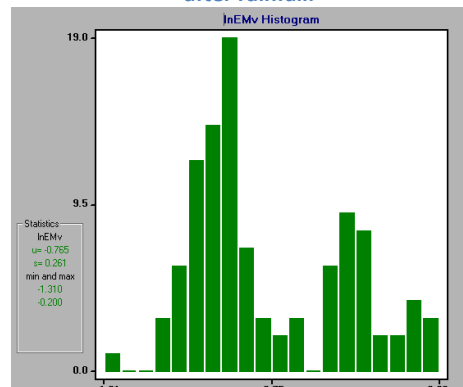


Figure IV.16. Histogram over log-transformed EMv, from citrus trees, after rainfall.



## V. Appendix - Spatial variation of EM38 measurements

### Initial conditions

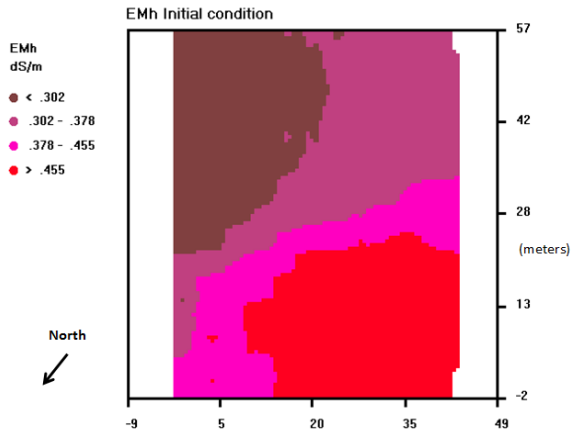


Figure V.1. Spatial variation of EMh, from citrus trees, under initial conditions.

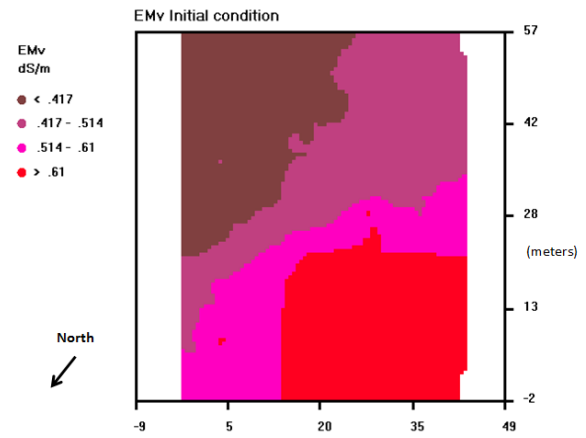


Figure V.2. Spatial variation of EMv, from citrus trees, under initial conditions.

### After one irrigation event

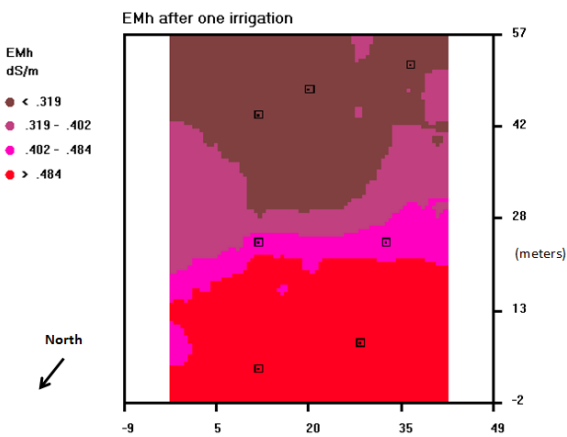


Figure V.3. Spatial variation of EMh, from citrus trees, after one irrigation event.

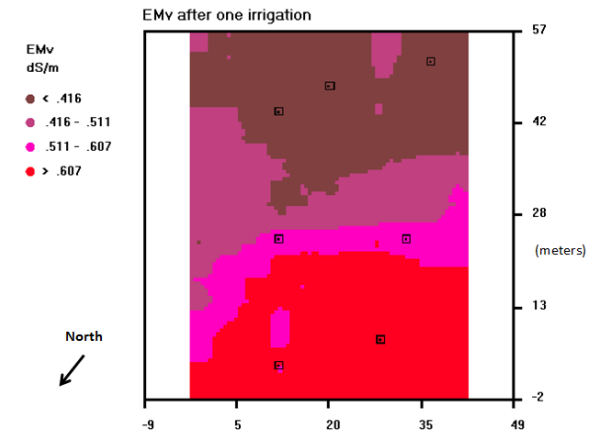


Figure V.4. Spatial variation of EMv, from citrus trees, after one irrigation event.

