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Site-specific irrigation:

Improvement of application map and a dynamic steering of modified centre pivot irrigation system

DISSERTATION
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by

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Preface

Even in the 21st century, water is still used for irrigation in order to produce food and feedstuff. Given a share of ca. 70 %, agriculture is the largest water consumer worldwide and will have to remain it in order to guarantee at least the supply of food. Therefore, it is always necessary to draw attention to careful and efficient water use in agriculture and to show potential improvements like in this study.

Based on prior studies on irrigation techniques at the Institute of Production Engineering and Building Research, the present dissertation discusses the very current topic of site-specific irrigation. The results gained in this study provide scientifically secured decision criteria, which allow the homogeneity of the soil as well as its different moisture to be taken into account and enable an application map for differentiated irrigation depths to be developed based on these criteria. At the same time, a technical solution is presented which allows precise, site-specific irrigation with a centre-pivot machine to be realized. The water and energy savings provided by this technique (while the level of production remains the same or is increased) are evaluated, and the costs are compared.

The author, who had a scholarship as a doctoral student at the Institute of Production Engineering and Building Research of the Federal Agricultural Research Centre for Agriculture in Braunschweig (FAL), made a contribution towards a more objective discussion about the use of site-specific irrigation and described future-oriented solution approaches.

Braunschweig, March 2008

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List of Abbreviations

AMBAV	Agrarmeteorologisches Modell zur Berechnung der Aktuellen Verdunstung
CEC	Cation Exchange Capacity
CP	Centre pivot irrigation system
CU	Christiansen Uniformity Coefficient [%]
CV	Coefficient of Variation [%]
CWB	Climatic Water Balance
DGPS	Differential Global Positioning System
DIC	Distributed Irrigation Control
dr	narrow spacing covered by drop tube
DWD	Deutscher Wetterdienst or German Weather Service
EC	Soil Electrical Conductivity [mS/m]
ECa	depth-weighted apparent soil electrical conductivity
EIB	European Installation Bus or Europäische Installationsbus
EM	ElectroMagnetic
EMI	ElectroMagnetic Induction
ET	EvapoTranspiration
ETc	EvapoTranspiration by crop
EU	Emission Uniformity [%]
F.C.	Field Capacity
F.P.I	Fuzziness Performance Index
FAL	Federal Agriculture Research Centre
FDR	Frequency Domain Reflectometry
GIS	Geographic Information System
GPS	Global Positioning System
ha	hectare
I_{max}	maximum Irrigation depth
IMZ	Irrigation Management Zone
IMZs	Irrigation Management Zones
I_n	net Irrigation depth
IRTs	InfraRed Thermometers (IRTs)
ISM	Instrumentation, Scientific and Medical
K_e	emitter discharge coefficient
kHz	Kilo Hertz
kPa	Kilo Pascal
kWh	kilo Watt Hour
l/h	litre/hour
l/min	litre/minute
LT	Length of drop Tube
m/h	meter/hour
m/s	meter/second
mA	milli Ampere
MAD	Management Allowed Depletion [%]
MARE	Mean Absolute Relative Error
MDI	Mobile Drip Irrigation
MPE	Modified Partition Entropy

Mph	meter per hour
mS/m	milliSiemens per meter
MuCEP	Multi-depth Continues Electrical Profiling
MZ	Management Zone
Ne	Number of emitters installed on the drop tubes
nFK	nutzbare Feldkapasität
P.W.P.	Permanent Wilting Point
PA	Precision Agriculture
PC	Personal Computer
PE	Prediction Efficiency [%]
PI	Precision Irrigation
PLC	Programmable Logic Control
PMDI	Precision Mobile Drip Irrigation
q_e	emitter discharge
q_{var}	emitter flow variation
r	distance between drop tube and pivot point
R	radios of irrigated area by centre pivot
R^2	coefficient of determination
SDI	Stationary Drip Irrigation
SMS	Short Message Service
SSM	Site-Specific Management
SV	Solenoid Valve
SWC	Soil Water Content
T	irrigation Time
TAWC	Total Available Water Content [mm]
Tc	canopy Temperature
TDR	Time Domain Reflectometry
VRI	Variable Rate Irrigation
VRT	Variable Rate Technology
WLAN	Wireless Local Area Network

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1 INTRODUCTION

World population is expected to grow from 5.8 billion people in 1997 to 7.5 billion people in 2020 (Brown, 1995). An ever increasing population, resource shortages and degradation of the ecological environment have added ever greater pressure on countries. Based on some estimates (UN 1997), annual irrigation water use will have to increase about 30 percent above the present level for annual crop production to double and to meet global food requirements by 2025. The present-day challenges with regard to food, water and energy security are immense. Historically, a desire to improve production efficiency and farm income has stimulated interest in innovative technologies. Advances in technology, as well as other factors such as farm policy have contributed to increases in the size of individual farmsteads and fields within a farmstead. With this larger scale of operation, the potential for the individual to effectively manage variability by means of observation and experience has declined precipitously. In addition, as individual farm fields grew in size, within-field variability generally increased as well. In the past centuries, the very small size of fields and their delineation by natural boundaries, such as water courses and varying soil types, may have enabled farmers to vary treatments manually. However, with the enlargement of fields, intensive production and mechanization in the latter half of the last century, it was not possible to take account of within-field spatial variability without a significant development in technology. However, in some developing countries (such as Iran) and in countries that need to stabilize yields, because of inadequate and/or uneven rainfall distribution such as Germany, special efforts in agriculture will be needed to optimise inputs and to save resources.

1.1 Background

A management concept for the sustainable utilization and efficient use of agricultural inputs is known as “Precision Farming” or “Precision Agriculture” (PA). PA is only a few years old and started to receive great interest as a new experimental tool since 1990. Under PA, agronomic practices are varied within a field to match locally and temporally varying conditions. PA (or more appropriately site-specific crop management) has been proposed as a means of managing the spatial variability of edaphic (like soil fertility, soil texture and total available water content), anthropogenic, topographical, biological and meteorological factors that influence crop yield with the aim of increasing profitability, increasing crop productivity, sustaining the soil-plant environment, optimizing inputs and/or minimizing detrimental environmental impacts. In other words, PA will allow several geographic units which are currently being managed as a single entity (a field) to be addressed as individual decision-making units. PA is the idea of doing the right thing at the right place at the right time. This idea is as old as agriculture, but during the mechanization of agriculture in the 20th century there was strong economic pressure to treat large fields using uniform agronomic practices. PA is a management strategy that has three components: capture of data at an appropriate scale, interpretation and analysis of that data and implementation of a management response at an appropriate scale and time. Each particular manageable factor has its own scale of variability.

The development of fast and less costly methods is, therefore, of great interest and one of the most promising new methods and techniques. It is dependent on the measurement of a representative property, which depends on and correlates with other soil properties, such as the sensor-based measurement of depth-weighted apparent soil electrical conductivity (ECa). Soil ECa can be used to indirectly estimate soil properties if the contributions of the other soil properties affecting the ECa measurement are known or can be estimated. Examples of this direct calibration approach include the estimation of the total available water content of the soil (Waine et al., 2000; Al-Karadsheh et al., 2002).

The PA concept, when applied to irrigation water management based on within-field variation of water requirement, requires looking at those conditions which could vary locally and which could influence the water management strategy known as "precision irrigation" (PI). A PI system would have the ability to apply the right amount of water directly where it is needed, therefore saving water by preventing excessive water runoff and leaching. Current commercially available centre pivot (CP), linear-move and another sprinkler irrigation systems are normally capable and managed to apply relatively uniform, controlled amounts of water and injected chemicals along the system lateral for efficient crop production. Thus, over- and/or deficit-irrigation in some portions of the field will be unavoidable due to soil variability. However, water or chemical application depth is determined and controlled by the modified sprinkler irrigation systems, pressure, nozzle size, spacing and system travel speed. Modernized irrigation systems with advanced technology have been developed in industrialized countries in the past 50 years (Sourell and Sommer, 2002; Maohua 2001; Faci et al., 2001). In the 20th century, great progress in water diversion technology in dry areas has been made. The development of irrigation technology in the last half of the twentieth century was due to the development of lightweight aluminium pipes, the development of sprinkler technology and the development of trickle irrigation in the 1970s. Self-propelled commercial travelling irrigation systems, such as CP and moving laterals, are particularly suitable for site-specific approaches because of their current level of automation and large area coverage with the aid of a single pipe lateral. Such irrigators equipped with control systems allow variable application depths to be realized in the direction of travel by adjusting system speeds. In most of the travelling irrigation systems in-use, such as booms, big guns, and CPs, irrigation depth can vary only in the direction of travel, but it remains uniform along the pipeline. Solenoid valves are available on the irrigation market, but they need a computer control system and software to control their operation (Al-Karadsheh et al., 2002; Fridgen et al., 2000a, b, c; King et al., 1999). Similarly, some fields contain areas that are not cropped and could benefit from the ability to apply varying amounts of irrigation water. In addition, PI systems provide an outstanding platform for the installation of sensors for the real time monitoring of plant and soil conditions which would interact with a control system for optimal environmental benefits.

Irrigation simulation models can simulate the real world and improve irrigation performance, by integrating knowledge about soil, climate, crops and management for better management irrigation decisions (Clemmens, et al., 1999; Dechmi, 2003; Boken et al., 2004). In addition, sound and sustainable agriculture without electronics is inconceivable today, as electronic systems are used to reduce farm inputs, protect the environment, secure farm income and produce high-quality products. For example, a Binary Unit System (BUS) is mandatory for the efficient use of electronics in agriculture in order to guarantee unimpeded data and information transfer between agricultural systems from different manufacturers, such as soil moisture sensors, tractors, implements and farm computers (Speckmann et al., 1999; Auernhammer and Frisch, 1993; Jahns and Speckmann, 1984).

Therefore, the next generation of irrigation machines and irrigation scheduling systems should be re-defined so that they are able to determine when/how much/ where to irrigate not just when/how much (Evans et al., 1996). Considerable research and development is needed to realize the potential benefits of site-specific irrigation and to ensure a net economic return to the producer. Cost-effective and reliable equipment and control systems need to be developed and tested. Techniques for efficient and effective real-time system management need to be developed, field tested and validated. Methodologies for predicting the potential environmental and economic benefit for a particular site are needed to facilitate the adoption and implementation of the technology where appropriate. Rapid and low-cost methods for the delineation of irrigation management zones are needed.

1.2 Problems and objectives

Spatial variation of irrigation on fields is necessary because of changing soil properties including fertility, texture, water holding capacity, infiltration rate, topography and the cultivation of different plants on the same field. Moreover, different soil conditions lead to the development of different root systems as well as changing water tension and evaporation. Therefore, the need for irrigation may differ between zones of a particular field. In addition, irrigation systems have some disadvantages, such as over-irrigation and deficit irrigation due to uniform water application (non site-specific water application), droplet evaporation and drift losses (in particular in centre pivot systems), canopy evaporation and runoff. Precision irrigation applies the right amount of water at the right place at the right time using the right instrument. Therefore it is expected to have the ability to optimize water and energy consumption by preventing excessive water runoff and leaching. Precision irrigation is just beginning to be explored and still at the developmental stages. More experimental work is needed to determine its feasibility and applicability. Interest in site-specific irrigation management has emerged over the past decade in response to successful commercialization of other site-specific application technologies in irrigated agriculture.

1.2.1 Problems of investigation

Several requirements must be established to realize precision irrigation. First, water requirement variations or irrigation management zones have to be delineated. The area of irrigation with the same irrigation depths is derived based on the spatial features of the soil. This determines the range of research on control elements. The simultaneous consideration of plant conditions and varying soil properties require a very complex precision irrigation management. Thus, only the variation of soil property and in particular the variation of the total available water content were considered and the plant conditions over the whole study field were assumed to be the same. Second, the system must be capable of applying a range of application depths to the small discrete areas. The irrigation application map shows the variation of irrigation water requirement and their within-field location. In-field soil variation of the total available water content (small scale) is determined using fast, non-destructive real-time sensor-based electrical conductivity measurements. Because of changing soil physical and climatic conditions, every irrigation management zone needs different irrigation depths during every irrigation pass.

1.2.2 Objectives

In this study, a commercial centre pivot irrigation machine is modified to perform precision mobile drip irrigation (PMDI). Variable water rates are applied by a programmable logic control and solenoid valve (pulse concept). Meanwhile, sprinklers are replaced by drop tubes. One quarter of a field irrigated by a centre pivot is equipped with soil moisture sensors, while irrigation in another quarter is controlled with the aid of a climatic water balance–model in order to calculate irrigation water requirements. Therefore, the main objectives of this study are the improvement of an irrigation application map and the dynamic control of a modified centre pivot irrigation machine. To reach these goals, the following research is carried out:

1. Description, development, and evaluation of the soil moisture sensor and the climatic water balance -model
2. Monitoring the within-field variation of the total available water content and delineation of irrigation management zones using two fast, non-destructive and sensor-based soil electrical conductivity measurement methods:
   a) a contact and electrode-based sensor (VERIS 3100, both superficial and deep readings) and
   b) a non-contact, EMI-based sensor (Geonics EM38, both horizontal and vertical orientations) and determination of the best sensor-based method using statistical analysis
3. Development and evaluation of the programmable logic control system for the application of variable-rate irrigation using precision mobile drip irrigation
4. Testing of the programmable logic control system at variable-rate irrigation in a centre pivot irrigation machine at the FAL
5. Development and evaluation of the performance of wireless sensor communication
6. Evaluation of the application uniformity achieved at various pulsation rates
7. Evaluation of the optimization of water and energy consumption as well as an economic analysis of precision mobile drip irrigation

The structure of the research strategy for precision irrigation is summarized in Figure 1.1. According to this strategy, it is suggested that sensor-based soil electrical conductivity measurements could be used as an auxiliary estimate to determine spatial variability in total available water content. Even though a variable rate centre pivot irrigation system exists on the market, no commercially available, variable-rate centre pivot irrigation system has been developed. Furthermore, real-time sensing and on-the-go scheduling methods have yet to be integrated into this type of application. This type of technology can be highly profitable for the producer.

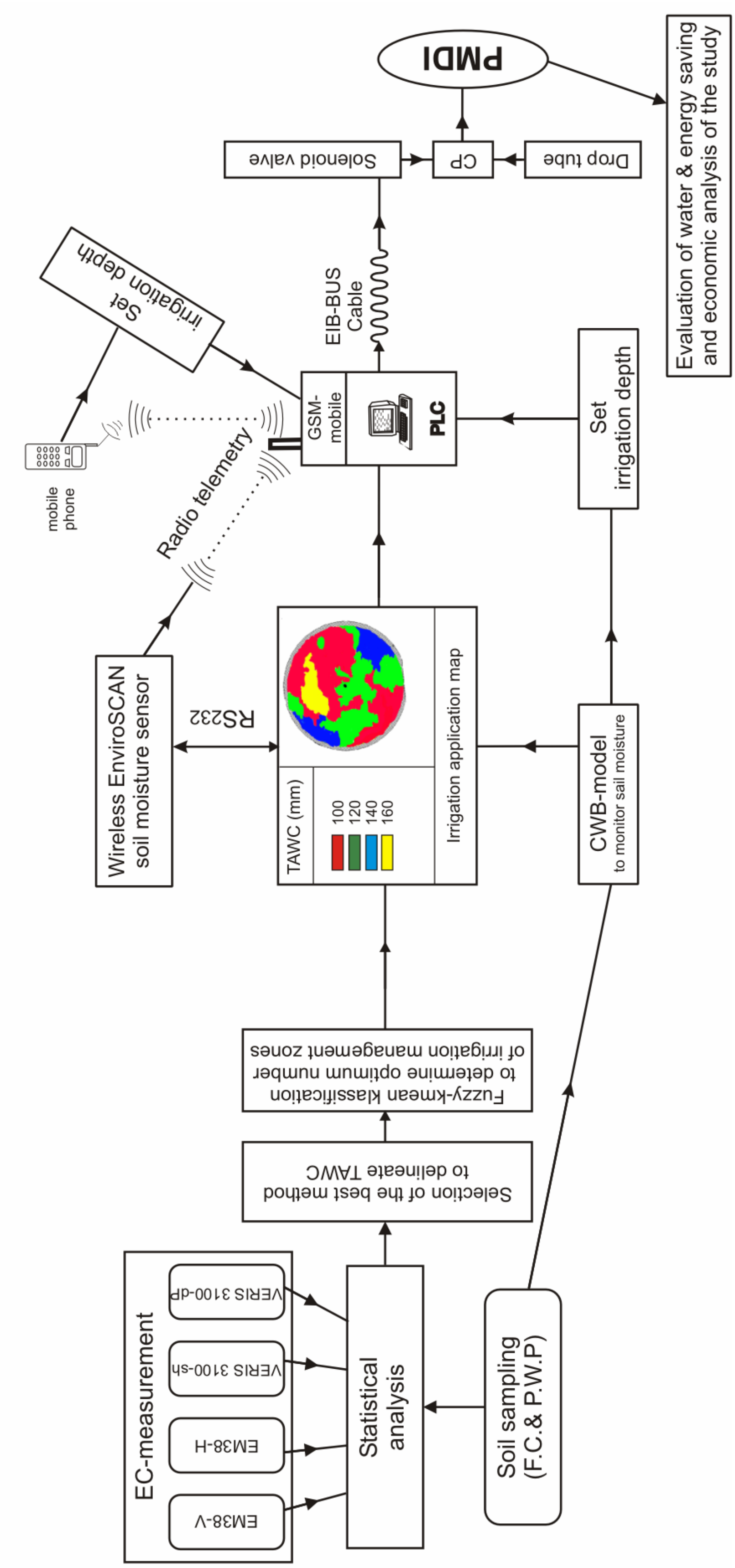


Figure 1.1: Structure behind establishing a strategy for precision irrigation

2 LITERATURE REVIEW

In this chapter, the literature is reviewed separately in two different sections: precision agriculture and precision irrigation.

2.1 Precision agriculture

The management of agricultural production is undergoing a change, both in terms of philosophy and technology. In conventional agriculture, decision-making is based on average conditions within those fields and uniform fields. Soil fertility was determined by combining soil cores into a single sample that was intended to best describe conditions across a field. Field scouting for crop conditions was done at a few locations within the field. However, soil is spatially heterogeneous, with most chemical and physical soil properties varying significantly within just a meter. Spatial soil heterogeneity is one of several factors that cause within-field variation in crop yield. Other spatially and/or temporally variable factors influencing within-field variation in crop yield include man-related factors, (e.g., irrigation management, compaction due to equipment, etc.), biological (e.g., disease, pests, etc.), meteorological (e.g., humidity, rainfall, wind, etc.), and topographical (e.g., slope, aspect, etc.) influences. The inability of conventional farming to address within-field variations in these factors not only has a detrimental economic impact due to reduced yield in certain areas of a field (Godwin et al., 2003), but also detrimentally impacts the environment due to over-application of agrochemicals and wastes finite resources. Precision Agriculture (PA) is regarded as a revolutionary approach for improved resource management for sustainable agricultural development and is a promising technology for site-specific management or management according to local conditions in the 21st century (Werner and Jarfe, 2002; Domsch, 2001a, b; Sparovek and Schnug, 2001; Heermann et al., 2000; Mulla and Schepers, 1997; Schueller, 1992). PA research started in the US, Canada, Australia, Germany with Pre-Agro (Werner and Jarfe., 2002) and in western Europe in the mid- to late 1980s.

2.1.1 Definition

PA is only a few years old and started to receive great interest as a new experimental tool since the 1990's. Given this inherent variability, management decisions should be specific to time and place rather than rigidly scheduled and uniform. PA has various names to describe the concept: precision farming; spatially prescriptive farming; farming by computer; farming by satellite; high-tech sustainable agriculture; soil-specific crop management and site-specific farming. A lot of research and commercial development has taken place in PA in recent years. PA simply means breaking up a field, grove or other area into small units, then managing each unit on an individual basis and applying agricultural inputs (fertilizer, herbicide, water, ...) depending on the requirements in every management zone (MZ). Lowenberg-DeBoer and Swinton (1997) define site-specific management (SSM) as the "electronic monitoring and control applied to data collection, information processing and decision support for the temporal and spatial allocation of inputs for crop production. Whole-field management is increasingly viewed as inefficient because it results in the over-application of inputs in low-producing areas and sub- optimal application in areas with high-production potential. SSM the spatially directed management of soils, crops and pests based on varying conditions within a field (Larson and Robert, 1991) provides an alternative to the use of the field as a primary management unit. The impact of PA technologies on agricultural production is expected in two areas: profitability for the producers and ecological and environmental benefits for the public. Increasing water, fertilizer and pesticide costs, coupled with environmental concerns caused by their use, lead to growing acceptance of the SSM concept as a means of improving economic (Griffith, 1995; Reetz and Fixen, 1995) and ecological outcomes in agriculture (Wallace, 1994; Castelnuovo, 1995; Larson et al., 1997). If soil conditions on the field vary significantly, and the fields are composed of high-yield areas and distinct weed patches, the basic requirements for variable rate application are present. However, they have proven difficult to measure (Lowenberg-DeBoer, 1996) and may prove to be beneficial for improving profit potential and for reducing the risks (Oriade and Popp, 2000). PA allows for precise and targeted application, the recording of all field treatments at the meter scale, tracking from operation to operation and transfer of recorded information including the harvested products (Stafford, 2000).

Variabilities exerting significant influences on agricultural production can be categorized into six groups defined as follows. (Zhang et. al., 2002):

1. Yield variability: Historical and present yield distributions.

2. Field variability: Field topography-elevation, texture, slope, aspect and terrace.

3. Soil variability: Soil fertility, soil physical properties (texture, density, mechanical strength, moisture content and electric conductivity), chemical properties of the soil (pH, organic matter, salinity and cation exchange capacity (CEC)), the water holding capacity of the soil, hydraulic conductivity and soil depth.

4. Crop variability: Crop density, crop height, crop nutrient stress, crop water stress, leaf-area index (LAI), biomass, crop leaf chlorophyll content and crop grain quality.

5. Variability in anomalous factors: Weed infestation, insect infestation, nematode infestation, disease infestation, wind damage and hay damage.

6. Management variability: Among variability types (fertilizer application, irrigation pattern, …), yield variability is often considered the ultimate dependent variable, whereas most other variability types are treated as independent variables. Many types of variability are both spatial and temporal in nature. Water requirement serves as an example. Spatial water requirement patterns may change during the crop-growing season.