After two irrigation events

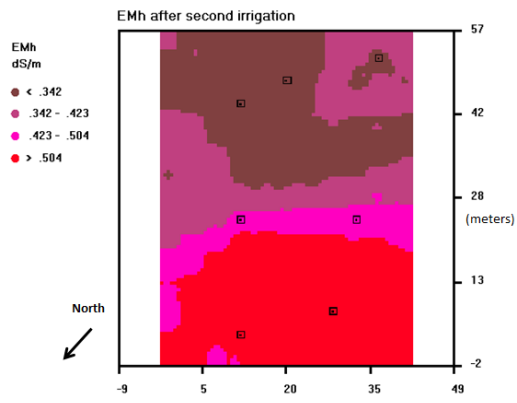


Figure V.5. Spatial variation of EMh, from citrus trees, after two irrigation events.

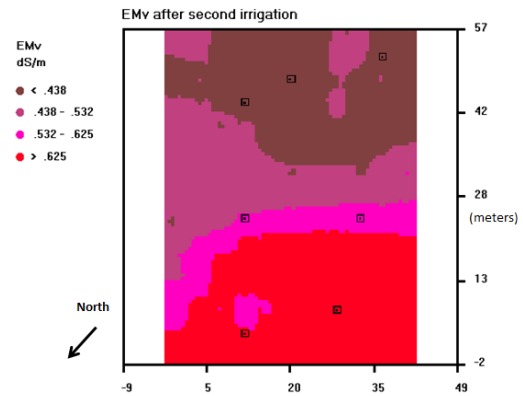


Figure V.6. Spatial variation of EMv, from citrus trees, after two irrigation events.

After rainfall

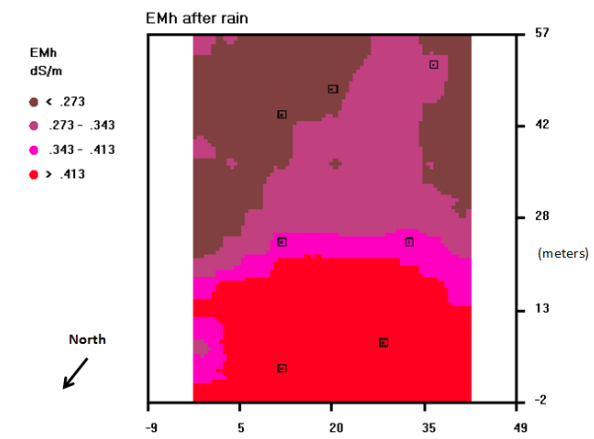


Figure V.7. Spatial variation of EMh, from citrus trees, after rainfall.

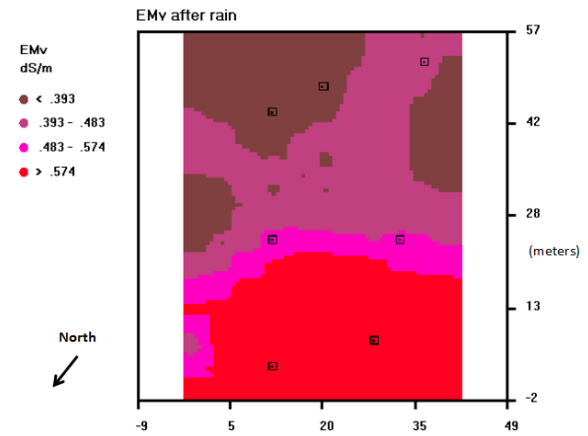


Figure V.8. Spatial variation of EMv, from citrus trees, after rainfall.

## VI. Appendix – Soil properties statistics

### Initial conditions

Table VI.1. Basic statistics and distribution of the clay content across the field. Note that R<sup>2</sup> indicates the linear correlation with ECe.

Depth (m)	Average	Standard deviation	Min	Max	R <sup>2</sup>
0-0.3	10.64	1.60	7.50	12.00	0.38
0-0.9	11	4.75	4	22	0.86
0-1.5	14	6.33	4	32	0.44

Table VI.2. Basic statistics and the distribution of the soil parameters, measured in the lab, representing the initial conditions. Note that ave is short for average, and R<sup>2</sup> is an indication of the linear correlation with the ECe

Depth (m)	ECe (dS/m)				Soil water content (volumetric)				
	Ave	Std	Min	Max	Ave	Std	Min	Max	R <sup>2</sup>
0-0.3	2.07	0.23	1.78	2.35	0.13	0.04	0.09	0.18	0.29
0-0.9	1.86	0.38	1.03	2.35	0.17	0.06	0.08	0.26	0.84
0-1.5	1.88	0.33	1.03	2.35	0.19	0.06	0.08	0.28	0.54

### After one irrigation event

Table VI.3. Basic statistics and the distribution of the soil parameters, measured in the lab, representing the conditions after the first irrigation. Note that ave is short for average, and R<sup>2</sup> is an indication of the linear correlation with the ECe.

Depth (m)	ECe (dS/m)				Soil water content (volumetric)				
	Ave	Std	Min	Max	Ave	Std	Min	Max	R <sup>2</sup>
0-0.3	1.85	0.13	1.59	1.93	0.18	0.03	0.16	0.23	0.22
0-0.9	1.92	0.43	1.14	2.77	0.21	0.05	0.13	0.31	0.07
0-1.5	1.95	0.50	1.00	2.83	0.23	0.05	0.13	0.31	0.15

### After two irrigation events

Table VI.4. Basic statistics and the distribution of the soil parameters, measured in the lab, representing the conditions after the second irrigation. Note that ave is short for average, and R<sup>2</sup> is an indication of the linear correlation with the ECe

Depth (m)	ECe (dS/m)				Soil water content (volumetric)				
	Ave	Std	Min	Max	Ave	Std	Min	Max	R <sup>2</sup>
0-0.3	1.58	0.32	1.02	1.92	0.12	0.02	0.09	0.14	0.32
0-0.9	1.42	0.36	0.71	1.96	0.21	0.05	0.14	0.29	0.70
0-1.5	1.40	0.31	0.71	1.96	0.22	0.04	0.14	0.29	0.46

*After rainfall*

Table VI.5. Basic statistics and the distribution of the soil parameters, measured in the lab, representing the conditions after rainfall. Note that ave is short for average, and  $R^2$  is an indication of the linear correlation with the ECe

Depth (m)	ECe (dS/m)				Soil water content (volumetric)				
	Ave	Std	Min	Max	Ave	Std	Min	Max	$R^2$
0-0.3	1.61	0.56	0.80	2.27	0.16	0.02	0.13	0.20	0.28
0-0.9	1.73	0.56	0.80	2.71	0.18	0.04	0.13	0.26	0.28
0-1.5	1.83	0.49	0.80	2.77	0.19	0.04	0.13	0.26	0.31

## VII. Appendix – Soil salinity maps

### Initial conditions

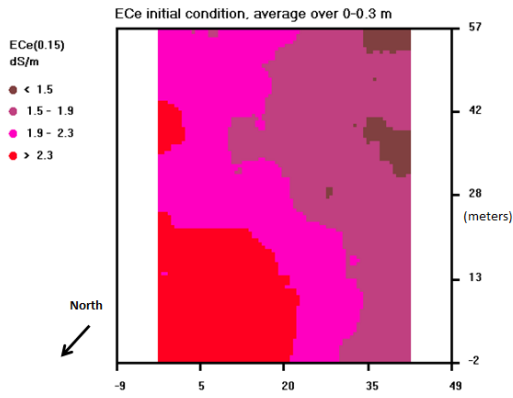


Figure VII.1. Spatial distribution of ECe in the upper most layer (0-0.3 m) under initial conditions.

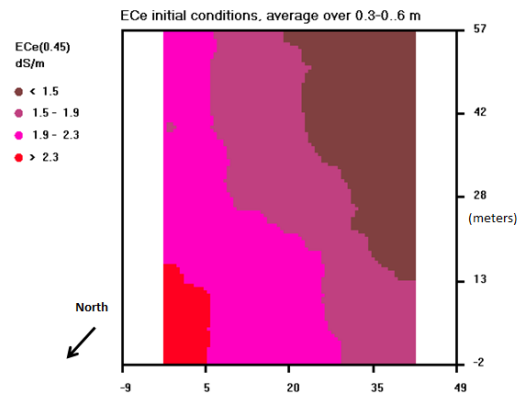


Figure VII.2. Spatial distribution of ECe in 0.3-0.6 m depth under initial conditions.