2.1.2 Managing variability

Site-specific applications of agricultural inputs can be implemented by dividing a field into smaller MZs that are more homogeneous in properties of interest than the field as a whole. An MZ is defined as 'a portion of a field that expresses a homogeneous combination of yield-limiting factors for which a single rate of a specific crop input is appropriate' (Doerge, 1998). Thus, MZs within a field may be different for different inputs and the delineation of MZs for a specific input involves only the factors directly influencing the effectiveness of that input in achieving certain goals. An MZ also can be delineated by more than one specific crop input and different delineations. In this case, a single rate is applied for each of the specific inputs within a zone. The number of distinct MZs within a field is a function of the natural variability within the field, the size of the field and certain management factors. MZs must be analyzed, evaluated and adjusted over time. They are not static and will change as the management style and capabilities of the farmer change. It may be prudent to combine zones that consistently perform similarly over time and to split zones that show more variability than first thought. As equipment with different capabilities is used, the zones may have to change and be adjusted. Depending on the pressure on the farm manager, the zones may be altered to best suit his or her needs. The minimum size of a zone is limited by the ability of the farmer to differentially manage regions within a field. If a GPS is involved to control the application or to guide the implement, there seems no reason for restrictions due to the shape of the zone. The removal of excessive details in within-field variability simplifies the shapes of the zones. Thus, it reduces the equipment requirements for Variable Rate Technology (VRT) (Chang et al., 2000; Zhang and Taylor, 2000).

2.1.3 Engineering innovations

While agronomists are playing the leading role in PA development, engineers have worked diligently to provide technologies needed to implement PA practices. Engineering innovations for PA involve the development of controls for remote-sensing technologies and sensors.

Controls: Engineering innovations of controls are VRT agro-chemical applicators (Bennett and Brown, 1999; Swisher et al., 1999), Automatic guidance systems (Goddard, 1997), Robotic harvesting systems (Iida et al., 1998; Umeda et al., 1999).

Remote sensing: Remote sensing techniques have seen limited use in PA due to the need for high spatial resolution images. According to recent literature, remotely sensed images have been used to predict nitrogen needs in corn (Scharf and Lory, 2000), to estimate clay concentration of surface soil (Chen et al., 2000), to detect weeds (Biller, 1998; Varner et al., 2000), or to quantify hail or wind damage in crops (Erickson et al., 2000). Satellite remote sensing has held much promise for within-field monitoring, but has yet to demonstrate hard evidence for complete success. Problems include timeliness, cloud cover, cost, poor spatial resolution and insufficient processing for the production of image data which are useful for crop managers (Deguise and McNairn, 2000).

Sensors: Yield sensors have been studied by Solie et al. (2000), Schueller et al. (1999), Pelletier and Upadhyaya (1999). Over the last decade new information technology, such as the Geographical Positioning System (GPS) and the Geographical Information System (GIS), have been introduced. These systems have allowed the scale of management to be reduced from the farm level to the field level and occasionally to the subfield level (Blackmore and Griepentrog, 2002). With a single GPS receiver, error is typically within 10 to 15 metres in absolute terms. A beacon receiver reduces this range to 1 to 5 metres. Differential Global Positioning System (DGPS) receivers, which provide a method of increasing the accuracy of positions derived from GPS receivers, enable position accuracy to be improved to less than 1 metre. Dux et al. (1999) used a geo-referenced audio recorder with a speech-recognition capability to generate field maps during field scouting (field sensors). An infrared thermometer was used to measure canopy temperature to control irrigation events (Evans et al., 2000; Michels et al., 2000). An on-line, real-time spectrophotometer developed by Anom et al. (2000) was used to map plant water, nutrient, disease and salinity stresses. A multispectral radiometer was employed to detect crop salinity stress. A near-ground scanning radiometer mounted on a tractor mapped vegetative-indices (Stafford and Bolam, 1998). Sudduth et al. (2000) designed an electromechanical sensor to count corn plants. Cotton plant height was measured by Searcy and Beck (2000) using mechanical fingers and infrared light beams (crop sensors).

Rapid methods for scanning large volumes of information, i.e., soil EC, are used extensively in precision agriculture decision making. Sensor-based measurement of depth-weighted apparent profile soil electrical conductivity (ECa) and resistivity (inverse EC) could provide an indirect indicator of important physical and chemical soil properties. Factors that influence ECa include soil salinity, clay content and clay mineralogy, soil pore size and distribution, soil moisture content and temperature (James et al., 2000; Hendrickx et al., 1992; McNeill, 1992). In saline soils, most of the variation in ECa can be related to salt concentration (Williams and Baker, 1982) but in non-saline soils, conductivity variations are primarily a function of soil texture, moisture content and CEC (Kachanoski et al., 1988). Soil ECa can be used to indirectly estimate soil properties if the contributions of the other soil properties affecting the ECa measurement are known or can be estimated. In some cases, within-field variation in

ECa is due to one predominant soil property, and ECa can be calibrated directly based on that dominant factor. In some situations, the contribution of within-field changes in one factor will be large enough with respect to variation in the other factors that ECa can be calibrated as a direct measurement of that dominant factor. Examples of this direct calibration approach include estimating soil salinity in California (Lesch et al., 1995), topsoil depth above a subsoil claypan horizon in Missouri (Doolittle et al., 1994; Kitchen et al., 1999; Sudduth et al., 2001), soil water content (Sheets and Hendrickx, 1995), clay content (Williams and Hoey, 1987), CEC and exchangeable Ca and Mg (McBride et al., 1990) grain yield (Kitchen et al., 1999) and total available water content based on ECa measured in field capacity (Waine et al. 2000; Al-Karadsheh et al., 2002). ECa can be measured remotely using electrodes and electromagnetic (EM) techniques. There are two types of soil EC sensors currently on the market for fast and non-destructive ECa measurement. They can be divided into two types based on the method of EC measurement: contact or electrode-based soil EC measurement and non-contact or EMI-based soil EC measurement.

Electrode-based EC measurement: A resistivity meter involves applying voltage to the ground through metal electrodes and measuring the resistance (inverse of conductivity) to the flow of the electric current. This type of sensor uses electrodes, usually in the shape of coulters, that make contact with the soil to measure the electrical conductivity. In this approach, two to three pairs of coulters are mounted on a toolbar, one pair applies electrical current into the soil while the other two pair measure the voltage drop between them, resulting in simultaneous EC measurements. By enlarging the electrode spacing, deeper layers are imaged. The contact method is more popular for precision agriculture applications, because this method makes it easier to cover more area and it is less susceptible to outside interference. Several commercial systems are available including the VERIS EC Mapping System from the United States (Veris Technologies, Salina, Kansas – www.veristech.com) and the Multi-depth Continues Electrical Profiling (MuCEP or ARP) (Dabas et al., 2000). Both systems use rotating metal discs as electrodes. The discs either cut several centimetres into the soil (VERIS) or have small probes that push into the soil (ARP). There are two commercially available types of VERIS units: VERIS 3100 and VERIS 2000XA. VERIS 3100 provides EC readings from two different depths, 0.30 m (1 foot) (VERIS 3100_sh) and 0.91 m (3 feet) (VERIS 3100_dp). VERIS 2000XA provides ECa measurements at only one depth (0.63 or 0.91 m). However, depth is adjustable and normally set at 3 feet. VERIS 2000XA is smaller in size and easier to maneuver on smaller farms. The

VERIS unit can be pulled behind a truck through the field at speeds of up to 10 mph and covers swaths 6 to 18 m wide, depending on the needed resolution or the amount of soil variability in the field. According to the results of this study, however, neither VERIS 2000 nor MuCEP are available in Germany.

Electromagnetic induction (EMI)-based EC measurement: Electromagnetic induction does not involve any direct contact with the soil surface. EM38 (manufactured by Geonics Limited of Mississauga, Ontario, Canada-www.geonics.com), GEM-300 (www.geoafrica.co.za/ reddog/SSI/GEM300.htm) and CM-138 are three popular models of non-contact sensors that are available on the market. The CM-138 Conductivity Meter is designed for fast shallow geophysical surveys (maximum effective depth 1.5 m). It has an operating frequency of 14.406 kHz and can measure apparent conductivity between 0.1-1000 mS/m. Also, GEM-300 is a digital and multi-frequency sensor that can operate in a frequency range of 300 Hz at an investigation depth of about 6 to 10 m and in a range of up to 24 KHz at an investigation depth of about 1 m. EM38 works only at a fixed frequency and has an effective measurement depth of 0.75 m in the horizontal dipole mode (EM38_h) or 1.5 m in the vertical dipole mode (EM38_v). The EM-based ECa sensor most often used in agriculture is the EM38. Details of the EM-sensing approach are given by McNeill (1980a, b and 1992).

Each of the commercial ECa sensors has operational advantages and disadvantages. EM38 and GEM-300 have one effective measurement depth with fixed frequency, but VERIS 3100 has two effective measurement depths, and MuCEP has three effective measurement depths with fixed frequency. The EM38 and GEM-300 require the user to complete a daily calibration procedure before use. Changes in ambient conditions such as air temperature, humidity and atmospheric electricity (spherics) can affect the stability of EM38 measurements. Sudduth et al. (2001) reported that EM38 output could drift by as much as 3 mS/m and this drift was not consistently related to ambient conditions. They suggested that drift compensation be accomplished using of a calibration transect or through frequent recalibration of the EM38. This lightweight system requires little power and makes it possible to collect data under wet or soft soil conditions. In addition, it is possible to collect data after a crop has been planted in 76-cm rows up until the time when the crop is 15 to 20 cm tall. In contrast, the VERIS 3100 system includes all necessary components and requires no user calibration. Thus, VERIS 3100 requires less user setup and configuration before use and has the advantages of a single-vendor system when it comes to troubleshooting. The disadvantage of the VERIS 3100 system is that it is usually bulky and can not be used under some small farm and plot conditions. VERIS 3100 is much heavier and requires a tractor or truck to pull it through the field, limiting its use to firmer soil conditions and unplanted fields. The newer VERIS 2000XA only has four coulters and one measurement terrain vehicle and can collect data between planted 76 cm crop rows. VERIS 2000XA is not available in Germany. For soil mapping, comparison of EM38 and VERIS 3100 was carried out by Dabas et al. (2003). During this field experiment, they found errors in positioning, instrumental errors and errors in data processing. The errors in positioning could originate from the accuracy of GPS (change in the number of satellites, ambiguities, differential signal, interference, multipath) and GPS offset. The errors in instrumentation could result from poor calibration of EM38, high contact resistance of VERIS 3100, disturbances coming from the near environment (temperature effect both in the air with electronic drift and in the soil, vibrations, presence of scattered metal objects) or influences which are even more complex to detect like random errors due to unknown reasons (spikes with EM38 for ex.). Finally, they found some problems during data processing, which are related to sampling rate and/or resolution, processing delay or latency in some instruments, which means that their output is buffered. This could originate from an integration of the data or poor synchronization of data with the GPS position.