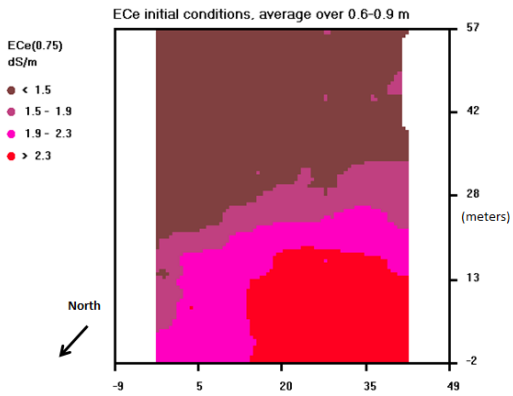


Figure VII.3. Spatial distribution of ECe in 0.6-0.9 m depth under initial conditions.

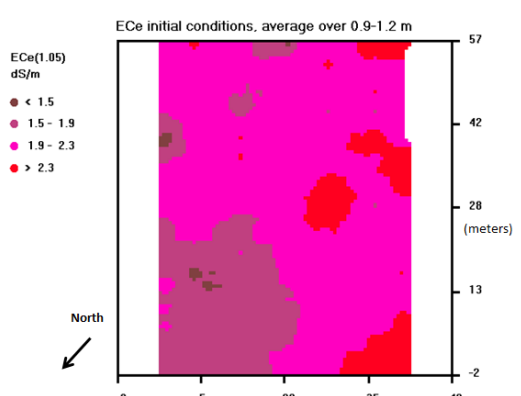


Figure VII.4. Spatial distribution of ECe in 0.9-1.2 m depth under initial conditions.

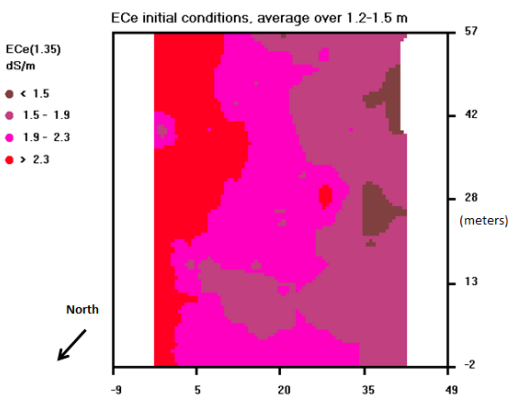


Figure VII.5. Spatial distribution of ECe in 1.2-1.5 m depth under initial conditions.

Table VII.1. Model parameters used to create the maps in Figure VII.1 - Figure VII.5 above, and the model performance represented by  $R^2$ , Root MSE (Root mean square error), Est. %CV (estimated coefficient of variation) and PRESS score.

Depth	$R^2$	Root MSE	Est. %CV	PRESS score	$b_0$	$b_1$	$b_2$	$b_3$
0-0.3	0.886	0.061	6.14	0.536	1.0215	0.1256	0.0948	-0.9869
0.3-0.6	0.898	0.078	7.82	0.328	0.8956	0.1110	-0.0403	-0.9581
0.6-0.9	0.869	0.199	20.09	4.880	0.5681	0.3123	0.0605	-0.2630
0.9-1.2	0.660	0.076	7.60	0.616	0.4822	-0.0664	-0.1407	0.6161
1.2-1.5	0.518	0.181	18.28	2.649	0.8180	-0.0396	-0.1504	-0.4182

After one irrigation event

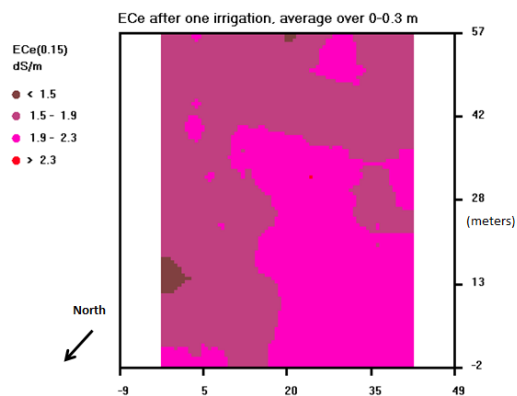


Figure VII.6. Spatial distribution of ECe in the upper most layer (0-0.3 m) after one irrigation event.

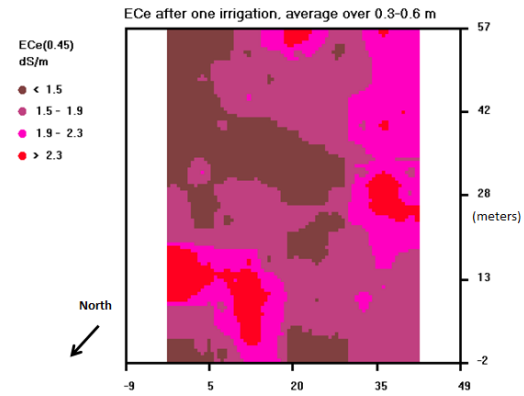


Figure VII.7. Spatial distribution of ECe in 0.3-0.6 m depth after one irrigation event.

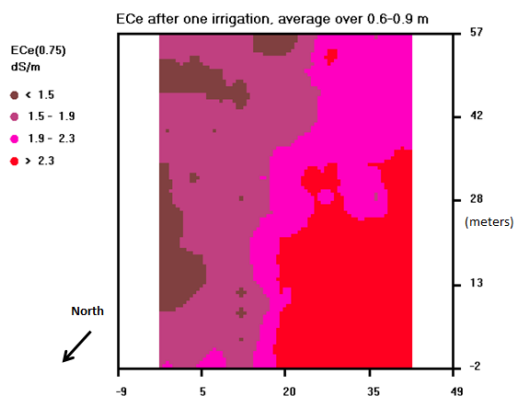


Figure VII.8. Spatial distribution of ECe in 0.6-0.9 m depth after one irrigation event.

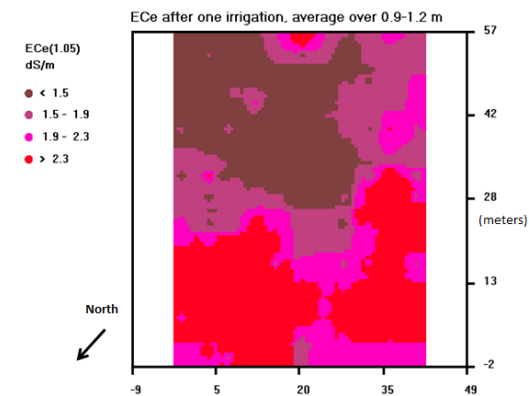


Figure VII.9. Spatial distribution of ECe in 0.9-1.2 m depth after one irrigation event.

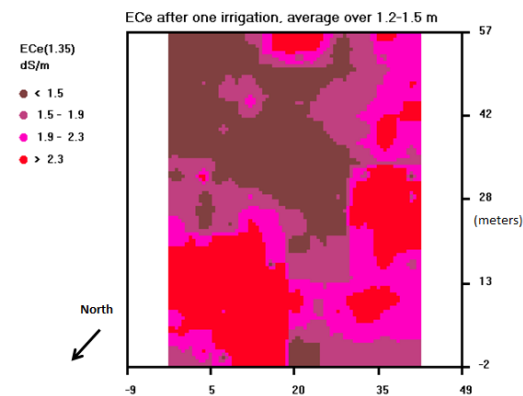


Figure VII.10. Spatial distribution of ECe in 1.2-1.5 m depth after one irrigation event.

Table VII.2. Model parameters used to create the maps in Figure VII.6-Figure VII.10 above, and the model performance represented by R2, Root MSE (Root mean square error), Est. %CV (estimated coefficient of variation) and PRESS score.

Depth	R <sup>2</sup>	Root MSE	Est. %CV	PRESS score	b <sub>0</sub>	b <sub>1</sub>	b <sub>2</sub>	b <sub>3</sub>
0-0.3	0.809	0.051	5.10	0.462	0.5831	0.0251	-0.0950	0.1273
0.3-0.6	0.204	0.356	36.80	25.780	0.4134	0.0158	0.2521	0.3542
0.6-0.9	0.526	0.344	35.42	23.785	0.3984	0.1066	-0.1410	0.7609
0.9-1.2	0.922	0.167	16.80	0.970	0.6293	0.2621	0.3771	-0.0382
1.2-1.5	0.779	0.278	28.32	2.110	0.5595	0.1934	0.5124	0.0880