2.2 Precision irrigation

By the year 2025, as much as "two-thirds of the world’s population could be under stress conditions and the number of countries facing water stress will increase from 29 today to 34" (World Meteorological Organization, 1997). Irrigation is a major player in the demand for water and already accounts for between 70-80 % of the total world consumption (Melvyn et al., 1997). Rainfed agriculture, covering 83 percent of the world’s farmland, accounts for about 60 percent of global food production and irrigated agriculture covers some 17 percent of cultivated land (about 270 million ha) and contributes nearly 40 percent of world food production. Although irrigation will remain the predominant water consumer in developing countries, an increase of 30 percent in irrigation withdrawals to double and meet global food requirements by 2025 may not be possible if other essential human needs are to be met (Gleick, 1998). The decrease in the availability of water for agricultural purposes, coupled with the requirement for higher agricultural productivity in irrigated areas due to population growth and the necessity to feed this growing population without enlarging agricultural areas means that the world has no option and water use efficiency has to be improved, especially in arid and semiarid regions such as Iran. There the ratio of water/area is less than “1”, and consumption per hectare of cultivated area will increase while water becomes scarcer. But how can water be saved and food production for a growing world population continue to expand within the parameters of likely water availability? There are many technologies for the reduction of water consumption. Wastewater can be treated and used for irrigation. This could be a particularly important source of water for peri-urban agriculture, which is growing rapidly around many of the world’s mega-cities. Water can be delivered much more efficiently to the plants and in ways that prevent soil waterlogging and salinization. Changing to new crops requiring less water (and/or new improved varieties), together with more efficient crop sequencing and timely planting, can also achieve significant savings in water use. Irrigation systems have been developed, but if the same amount of water is still applied on the entire the field without taking the spatial variability of the soil into consideration, some areas may receive too much water and others not enough within one field. Excessive water application could contribute to surface water runoff and/or leaching of nutrients and chemicals into the groundwater. Inefficient water application causes reductions in yield quantity and quality, inefficient use of fertiliser and other inputs and lower overall water use efficiency. The challenges lie in the development of criteria and appropriate strategies for integrated water, nutrient and pest control programs. On-board and field sensor systems are needed to monitor soil and plant conditions for proper management. Interest in site-specific irrigation management has emerged over the past decade in response to the successful commercialization of other site-specific application technologies in irrigated agriculture. This interest is due partially to the desire to improve water use efficiency and partially to the need to implement site-specific water management to complement the site-specific management of other crop inputs such as nitrogen for groundwater protection. A holistic approach to site-specific crop management in irrigated agriculture includes water as one of the primary inputs. In this case, the use of PA for irrigation water management/scheduling, which is known as PI, will be a good solution to avoid over- and deficit- irrigation because of soil physical variability.

2.2.1 Background

Irrigation must vary spatially in fields because of spatial soil variability (texture, topography, water-holding capacity and infiltration and drainage rate). Therefore, the need for irrigation may differ between different zones of a particular field. The extension of the site-specific crop management concept to irrigation follows from the fact that excessive and deficient water availability greatly impacts on crop yield, quality and economic aspects. Interest in PI is due partially to the desire to improve water use efficiency and partially to the need to implement site-specific water management to complement the site-specific management of other crop inputs. These inputs include nitrogen for groundwater protection and many pesticides that are very readily dissolved in water, thus moving through the soil with excess water. Spatial variability in available soil water often develops during the irrigation season under the conditions of conventional uniform irrigation. This can cause problems in irrigation scheduling for optimum crop yield and quality, particularly for shallow-rooted, water-sensitive crops such as potatoes. Also, evapotranspiration that has an effect on irrigation requirement is dependent upon micro-meteorological conditions and crop growth, both of which vary spatially and temporally. Also, water application is influenced by many factors that vary spatially and temporally. For this reason, water supply must vary spatially in fields. Although soil moisture is near F.C. after first irrigation across the entire field and within different irrigation zones even though it depends on soil water capacity after first irrigation, the water content is the same only for a very short time, and reduced soil moisture will be different within different irrigation zones because of different deep percolation (Sanders et al., 2000; Jordan et al., 1999), different evaporation rates on the soil surface and different root system development. In humid environments where irrigation supplements rainfall, the general management strategy is to irrigate enough to supply the crop needs until the next rainfall. Thus, it may be desirable to apply more water to an area with low TAWC than to an area with high TAWC. In some situations, it may be desirable to apply smaller irrigation amounts when resuming irrigation after rain in order to have adequate storage capacity for future rainfall. Depending on parameters which have an effect on irrigation water requirements on the field, plant type and variety, plant spacing and plant size may vary within same field (Torre et al., 2000). Moreover, soil depth sometimes has an impact on the site-specific irrigation schedule (Oliveira et al., 2003). In these cases, the irrigation system has to be able to irrigate variably. But in commercial agriculture, this is not normal and logical. Moreover, infiltration rates on a field may vary from very low to very high due to changes in the soil characteristics which control infiltration characteristics (Jordan et al., 1999). Since it is difficult to change soil conditions, the same result can be achieved through site-specific application of irrigation water. Based on this concept, the field is divided into zones with homogenous infiltration characteristics, with each zone being irrigated differently (Ersahin and Karaman, 2000). In this case, the maximum irrigation application rate must be lower than the infiltration rate. Therefore, the implementation of PI is expected to provide the possibility to optimize and reduce (Perry, et al., 2004) water and energy consumption by preventing excessive water runoff and leaching. In addition, total yield, marketable yield and gross income are expected to grow as compared with conventional uniform irrigation management (King et al., 2006). Moreover, the problems which have been described previously will become less severe. Therefore, PI or site-specific irrigation can not only optimize water consumption during first irrigation, but it can also optimize the water consumption during subsequent irrigation (Personal communication, Prof. Paschold, Dr. R. G. Evans and Prof. C. Sommer, 2005).

PI is still at the development stages. Since it is a relatively new concept in agriculture, its realization is no simple task and requires a lot of experimental work to determine its feasibility and applicability. Literature on this topic is limited and mostly from 1992 and later. PI is also called Site-specific Irrigation (SSI) or Variable Rate Irrigation (VRI). PI is an exciting aspect of site-specific farming that is just beginning to be explored and is still very much a research issue (Sourell and Sommer, 2002). Fully integrated packages have not yet been created, much less made commercially available. However, assuming the farm economy will recover enough for capital investment, the situation may change quickly. PI technology brings with it the promise of increased yields, greater economic return and decreased impact on the environment in spite of field variability. PI needs systems which are able to supply water to plants only when and where they need it and in the right quantity. First, however, Irrigation Management Zones (IMZs) must be delineated and an Irrigation Application Map (IAM) must be created as the water needs vary spatially in many fields (Schmitz and Sourell, 2000; Sanders et al., 2000; Türker, 2001a; Duke et al., 1997).

It is well known that soil properties may vary at a geographic scale much smaller than at the commercial agricultural field scale. The primary factor that will influence the need for spatial variation of irrigation application is the Total Available Water Content (TAWC) of the soil, which depends on irrigation frequency and depth. The amount of water that is held by the soil and is available to the plants is dependent on the soil type. TAWC is the total amount of water in the plant root zone that is between field capacity (F.C.) and the permanent wilting point (P.W.P.). Typical values of the TAWC for a range of soil types are tabulated in Table 2.1.

Spatial variability in TAWC is mainly due to spatial soil texture variability that causes spatial variation of irrigation requirements. Silt loam holds two and a half times more water than fine sand. This is an important consideration when trying to determine irrigation frequency and duration. The concept of TAWC assumes that a soil can hold a certain amount of water that is readily used by crops in the root zone (Schmitz and Sourell, 2000). TAWC is more useful for management decisions than the volumetric moisture content, since the volumetric moisture content is defined as the proportion of water in a given volume of soil, whereas TAWC expresses the plant's ability to remove water from the soil. Thus, delineation of IMZ with different TAWC is one of the most important basics tasks during PI implementation (Oliveira et al., 2003).

Table 2.1: TAWC of ten soil types (Rhoads et al., 2000)

Soil type	**Textural characteristics**	**TAWC** [cm/m]
0	Sandy clay loam	17
1	Silty clay loam	15
2	Clay loam	15
3	Loam, very fine sandy loam, silt loam with 2 % organic matter	17
4	Loam, very fine sandy loam, silt loam with 3 % organic matter	21
5	Fine sandy loam	15
6	Sandy loam	12
7	Loamy sand	9.2
8	Fine sands	8.3
9	Silty clay,clay	13.3

In order to accomplish this basic goal, Oliveira et al., (2003) delineated management units for site-specific Irrigation. They grouped areas of the field into minimum management units, which have the least amount of TAWC variability. This included the development of a merging algorithm which allowed adjacent sub-areas with different TAWC values to be recursively combined until the whole field was merged into one management unit with area-weighed average TAWC.

Strategies for Variable TAWC: The strategic response to variable TAWC depends on the irrigation management objectives. For many crops, the irrigation objective may be summarized as full irrigation. Each irrigation is designed to refill the root zone. The net application amount should equal the amount of water used by the crop since the last irrigation. The irrigation frequency is chosen to ensure that the soil never gets "too dry" between irrigations. Field locations with lower TAWC will need more frequent irrigation and lower irrigation depth, whereas higher TAWC locations need less frequent irrigation and deeper irrigation depth. In general, the time between irrigations is determined by how much water can be used by the crop before undesirable stress sets in (related to TAWC) and by how fast the crop is using water (ETc). Only a portion of the available water is easily used by the crop. The maximum soil water deficit is the amount of water stored in the plant’s root zone that is readily available to the plant. To prevent plant water stress, an allowable depletion factor is used to calculate manageable allowable depletion. Table 2.2 presents the estimated maximum moisture deficiency levels for the ten soil types in Table 2.1 at various crop rooting depths. This table shows that soil moisture tension between irrigations increases more rapidly in coarse soils than in fine soils. Moreover, moisture deficiency is related to the type of crop. Table 2.3 shows the optimum range of soil moisture for important crops (Wilamowitz Moellendorff et al., 1985). Non-simultaneous irrigation of different portions of field a with different TAWC seems to be time-consuming and uneconomical, while simultaneous variable irrigation of the whole field, including different TAWC, seems to be better as shown by King et al. (2006) for a potato field and by Moore et al. (2005) for cotton.

However, the amount of water to add back to the soil during each irrigation depends on how much time has passed since the last irrigation and how much water the crop has used since then. This means that even in variable TAWC fields, irrigations can be effectively managed by selecting the irrigation interval appropriate to the those locations with minimum TAWC that will provide an irrigation regime acceptable for all soils and by setting the irrigation amount

Table 2.2: Management allowed depletion of soil moisture for ten soils at various soil types, 1ft = 0.305 m (Rhoads et al., 2000)

Root depth [ft]	**Soil type**									
	0	1	2	3	4	5	6	7	8	9
	Management allowed depletion [cm]									
1.5	3.8	3.6	3.6	3.8	4.8	3.6	2.5	2	2	3
2	5.1	4.6	4.6	5.1	6.4	4.6	3.6	2.8	2.5	4.1
2.5	6.4	5.6	5.6	6.4	7.9	5.6	4.6	3.6	3	5.1
3	7.6	6.9	6.9	7.6	9.7	6.9	5.3	4.1	3.8	6.1

Table 2.3: Optimum range of maintenance soil moisture for important crops (Wilomowitz Moellendorff et al., 1985)

Crop	**% TAWC**
Cereals	40-60
Early Potato	50-75
Sugar beet, Fodder beet	50-80
Leguminous plants	about 60
Grass, Clover	60-85
Corn	50-70

appropriate to this interval and the crop water use rate. Those areas with higher TAWC will receive water a little more frequently and in somewhat smaller amounts than during managed irrigation. However, this has no detrimental effects. They will also remain above the critical stress-generating water level. Therefore the strategy for locally variable TAWC involves locally variable irrigation applications.

2.2.2 Irrigation systems with special focus on mobile drip irrigation systems

Irrigation is defined as the application of water to a crop to replace the climatic moisture deficit over an irrigation interval and has a vital role in increasing crop yields and stabilizing production. There are three main classifications for irrigation systems: localized, sprinkler and surface irrigation (Figure 2.1).