After two irrigation events

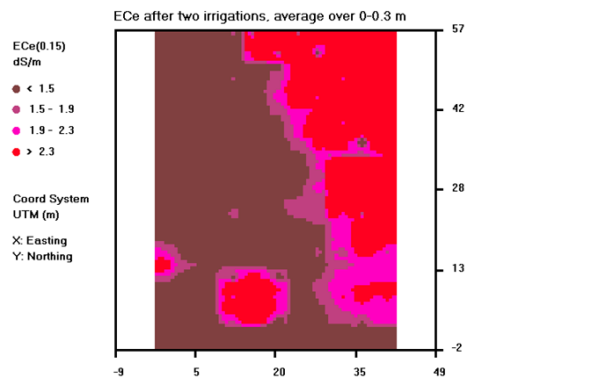


Figure VII.11. Spatial distribution of ECE in the upper most layer (0-0.3 m) after two irrigation events.

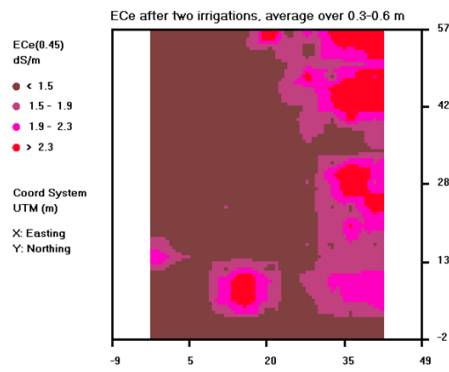


Figure VII.12. Spatial distribution of ECE in 0.3-0.6 m depth after two irrigation events.

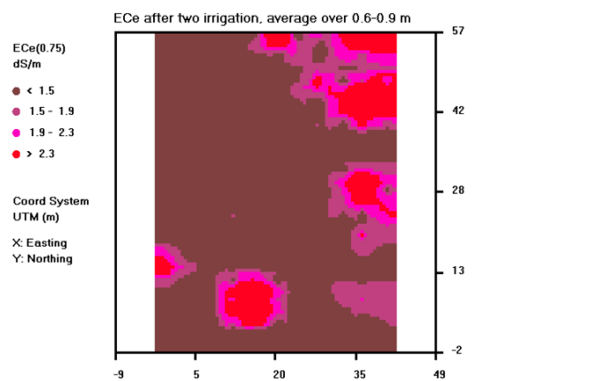


Figure VII.13. Spatial distribution of ECE in 0.6-0.9 m depth after two irrigation events.

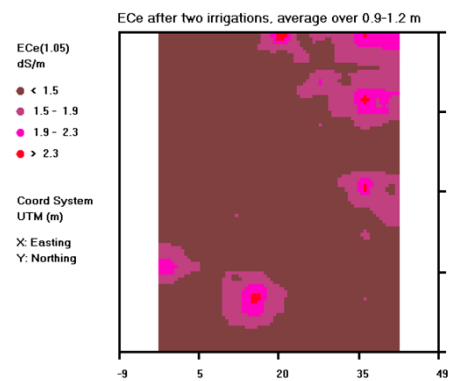


Figure VII.14. Spatial distribution of ECE in 0.9-1.2 m depth after two irrigation events.

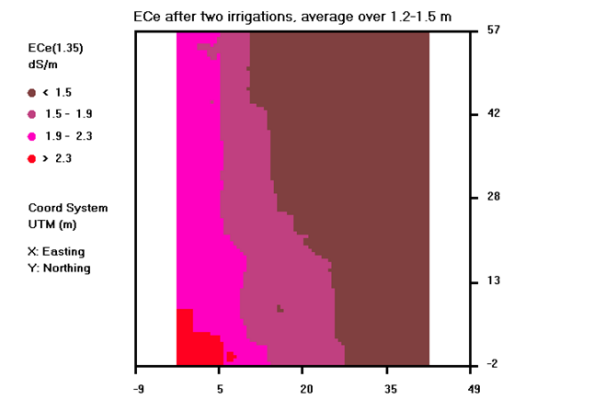


Figure VII.15. Spatial distribution of ECE in 1.2-1.5 m depth after two irrigation events.



Table VII.3. Model parameters used to create the maps in Figure VII.11-Figure VII.15 above, and the model performance represented by R<sup>2</sup>, Root MSE (Root mean square error), Est. %CV (estimated coefficient of variation) and PRESS score.

Depth	R <sup>2</sup>	Root MSE	Est. %CV	PRESS score	b <sub>0</sub>	b <sub>1</sub>	b <sub>2</sub>	b <sub>3</sub>
0-0.3	0.979	0.0524	5.25	0.132	-0.7508	-0.0571	0.6788	2.8971
0.3-0.6	0.962	0.0741	7.42	0.064	-0.4254	0.0943	0.4590	1.6502
0.6-0.9	0.767	0.2958	30.24	1.575	-0.7357	0.1273	0.6886	1.8181
0.9-1.2	0.881	0.0858	8.60	0.242	-0.0834	0.0291	0.3311	0.6999
1.2-1.5	0.901	0.1018	10.20	0.250	0.8088	0.1125	-0.0549	-1.3980

After rainfall

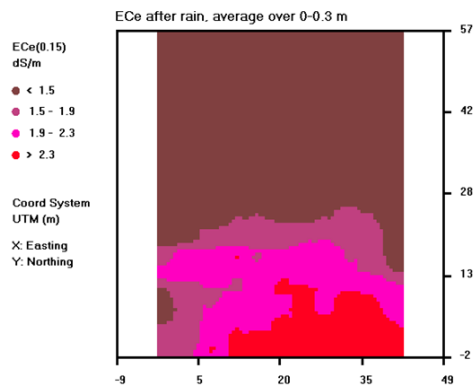


Figure VII.16. Spatial distribution of ECE in the upper most layer (0-0.3 m) after rainfall.

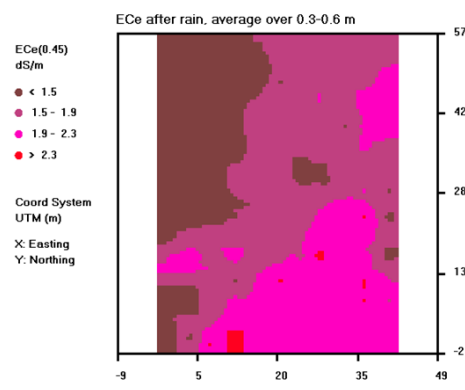


Figure VII.17. Spatial distribution of ECE in 0.3-0.6 m depth after rainfall.

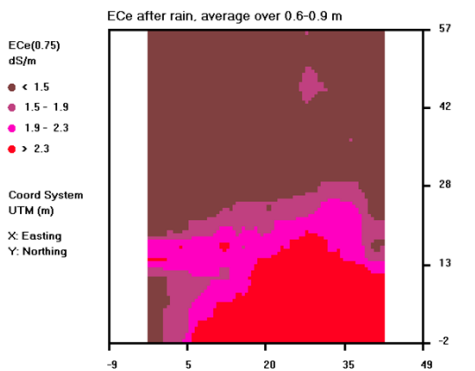


Figure VII.18. Spatial distribution of ECE in 0.6-0.9 m depth after rainfall.

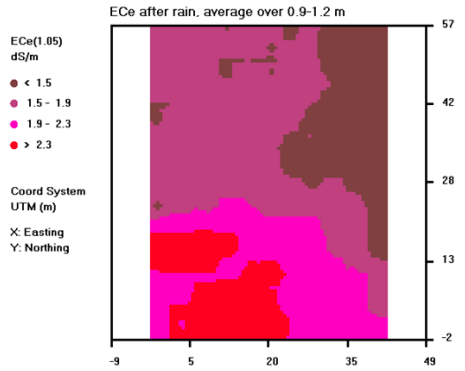


Figure VII.19. Spatial distribution of ECE in 0.9-1.2 m depth after rainfall.

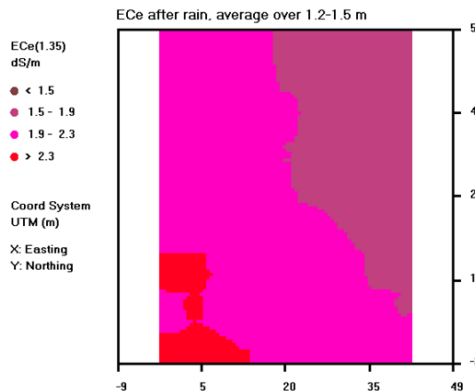


Figure VII.20. Spatial distribution of ECE in 1.2-1.5 m depth after rainfall.

Table VII.4. Model parameters used to create the maps in Figure VII.16-Figure VII.20 above, and the model performance represented by R<sup>2</sup>, Root MSE (Root mean square error), Est. %CV (estimated coefficient of variation) and PRESS score.