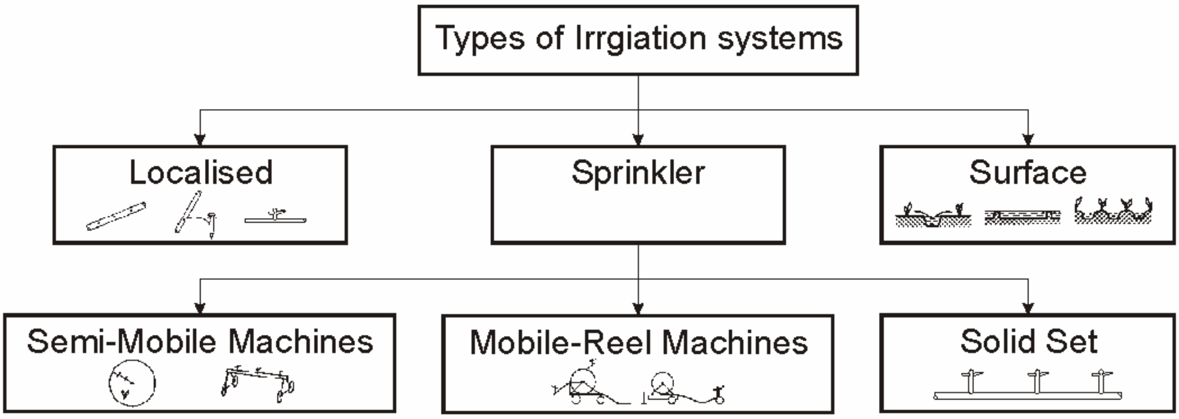


Figure 2.1: Irrigation systems (Sourell, 1998)

Water management research frequently necessitates varying irrigation water application (Fraisse et al., 1995a, b). The use of suitable irrigation systems can save water and energy. The amount of water that can be conserved by means of improved irrigation systems and practices depends on the ability of a particular type of irrigation system to implement improved management. Improved irrigation systems should offer opportunities to conserve water, to reduce the risk of either deficit or over-irrigation and to reduce potential leaching of fertilizers into the ground water. In the design and management of irrigation systems, the efficient use of water as well as crop production a are now often major goals, but water costs and farm sustainability, as well as the potential for the pollution of resources by over-irrigation must also be taken into consideration (Burt et al., 1997). Unfortunately, irrigation systems that spatially vary either water or nutrient application have still not been perfected and or made commercially available, let alone systems changing both inputs simultaneously (Schepers, 1996). The required techniques are at the test stage, but individual products, such as electronic roll-up speed control for mobile systems, are establishing themselves in practice (Sourell and Sommer, 2002). CP and moving-laterals types of sprinkler irrigation systems are commonly used in new irrigation developments all over the world (Faci et al., 2001) and have the ability to move during the irrigation process. Therefore they can cover a large irrigated area with minimum human effort, which leads to an extension of row crop and grain production areas.

Rolling topography, soils whose hydrologic properties are hard to manage and fields with variable fertility (Schepers; 1996) can make water and nutrient management on such spatially variable fields a nightmare due to difficulties encountered in scheduling under such irrigation systems, which make them prime candidates for variable rate water and fertilizer application. These systems are often advantageous compared to other irrigation systems. As recognised by the American Society of Agricultural Engineers (ASAE), the most important features of a properly designed sprinkler irrigation system are that a) The rate of water application should be less than the soil infiltration capacity so that no runoff or ponding occurs b) water distribution should be reasonably uniform and c) the amount of water applied during the irrigation event should be consistent with moisture storage capacity within the crop root zone (Bittinger and Longenbaugh, 1962). This is valid not only for the plot as a whole, but also for the varying parts of the field.

High distribution uniformity, precise water applications and operational flexibility in time and space are required in irrigation systems. The depth of water applied by such a sprinkler irrigation system is a function of the application rate and lateral travel speed. The application rate does not depend on the system speed, but is a function of the operating pressure, nozzle size and type and sprinkler spacing along the lateral (Duke et al., 1992a, b; Camp et al., 2000). The development in irrigation technology, especially in PE pipes after 1970, helped in the further development of mobile-reel irrigation; which allows a greater area to be irrigated using less energy, water and labour (Sourell, 1999). High water distribution uniformity is required to attain a satisfactory level of irrigation efficiency (Dechmi et al., 2003). Dukes and Perry (2006) found that a variable-rate CP and linear move control system was able to apply water uniformly through pneumatically actuated solenoid valves, but the use of electric solenoid valves caused some delay during valve opening and closing because of the time required for the valve mechanism to function. Al-Kufaishi et al. (2005) reported on the contrasting patterns of two VRT used in precision irrigation: pulse width modulation and bi-model sequencing. The results of the different distribution uniformity performance variables revealed that the pulse width modulation system performed more efficiently than the bi-model sequencing system at all nozzle pressures.

Also, there is increasing interest among growers in achieving the most efficient use of their energy and more efficient use of their water resources (through decreasing wind losses and increasing uniformity) that can be usually achieved by increased investments in modern sprinkler systems. Drip irrigation as a capital-intensive irrigation procedure with the ability to conserve water and energy did not gain the desired acceptance. Apart from the high capital requirement, the high work time requirement for the set up and removal of the drip irrigation system in one-year cultures is to be mentioned. However, a combination of CP and moving lateral machines which is called mobile drip irrigation (MDI) can create a highly efficient irrigation system.

Mobile Drip Irrigation: Trickle irrigation is gaining in importance in the world, especially in areas with limited and expensive water supplies, since it allows limited resources to be more fully utilized. Replacing the sprinklers on a CP or linear move machine by using polyethylene “PE” tubes with emitters to convey irrigation water directly to the soil surface converts a traditional CP or linear move to a MDI. In stationary drip irrigation, closed plastic tubes with emitters are used to deliver irrigation water to the plants using low pressure. No water losses due to wind drift and spray evaporation occur in sprinkler systems and especially in CP machines. The idea of mobile drip irrigation is a combination of the advantages of stationary drip irrigation with CP or linear move or boom trailer irrigation machines. The advantages of the stationary drip irrigation are its low operating pressure, low water losses and high irrigation efficiency. The advantages of the CP machine are its low capital requirements, flexibility and low labour requirements. In addition, soil cultivation under CP machines is easy. The operating pressure of the drip tubes can be much lower than that of sprinkler systems. The operating pressure at the inlet of a traditional CP with sprinklers ranges from 400 to 500 kPa as compared with 175 to 225 kPa at the inlet of the pivot machine with MDI. Thus, pressure reduction in mobile drip irrigation enables energy to be conserved.

The use of drip tubes with a moving irrigation system appears to have been introduced first by Rawlins et al. (1979). They mentioned the use of micro-basins and noted that crop response is similar to a stationary drip installation with closely spaced emitters. One advantage they mentioned was that saline water will not damage the foliage if such a system is used. In trickle irrigation systems, no water is lost by wind drift and spray evaporation like in sprinkler systems, which depend on the soil to deliver water to the end of the field. Because of these factors, trickle irrigation can deliver water to crops at efficiencies above 80 %, whereas surface irrigation usually operates at lower efficiencies between 60 and 75 % and is thus potentially able to conserve water and energy (Phene et al., 1981). However, the labor requirements for the annual installation and retrieval of trickle tube laterals and the large capital investment prevent the general adoption of trickle irrigation for field row crops. Discontinuous motion resulting from conventional mechanical guidance used in travelling sprinkler irrigation systems, which depends on mechanical tension to trigger electrical or hydraulic switching of individual tower drives, would cause excessive ponding of water in some areas and insufficient water supply in others. This is not critical in the case of travelling sprinkler irrigation systems because sprinkler heads cover a large enough soil area and provide sufficiently uniform water distribution for practical purposes. Sometimes, this practice creates mechanical and structural stress, which can result in structural failures and/or damage (Phene et al., 1981).

Efforts were made to commercialize the technology as early as 1992 under the name of Drag-N-Drip by Sherman Fox of Trickle Irrigation Specialties Co. of Salt Lake City, Utah. Newer efforts at commercializing the technology are being made by T-L Irrigation of Hastings, Nebraska, (www.tlirr.com) under the trade name of Precision Mobile Drip Irrigation (PMDI), which utilizes in-line drip hoses to distribute water directly to the ground. The hoses are spaced at 0.75 m or 1.5 m between lines being dragged through crops using a CP or linear move irrigation system. Many authors have described the MDI, but the classic dripping irrigation materials were never used. In some cases, holes in pipes, similarly long hoses with different types of emitters, and similarly long hoses with one type of emitters were used in linear and CP machines. In these cases, irrigation intensity was very high. At the same time, the classic drip irrigation materials in a CP were never used. Therefore, the application of MDI in CP machines will be important.

A CP irrigation machine can be adapted to provide the mobility and the water supply for such a concept (Chu, 1983). Lamm (2003) installed drip irrigation laterals on CP irrigation to implement MDI. Trailing drop tubes were 12 m long in some places. As a result drop tubes tangled into the CP sprinkler drive mechanism. This study provided the following results: a) a need to filter water for successful long term use because of clogging problems experienced and b) Contend of MDI with evaporation directly from the emitter surface were found. Evaporation can potentially leave chemical precipitation and biological growth on the emission point which can start the clogging process earlier and at a faster rate as compared to subsurface drip irrigation systems. Also, the limited irrigation capacity of this system caused some uneven drip line watering as evidenced by crop colour and height differences. Moreover, sometimes drip lines were tangled in the CP sprinkler drive mechanism. Also, Derbala (2003) developed and evaluated MDI with a CP machine and compared the total costs of stationary drip, mobile drip and traditional CP with sprinklers. He calculated the length of the drip tube about 1 m at the first and

16 m at the last tower for 20 mm irrigation depth, 48 hr irrigation time and 7.25 l/h emitter discharge at 50 kPa and 85 % to 100 % distribution pattern efficiency. The results indicated that the total costs of stationary drip irrigation (SDI) were very high and that they were low for the CP sprinkler. In the case of MDI, however, the total costs were close to the total costs of a CP sprinkler machine. But he did not achieve a complete economic analysis, because he did not consider the total yield of the area irrigated by each system.

One of the primary goals in the design of a trickle irrigation system is to have a hydraulic balance to ensure uniform discharge. Emitters or drippers, as the heart of a trickle irrigation system, represent the most important element of a trickle irrigation installation with respect to uniform water application and high irrigation efficiency. In reality, unit-to-unit emitter discharge is variable, as observed by Bralts et al. (1981) and Solomon (1979). With this purpose in mind, it is essential that the emitter flow variation and/or the uniformity of the water distribution be known, in particular since drip irrigation system efficiency depends on application uniformity and a successful uniform drip irrigation system application depends on the physical and hydraulic characteristics of the drip tubing (Al-Amound, 1995).

Accurate emitter manufacturing is necessary in order to achieve a high degree of system uniformity. However, the complexity of emitters and their individual components make it difficult to maintain precision during production. Changes in production temperature, mold damage and nonuniform mixing of raw materials are some of the factors affecting emitter homogeneity. Manufactures normally supply discharge curves. However, they seldom publish information relating pressure to emitter discharge variability. Ideally, all emitters in the system should discharge equal amounts of water, but due to manufacturing variations, pressure differences, emitter plugging, aging, friction head losses throughout the pipe network, emitter sensitivity to pressure and irrigation water temperature changes, flow rate differences between two supposedly identical emitters exist (Mizyed and Kruse, 1989).

2.2.3 Implementing precision irrigation

To implement precision irrigation, two basic tasks must be accomplished. The delineation of IMZs and precision irrigation control.

2.2.3.1 Delineation of irrigation management zones

Zones in the field that are to be irrigated with differing amounts and frequencies must be identified. There are three options to delineate IMZ (different TAWC).

2.2.3.1.1 Delineation of irrigation management zones by soil sampling grid

A soil sampling grid and laboratory analysis can be established and the soil can be evaluated to determine TAWC or soil texture at a site within each grid cell. At each site, the soil should be evaluated to a depth equal to the rooting depth of the crop (Oliviera et al., 2003; King et al., 2006). These procedures are costly, time-consuming and provide relatively low resolution data.

2.2.3.1.2 Delineation of irrigation management zones by remote sensing (reflectance measurement)

One option for determining where to dig soil pits in a field is aerial infrared imagery that shows different colours which are characteristic of different soil textures (Figure 2.2). The effects of eroded soil on crop vigor are evident in this photograph. The deep black colour of the centre pivot irrigated corn is underlain by Holdrege silt loam soils. Aerial imagery has held much promise for within-field monitoring, but has yet to demonstrate hard evidence for complete success. Aerial imagery quantifies the reflectance of the soil surface; therefore aerial imagery can distinguish between fine sand, loam and clay soils. Once the farmer knows where the surface soils change, soil evaluation costs can be reduced by selecting one site per soil zone identified by means of aerial imagery.

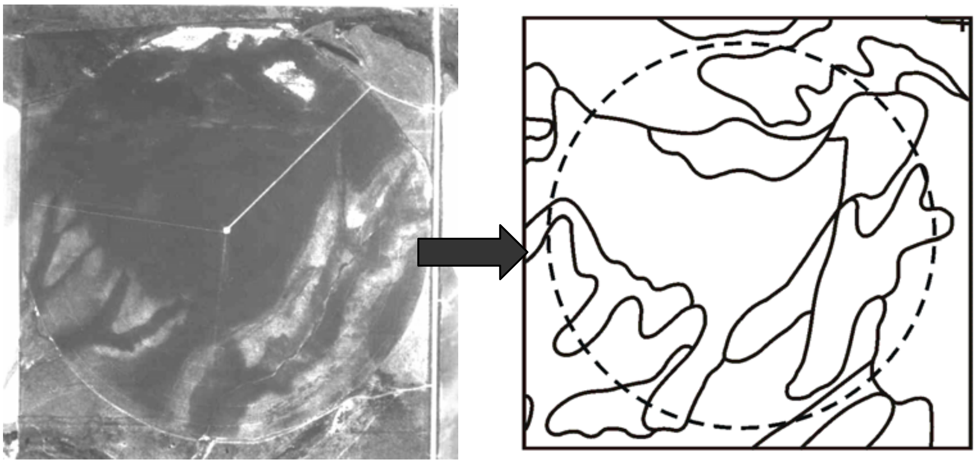


Figure 2.2: Determining soil types using aerial photos. The lines show the border of soil texture (Rundquist and Samson, 1988)

Dependable relationships are only possible when imagery is acquired over fields with uniform tillage conditions and often the response is only strong enough to identify the textural class of the soil (Branes and Baker, 2000). Reflectance measurements over tilled fields have beenused to develop predictive equations for the fraction of sand, silt and/or clay (that is a good index of the TAWC) at the soil surface with varying levels of success (Suliman and Post, 1988; Coleman et al., 1993). Barnes and Baker (2000) used multi-spectral airborne (green, red, near infrared (NIR) and thermal) and satellite (SPOT and Landsat TM) to derive soil textural class maps for 350 ha of a 770 ha research and demonstration farm in Maricopa, Arizona. However, using spectral classification procedures on a field-by-field basis, it was possible to map areas of one soil textural class with reasonable accuracy. These results are specific to the study area and may not apply at other locations due to the numerous factors that can contribute to a soil's spectral response. To minimize the effects of soil properties other than texture (e.g., soil moisture, organic matter and minerals other than quartz), Salisbury and D´Aria (1992) used a combination of visible, near-infrared (NIR) and thermal-infrared data. Directed sampling approaches can also be useful for interpreting bare soil imagery in terms of soil texture. Hong et al. (2002) found that airborne hyperspectral images in blue wavelengths were most highly correlated with ECa measurements of EM38-v and VERIS 3100-deep (that can be a soil type indicator in non-saline soils). However, one must be aware of the fact that just because the surface soils are similar does not mean that the sub-soils are the same. Moreover, problems include timeliness, cloud cover, ground cover, cost, poor spatial resolution and insufficient processing. As a result, this technique does not always provide image data which are useful for the crop managers (Deguise and McNairn, 2000).

2.2.3.1.3 Delineation of irrigation management zones by means of sensor-based ECa measurement

A third method of determining a TAWC map is based on a fast and non-destructive measurement of the apparent electrical conductivity of the soil (ECa) with the aid of electrode-based and electromagnetic methods (ECa). Factors that influence ECa include soil salinity, clay content and clay mineralogy, soil pore size and distribution, soil moisture content and temperature (James et al., 2000; Hendrickx et al., 1992; McNeill, 1992; Rhoades et al., 1981). The soil ECa can be used to indirectly estimate soil properties if the contributions of the other soil properties affecting the ECa measurement are known or can be estimated. In some cases, the within-field variation in ECa is due to one predominant soil property, and ECa can be calibrated directly based on that dominant factor. Generally, studies indicated that for soils with low concentrations of dissolved electrolytes the non-invasive electromagnetic induction-based and electrode-based measurement of soil electrical conductivity can be used to determine the soil water content at the field scale. Previous studies have shown that the controlling factor in some areas is clay content (Durlesser, 1999; Cook and Walker, 1992; Triantafilis and Lesch, 2005; Hedley et al., 2004; Dalgaard et al., 2001), salinity (Rhoades et al., 1989; Lesch et al., 1995) and water content (Kachanoski et al., 1988 and 1990; Sheets and Hendrickx, 1995) and can include all three factors in different parts of a study area (Paine et al., 1998; Scanlon et al., 1999). Kachanoski et al. (1988) found that spatial variation of the total water content stored in the top 0.5 m of a 1.8 ha field near Brantford, Ontario, Canada, was highly correlated to spatial variation of bulk soil electrical conductivity measured by electromagnetic induction meters (R^2 = 0.96). In another study 50 km west of Saskatoon, Saskatchewan, Canada, Kachanoski et al. (1990) found that bulk soil electrical conductivity explained more than 80 % of the variation of water storage in the top 1.7 m of a moderately fine-textured and moderately calcareous soil along a 660 m transect. Sheets and Hendrickx (1995) conducted a similar study that used 65 neutron probe access tubes at 30-m intervals and compared water content measurements with ECa readings using an EM31 (manufactured by Geonics Limited of Mississauga, Ontario, Canada-www.geonics.com) along a 1950 m transect in New Mexico for 16 monthly measurements. The lower R^2 (0.64) calculated for this study relative to that calculated by Kachanoski et al. (1988, 1990) was attributed to the deeper penetration of the EM31 meter (4 m) relative to the water content monitoring (1.50 m) and the distance between the EM measurements and the neutron probe access tubes (10 m). Also, the use of electromagnetic induction measurements was evaluated to predict the water content in the upper 1.50 m of a prototype engineered barrier soil profile designed for waste containment by Reedy et al. (2003). They monitored the water content with a neutron probe and a Geonics EM38 bulk soil electrical conductivity meter in the upper 1.50 m of a barrier soil profile. A simple linear regression model accurately predicted the average volumetric water content of the profile at any location at any time (R^2 = 0.80) and the spatially averaged volumetric water content over the entire area at any time (R^2 = 0.99).

A good correlation between clay content and soil electrical conductivity measurements with the aid of the EM38 method was found by Dalgaard et al. (2001) (R2 = 0.79) in Denmark, by Durlesser (1999) (R2 = 0.9) in Germany, by Doolittle et al. (2002) (R2 from 0.63 to 0.90) in the USA and by Hedley et al. (2004) (R2 = 0.72) and Triantafilis and lesch (2005) (R2 = 0.81) in Australia. Domsch and Giebel (2004, 2001), Greve et al. (2004), James et al. (2003); Al-Karadsheh et al. (2002); Anderson, et al., (2002); Kitchen et al. (2002); Nehmdahl and Greve (2001) and Waine et al. (2000) used ECa derived by EM38 or VERIS 3100 to generate a soil texture map.

In non-saline soils and when the field is at field capacity, TAWC will be a dominant factor which has an effect on the ECa. Waine et al. (2000) described a methodology which uses EMI for TAWC maps based on EM38. They calculated TAWC and the soil moisture deficit by examining moisture release curves for UK soils and plotting calibrated data on texture-moisture data when the field was at field capacity. They derived a good correlation (R^2 = 0.88) between the TAWC against the EMI data for the Gamlingay site. Also, they classified ECa between 0-10 mS/m as sandy loam, 10-20 mS/m as clay loam and greater than 20 mS/m as clay. An approach for establishing a strategy for precision irrigation was the focus of a study on the suitability of EM38 by Al-Karadsheh et al. (2002) at the Federal Agricultural Research Centre (FAL, Braunschweig, Germany) and VERIS 3100 by Moore et al. (2005) at Clemson University, USA, for TAWC delineation in the field as an indicator or surrogated property for the quantification of in-field spatial variability in order to develop more precise variable rate water application maps. Al-Karadsheh (2003) classified the TAWC at different EC-zones in non-saline soils, when the field was at field capacity in the upper 60cm on three different fields as shown in Table 2.4. Moreover, Moore et al. (2005) divided the field into different irrigation management zones based on soil texture because of a strong correlation between soil EC and soil texture. The zones provided each treatment with a different soil texture, which was directly proportional to water holding capacity. Also, Delin and Berglund (2005) found a positive correlation (r = 0.54) between TAWC and ECa measured with EM38 between at a depth of 30 to 100 cm on a sandy field. According to results of Ristolainen et al. (2004), soil type classification based on ECa measured with a resistivity fork (Geological Survey of Finland, Puranen et al., 1999) and permittivity measured with a percometer (Adek Ltd, Estonia) were based mainly on differences in soil water holding capacity. Recently, Brevik et al. (2006) showed that ECa has its greatest potential to differentiate between soils when the soils are moist. They mentioned that ECa techniques may prove to be a more effective soil-mapping tool in the spring or at other times when the soil profile is moist and less effective during dry periods. Therefore, with due attention to the possibility of monitoring the within-field variation of the total available water content using many available ECa sensors on the market which have different nominal investigation depths, it is better to compare the ability of electrode-based and EMI-based ECa sensors to find the best ECa sensor-based delineation of irrigation management zones for the creation an irrigation application map.