<b>Depth</b>	<b>R<sup>2</sup></b>	<b>Root MSE</b>	<b>Est. %CV</b>	<b>PRESS score</b>	<b>b<sub>0</sub></b>	<b>b<sub>1</sub></b>	<b>b<sub>2</sub></b>	<b>b<sub>3</sub></b>
<b>0-0.3</b>	0.897	0.198	19.95	0.578	0.2701	0.3340	0.1149	-0.0026
<b>0.3-0.6</b>	0.631	0.269	27.34	3.301	0.2935	0.1096	0.1689	0.5308
<b>0.6-0.9</b>	0.936	0.166	16.69	0.694	0.1876	0.3212	0.1784	0.4839
<b>0.9-1.2</b>	0.992	0.030	3.03	0.009	0.7263	0.1731	0.1187	-0.5364
<b>1.2-1.5</b>	0.920	0.036	3.59	0.076	0.8183	0.0563	0.0146	-0.3994



### 3.2 Forage, industrial crop (e.g. tobacco) and/or market vegetables

Crop	Size (ha)	Irrigation or rainfall	Production (t/ha)	On same field as other crop? (Yes/No)

### 3.3 Why do you grow these crops?

- Tradition     
  Good production     
  Other: .....

## 4. Fertilizers during agricultural year 2011-2012

### 4.1 Use of fertilizers

Crop	(Ammonium) Ammonitre		Phosphate Which? .....		Potassium Which? .....		Organic Matter	
	Yes	No	Yes	No	Yes	No	Yes	No

### 4.2 Why do you use these fertilizers?

- Tradition   
  Increased production   
  Common use   
  Other .....

### 4.3 How do you regulate the usage of fertilizers?

- Tradition   
  Visual estimation   
  Soil analysis   
  Other .....

### 4.4 Do you use any pesticides? Yes      No

### 4.5 Do you use any insecticides? Yes      No

## 5. Livestock

### 5.1 Do you have any livestock? No

- Yes    **5.1.1** If yes, how many? .....

**5.1.2** What kind?.....

**5.2 Livestock economy**

	Manure
Quantity produced	
Quantity for own consumption	
Profit? (Yes/No)	

**6. Irrigation**

**6.1** What is your main source of irrigation water?

- Wastewater     Well, salinity (g/l):.....     Others:.....salinity (g/l):.....

**6.1.1** Why?.....

**6.2** Do you use other additional water sources?

- Wastewater     Well, salinity (g/l):.....     Others:.....salinity (g/l):.....

**6.2.1** Why? .....

**6.3** What does the irrigation water cost (DT/hour)? .....

**6.4** Your irrigation

Crop	Irrigation system	Average duration of irrigation (hours)	Average irrigation frequency (days)

**6.5** If you use a traditional submersion as an irrigation system, why do you not change it to save water?.....

**6.6** What is the average channel length?.....

**6.7** Do you know the crop water irrigation need:  Yes     No

**6.8** How do you decide the irrigation schedule (dose and frequency) :

- Tradition     Measurements     Visual estimation     Other:.....

**6.9** Are there any constraints on the water (TWW) availability?  Yes     No

**6.9.1** If Yes, why and when?.....

**6.10** Do you use any personal protection when using TWW?

Yes      **6.10.1** If yes, what kind? .....

No      **6.10.2** If no, why not?.....

**6.11** Have you taken any vaccination for your agricultural work?  Yes       No

## 7. Salinity management

**7.1** Do you use soil chemical analysis? Yes      No

**7.2** What is your opinion about the irrigation water quality (salinity)?

.....  
.....  
.....

**7.3** According to you, what are the consequences of the water quality on your crop growth and soil?.....

.....  
.....

**7.4** Do you do anything to manage the soil salinity?

Yes    No    **7.4.1** If yes, what? .....

## 8. Economy

**8.1** Do you make any profit from this farm?

Yes, a substantial profit    Yes    Yes, barely    No

**8.2** What is the main constraints of your exploitation? (Classify from 1)

Land surface      Irrig.Water scarcity      Irrig.Water quality

Type of crop grow with TWW      Marketing       Labors      Economy

Others problems :.....

## 9. GDA

**9.1** How do you perceive the cooperation with GDA? .....

.....  
.....  
.....  
.....