Table 2.4: TAWC on three fields in different EC-zones in the FAL, Institute of production engineering and building research (Al – Karadsheh, 2003)

Field No	EC zones [mS/m]	TAWC [cm/m]
1	10-14	10.4
	14-18	10.6
	18-23	10.7
2	10-16	11.6
	16-22	12.0
3	10-13	7.4
	13-16	7.9

2.2.3.2 Precision irrigation control (PIC)

The irrigation system must be designed and installed such that it is capable of sending water to each of these zones according to different schedules. The PIC system can be neatly broken down into three areas:

- Determination of irrigation depth within each MZ
- Communication and protocols
- Controller

2.2.3.2.1 Determination of the irrigation depth within irrigation management zone

With due attention to different TAWC between delineated management zones, soil moisture, and consequently irrigation depth, will be different before irrigation. Thus, before every irrigation, appropriate irrigation depth has to be determined for every management zone. Equipment which allows the soil moisture status to be monitored in the various zones may be a desirable addition to the installation. Discussing the zoning of the field and the irrigation block layout with the irrigation designer should help in determining the number and location of soil moisture sensors to be used. There are many options for the quick determination of field-soil moisture. For the purpose of this review, it is useful to start with a survey of measurement technologies before considering their capacity to measure soil moisture. In this work, the assessments were restricted to technologies that have the potential to be used for practical field-based soil measurement in the coming decade. The development of measuring technologies that at present are either very expensive or at a very preliminary stage of development should be given great attention.

a) Capacitance sensors: Capacitance probes like EnviroSCAN: Complete, continuous soil moisture monitoring solution; Diviner 2000: Portable soil moisture monitoring for instant infield decision-making; EnviroSMART: Highly integratable soil moisture monitoring; EasyAG: Easy to install and ideal for shallow rooted crops with flexible connectivity use telemetry (linked to mobile telephone systems or radio networks) and are now routinely used in irrigated agriculture (e.g. www.sentek.com.au). These systems have obvious applications for dryland systems and the main issue is cost. Charlesworth (2000) provides details about costs and operating options for the Adcon addIT system. These figures suggest it could be somewhat expensive to instrument a reasonable area. However, a significant fraction of the cost resides with the probes themselves rather than the telemetry system.

b) Electrical conductivity (electromagnetic induction and resistivity The methods rely on either electromagnetic induction or resistivity and they can be used to characterise large volumes of soil (with depths from less than 1 metre to several hundred metres), although the extent of measurement is often not specified with any great precision. The soil ECa can be used to indirectly estimate soil properties if the contributions of the other soil properties affecting the ECa measurement are known or can be estimated. In some cases, the within-field variation in ECa is due to one predominant soil property and ECa can be calibrated directly based on that dominant factor. As the results from Kachanoski et al. (1988 and 1990), Sheet and Hendrickx (1995) and Reedy et al. (2003), show, the rapid and inexpensive measurement of the apparent electrical conductivity of the soil can provide important information on within-field soil moisture variability. Recently Brevik and Fenton (2006, 2002) found that SWC was the most important of the mentioned factors influencing ECa in central Iowa.

c) Ground-penetrating radar: Ground-penetrating radar (GPR) is a subsurface imaging technique that uses the reflection of very short pulses of electromagnetic energy from dielectric discontinuities in the ground to form an image of the subsurface. This technique is based on the same principle as time domain reflectometery (TDR), but does not require direct contact between the sensor and the soil. When mounted on a vehicle or trolley close to the soil surface, it has the potential of providing rapid, non-disturbing, soil moisture measurements over relatively large areas, whereas TDR is better for detailed measurements over small areas. Almost any reasonably abrupt variation in material type will produce a reflection of energy and show up as an image. Since water has a high dielectric constant (~80) compared to most dry soil materials (~3-10) and air (~1), soil water content is important (Huisman et al., 2003). GPR is a valuable technique for the measurement of shallow or surface soil water content. The zone of GPR influence is in the range of 0.4 to 0.5 m above and below the middle of the antennae depth (Galagedara et al., 2002). However, slowly changing water contents are hard to detect with GPR and, in general, water profiling is not possible with traditional types of GPR. More rapid changes, such as wetting fronts, are easier to detect and this use of GPR is more appropriately applied in irrigated regions.

GPR is very material-dependent. Under good conditions, near-optical clarity of images is obtainable. However, in poor conditions (e.g. high clay and water contents), GPR may be almost useless. The report of Huisman et al. (2003), suggests that the main use of GPR will be for subsoil water content measurement. The high cost and complexity of GPR, coupled with the need for some expertise in operation and image processing and interpretation, mean that subsurface imaging is likely to be limited to particular investigations of subsurface features where its unique imaging capability can be valuable. Although the GPR technology has been developed in the same period as the successful TDR methodology and was successfully applied to determine the volumetric water content of soils by Schmalholz (2007), there is still a large difference between these methods for soil water content determination (Huisman et al., 2003). Although it has been applied successfully to many field situations, GPR has not been widely used because the methodology and instrumentation are still only in the research and development phase (Davis and Anna, 2002; Rubin, 2003). Although it is mentioned that small, compact and inexpensive GPR systems will be available in the near future for routine field studies, this seems to be really difficult to accept.

d) Irrigation simulation models: Irrigation simulation models can simulate the real world and improve irrigation performance; thus saving water and increasing farm productivity (Clemens, et al, 1999; Dechmi, 2003). Simulation models allow the system operator to run the model several times under specified environmental conditions in order to determine the best method of controlling or managing the irrigation process. Boken et al. (2004) demonstrate that these models are also used to integrate knowledge about soil, climate, crops and management for better management irrigation decisions. According to Sadler et al. (2000), the growth models developed do not have as one of their objectives the process of describing within-field variation. In precision irrigation with many management zones, the model operates many times in order to incorporate site specific in soil texture spatial variations. Some option of irrigation models are: CROPWAT Irrigation Model (FAO, 1992), EPIC-phase model (Williams et al., 1989), WaSim technical manual (Hess, 2000), AMBAV model (Löpmeier, 1994; Braden, 1995), a site-specific irrigation decision support model (Reeder 2002), mechanistic agronomic models such as CERES-MAIZE (Jones and Kiniry, 1986) and CROPSYST (Stockle et al., 1994).

e) Reflectance measurement: In recent years, several research efforts have focused on the development of remote-sensing techniques to characterize the spatial and temporal variability of soil moisture over large regions. Many studies have successfully demonstrated the use of infrared, passive and active microwave sensors of different bands for the collection of soil moisture information (Capehart and Carlson, 1997; Jackson, 1997; Mancini et al., 1999; Moran et al., 1997 and 1998; Milfred and Kiefer, 1976; Janik et al., 1995; Viscarra Rossel and McBratney 1998b; Hummel et al., 2001; and Sibusawa et al., 2001, 2003). In aerial photographs, which measure the reflectivity or albedo of a surface, areas of higher moisture content appear as darker areas, since water lowers the albedo of an object. Because of its all weather, day and night characteristics, microwave remote-sensing of soil moisture shows the highest potential for operational applications (Lillesand and Kiefer., 1979). The approach is limited to the presence of vegetation the presence of clouds, and the time lag between consecutive images with field-scale resolution (Christopher et al., 2003) and it is often only sensitive to conditions at the surface. It gives only a measure of the moisture content within the first few centimetres of the soil profile (nearly 5 to 20 cm depth).

Canopy temperature (Tc) measurement by means of infrared thermometers (IRTs) is another remote sensing method used to monitor crop water status. Technological advances have miniaturized IRTs and reduced power requirements so that inexpensive self-powered units are now commercially available. Measurements should be done at or just after solar noon when the plant water deficit is maximized. Since plant water status changes over the course of the day, measurements of the population must be done within about two hours. Since the assessment of plant stress by means of canopy temperature within a breeding population is relative, atmospheric conditions during measurements should be relatively stable. Cloudy or windy conditions should be avoided. Transient cloudiness which has an immediate effect on leaf temperature is particularly difficult. The thermometer should not be unnecessarily exposed to heat, such as by letting it lie in the sun. As shown by results, the Tc measured by non-contact IRTs provides an efficient method for rapid, non-destructive monitoring of whole plant response to water stress (Idso et al., 1981; Jackson et al., 1981).

2.2.3.2.2 Agricultural communication protocols and wireless sensors

Future agricultural engineering developments will include automation systems which reduce farm inputs, protect the environment, secure farm income, produce high quality products and optimise the efficiency of each process. There is no need to visit the field as data retrieval can take place remotely via e-mail, satellite or GSM (Global System for Mobile communications) modem, hard-wired serial link or via a low powered radio. Some traditional limitations in collecting agricultural data such as soil moisture for irrigation needs includes real-time and time-liness of data transfer to the appropriate locations or central databases and the protection of data from equipment malfunction or battery loss. In this case, Damas et al. (2001) developed and tested a distributed, remotely controlled, automatic irrigation system to control a 1500 ha irrigated area in Spain. Moreover, wireless sensors were used by Evans and Bergman (2003) in linear move and centre pivot irrigation systems to assist irrigation scheduling using combined on-site weather data, remotely sensed data and grower preferences.

Adopting a standard interface for sensors and actuators allows common hardware and communication protocols, such as communication interface and control algorithm software, to be reused. Among several agricultural serial communication protocols, some can be highlighted since they were already applied on agricultural related systems (Guimarães, 2003). Some of these protocols are RS232, RS485, CAN Bus (ISO11783 or ISOBUS), SAE J1939, DIN9684 (standard for the agricultural BUS system or Landwirtschaftliches BUS system, LBS). These protocols were developed to standardise the method and format of data transfer between sensor, actuators, control elements, information storage, and display units whether mounted or part of the tractor, or any implements which reduce connector and cable clutter and thus also damage to terminals. Equipment purchased without this connectivity standard will have an accelerated rate of obsolescence.

RS232 and RS485: RS232 is created for a bi-directional data communication between two devices, with a maximum network length varying from 150 to 300 meters, depending on the baud rate and the applied cabling, but in this study it was used for a less than 4 m distance. Some important advantages of the RS232 are its compatibility to most of the existing microprocessors and microcontrollers, its very easy implementation and being well known around the world. On the other hand, some important disadvantages of the RS232 are the difficulties of network expansion and the restrictions regarding the implementation of a DIC (due to the required amount of wiring harness and concerns related to electromagnetic compatibility). The evaluation of all characteristics of the RS232 shows that, it does not fulfill all requirements necessary for an agricultural protocol although it is well known throughout the world and easy to implement. In most higher level protocols, one of the nodes is defined as a master and sends queries or commands over the RS485 bus. All other nodes receive these data. Depending of the information in the sent data, zero or more nodes on the line respond to the master. In this situation, almost 100 % of the bandwidth can be used. There is no need for the senders to explicitly turn the RS485 driver on or off. RS485 drivers automatically return to their high impedance tri-state within a few microseconds after the data has been sent. Therefore no delays between the data packets on the RS485 bus are necessary. RS485 is used as the electrical layer for many well known interface standards, including profibus and modbus. Advantages of this protocol are its simplicity of implementation, less wiring and higher immunity to electrical noise. Regarding its disadvantages, the fact can be highlighted that it is not a fully distributed system, according to some authors, since is establishes master-slave communication. From an agricultural application standpoint, the low efficiency of this network, due to its master-slave concept, makes its usage difficult on applications that need fully distributed control.

CAN Bus ISO 11783: The international CANBus ISO 11783 standard (Controller Area Network, plus a Bus or data path shared by many devices), sometimes called ISOBus, has been widely accepted for agricultural applications (Benneweis, 2006). Equipment that is ISOBUS compliant promises to communicate seamlessly (i.e., plug and play) with other equipment to form systems of machines and implements that can be flexibly configured to meet user needs. This standard forms the backbone of the autonomous agricultural machine system. CANBus is a complex communication protocol and was originally developed in Germany by Bosch primarily for use in automotive applications.

DIN 9684 or LBS: In 1986, under the leadership of the German Agricultural Machinery and Tractor Association (LAV) a working group was set up, out of which the ad hoc group ‘BUS system’ evolved one year later to standardize a serial BUS for agricultural purposes. Valuable contributions from many enterprises and institutions in Germany and other parts of Europe working with this ad hoc group finally resulted in the German standard DIN 9684 (DIN, 1989-1998). Results, actors and chronology of the work (1986–1993) of the ad hoc group are presented in the KTBL-Arbeitspapier 196 (Auernhammer and Frisch, 1993). The standard defines the bit-serial data exchange between the vehicle and implement and the data exchange between the mobile tractor-implement combination and the farm's stationary computer. It also defines the information exchange between the operator and the technical system, known as the man-machine interface. Speckmann and Jahns explained the needs and the goals of a standardized BUS (Speckmann and Jahns, 1999). They developed and applied the BUS using the DIN9684-LBS protocol.

European installation bus (EIB): EIB is an electrical bus system based on the EN50090 standard in Europe which was originally used by Siemens since 1987 for the installation and interconnection between sensors and actuators in a house. The EIB is a decentralized system. Each sensor or actuator has its own microcomputer. Thus, a central controller becomes redundant and thus the loss of an individual participant means only the loss of an individual function in the system. Advantages of the EIB-Bus are that it is easy to install, reacts very flexibly to changes, can be installed at low cost, has an emergency alarm, displays malfunctions if desired, uses energy efficiently and is inexpensive. Its disadvantages are relatively high construction costs and the complexity of error-finding.

Wireless technology: A wired system for data transfer from an in-field sensing station to a base station is time-consuming and costly to install and maintain. It may not be feasible to get the system hard wired for long distances. A wireless data communication system can provide dynamic mobility and cost-free relocation. Wireless technology is the process of sending information through invisible waves in the air. It has the obvious advantage of significant reduction and simplification in wiring and harness (Sensors Magazine, 2004). Wireless technologies have been under rapid development during recent years. Radio frequency technology has been widely adopted in consumer's wireless communication products and provided opportunities to deploy wireless signal communication in agricultural systems. In this case, various wireless standards have been established. Among them, the standards for IEEE 802.11b Institute of Electrical and Electronics Engineers ("WiFi" wireless fidelity, usually refer to any type of IEEE 802.11 network) (IEEE, 1999) is a standard for WLAN (Wireless Local Area

Network) with 100 to 500 m range, IEEE 802.15.1 (Bluetooth) (IEEE, 2002), IEEE 802.15.4 (ZigBee) (IEEE, 2003). WLAN is used more widely for measurement and automation applications. Spectrum bands of 902~928 MHz, 2.4~2.48 GHz and 5.7~5.85 GHz were allocated for license-free spread spectrum devices (Kulkarni, 2005). Table 2.5 compares some wireless standards that are suitable for wireless sensor network. All these standards use the instrumentation, scientific and medical (ISM) radio bands, including the sub-GHz bands of 902–928MHz (US), 868–870 MHz (Europe), 433.05–434.79 MHz (US and Europe) and 314–316 MHz (Japan) and the GHz bands of 2.400-2.4835 GHz (acceptable worldwide). 8N1 and Theimeg serials aeother serial protocols which are developed by their companies and have a transferring rang up to 300 m and 4.5 km data. In general, lower frequency provides a longer transmission range and stronger capability to penetrate through walls and glass. However, due to the fact that radio waves with lower frequencies are more easily absorbed by various materials, such as water and trees, and that radio waves with higher frequencies are easier to scatter, the effective transmission distance of signals carried by a high frequency radio wave may not necessarily be shorter than the transmission distance of a lower frequency carrier which has the same power rating. The 2.4 GHz band has a wider bandwidth that allows more channel and frequency hopping and allows compact antennas to be used. Hardware requirements for wireless sensors include: (1) robust radio technology, (2) a low cost, energy-efficient processor, (3) flexible I/O for various sensors, (4) a long-lifetime energy source and (5) a flexible, open source development platform (Ning et al., 2006).

Table 2.5: Comparison between some available wireless standards on the market (Source: www.adcon.com, www.theimeg.de and Wang et al., 2006)

Feature	**Range [m]**	**Data rate**	**Battery life**	**Complexity**
WPAN (Bluetooth-IEEE 802.15.1)	10	1 Mbps	1 week	Very complex
WPAN (ZigBee-IEEE 802.15.4)	70	250 kbps	>1day	Simple
WLAN (WiFi-IEEE 802.11b)	100	11 Mbps	Some hours	Complex
8N1	300	2.4 GHz	-----	-----
WLAN	100-500	5 Mbps – 2 GHz	-----	Complex
A723 addIT	1000	430–470 MHz	-----	-----
Theimeg	until 4500	**-----**	-----	-----

2.2.3.2.3 Irrigation controller

A controller is an integral part of an irrigation system used to apply water in the necessary quantity and at the right time. One of the most important parts for the control of irrigation depth can be solenoid valves (SV) as the heart of the irrigation control system which uses electric actuators. A SV is an electromechanical valve for use with liquid or gas controlled by running or stopping an electrical current through a solenoid, which is a coil of wire, thus changing the state of the valve. A solenoid valve has two main parts: the solenoid and the valve. The solenoid converts electrical energy into mechanical energy which, in turn, opens or closes the valve mechanically. Generally, the actual power transfer to the control element is hydraulic pressure activated by the electrical power delivered to the actuator. The flow control element can be in the form of a plug, disk, piston or other similar device allowing for closing or opening of the flow path in the control valve. The SV, which is commonly used in irrigation systems, relies on an electromagnetic force to move the disk directly or to initiate the piloting action that allows line fluid to open or close the valve. Electric control valves can also be closed or opened manually. When the coil is energised, the armature is attracted by its magnetic field and the valve is opened or closed leaving a passage through the valve orifice. In countries like Germany, where the climate is cold and frosty in the winter, the remaining water must be drained from the system at the end of the irrigation season. In this case, solenoid valves, which are normally opened without any electrical energy (coil is de-energised), are used even though they are expensive. But in warm regions like Iran or south Europe it is possible to use cheap solenoid valves which close without any actuator during rest position. Some important companies which produce solenoid valves are M & M International, UK (www.mmint. co.uk), Buschjost, Germany (www.buschjost.de), Parker, USA (www.parker. com), and STC (Sizto Tech Corporation), USA, http://stcvalve.com. With due attention to possibility of variable rate irrigation using SV, it was used by Kincide (2005), Al-Karadsheh et al. (2002), Camp et al. (1998), Duke et al. (1992), Fraisse et al. (1995), King et al. (1999), Evans et al. (1996), Bordovsky, (2000) and Miranda et al. (2005) to control irrigation depth.

The two methods of VRI are map-based and sensor-based. Map-based VRI requires GPS, GIS and software for map production. In sensor-based VRI, some sensors may be connected (hard wire or radio linking is possible) to a computer or data logging system to provide real-time soil moisture monitoring. A fully automated system would link the soil moisture sensors through a computer program to the irrigation pump and block valves. A fully automated system operates under the control of a computer program. Most computer programs allow the farmer to choose what triggers will start and stop irrigation cycles. These triggers could be soil moisture readings, evapotranspiration readings and/or temperature readings. When one of the start triggers has been reached, the computer program sends a signal to the irrigation block needing water and opens the block valve and starts the pump. When that irrigation block's stop trigger has been reached, the computer program will send a signal to turn off the pump and shut off the block valve. Most farmers who have installed automated irrigation systems recommend that the system should measure more than just one variable (i.e., soil, plant or environment). Additionally, someone must monitor the fields frequently to verify that the computer screen coincides with what is actually happening on the field.

However, technology for the variation of water application along the mainlines of self-propelled sprinklers is not commercially available. Several technologies have been developed by researchers to variably apply water with self-propelled sprinkler systems. There are four main techniques to implement VRI:

a) Changing travel speed of the travelling irrigation system
b) Dynamic VRI in a step-wise manner using either combination of individual sprinklers at a single location or combinations of manifolds
c) Pulse concept to control single sprinklers
d) Variable orifice sprinkler

a) Changing travel speed of the travelling irrigation system: Another type of VRI is dynamic variable rate application that can be achieved in a step-wise manner using either a combination of individual sprinklers at a single location or combinations of manifolds, each with fixed, continuous flow rates. Multiple manifolds with sprinklers or nozzles delivering combinations of fixed flow rates have been used to achieve VRI on moving irrigation systems (Roth and Gardner, 1989; Stark et al., 1993; Omary et al., 1997; Camp et al., 1998). Roth and Gardner (1989) modified a lateral move irrigation system to test different application depths of water and nitrogen. The system consisted of three lines, of which one applied five, different application depths to five different treatments in one experimental block along the irrigation system. The second line applied a different arrangement for the same application depths to irrigate different blocks. The third line applied uniform depth along the irrigation system. The system did not have the possibility of combining application depths to apply different depths in the moving direction. Therefore it cannot be used for site-specific management where the different application depths depend on the natural field soil layout and not on a specifically designed layout. Stark et al.

(1993) reported on the development of a centralized control system for the site-specific application of water and chemicals that could be used on linear and CP irrigation systems. This system consisted of three conventional sprinklers at each location, each controlled by a microprocessor and sized 1/4, 1/4 and 1/2 of full flow, to provide 1/4, 2/4, 3/4 and full irrigation rates. A U.S. patent was awarded to this system for variable rate application of irrigation water and chemicals (McCann and Stark, 1993). The above systems developed to control the flow rate of one or more individual sprinklers require medium to high (200-400 kPa) water pressure and have a wetted radius of several meters (> 4.9 m). A large wetted radius makes it difficult to confine water application to small areas without undesired application to adjacent areas. Also, unnecessary overlapping can adversely affect application uniformity. In the case of systems with low energy precision application (LEPA), water is delivered near the ground surface. This may not be effective for the canopy wetting of tall crops. Similarly, a multiple-segment water application system was developed and attached to a commercial CP irrigation system to provide variable application depths within each segment at a given speed. Each segment was 9.1 m long and consisted of three parallel manifolds sized to provide 1x, 2x and 4x, where x is a minimum application depth. According to Omary et al. (1996), the three manifolds could be operated individually or in various combinations to provide eight application rates (0-7x) at any given tower velocity. Water flow to each manifold was controlled by a solenoid valve that was connected to the control system, and the pressure was regulated. The results show that spatially varied water and chemical application was achieved with the same accuracy as that of conventional uniform application.

c) Pulse concept to control single sprinkler: The third option of VRI is to take advantage of the pulse concept to control single sprinklers (Duke et al. 1992; Fraisse et al., 1992 and 1995a, b; Giles et al., 1996; King et al., 1996; Sadler et al., 1996; King and Wall, 2001; Sadler et al., 1996; Evans et al., 1996; Harting, 1999; Perry et al., 2003; Al-Karadsheh et al., 2002, Moore et al, 2005). Control systems and solenoid actuated control valves are installed at each power control flow. The control system consisted a PLC linked with a set of control switches that could be activated either manually or controlled by the computerized standard control panel. The PLC is programmed to apply varying water depths depending on the settings of the control switches. Al-Karadsheh et al. (2002) modified the commercial CP irrigation system using solenoid valves and controlled it with the aid of programmable logic control (PLC) for variable-rate water application to irregularly-shaped areas. The PLC receives the positional information and opens/closes the addressed solenoid valves to determine target depth. Results showed that the PLC is successful in varying the amount of water throughout the field with some deficiencies.

d) Variable orifice sprinkler: The water application rate can be varied by moving a pin into the sprinkler orifice to reduce its area (King and Kincaid, 2004; King et al., 1997). As an alternative, inserting and removing the pin using a linear actuator provides a time-averaged application rate. This method is similar to the pulsing concept but does not completely turn the flow off. Maximum flow occurs when the pin is removed. When the pin is inserted, the flow is reduced by the ratio of the cross sectional area of the pin to the cross section of the sprinkler orifice to a known lower limit.

Each of the above methods of providing variable flows has certain disadvantages. In moving irrigation systems, application depth remains uniform along the pipeline. Unfortunately, more areas requiring similar treatment in the field don't have the same size and shape as the irrigation system control areas. Consequently, new or modified irrigation systems are needed to apply water and nutrients to areas of similar variation within the field or irrigation system. The pin insertion method, though continuously variable from 40 to 100 %, cannot provide rates below 40 % of full flow. While this may be acceptable in arid areas, lower application rates (near zero in some cases) would be needed for precision water and nutrient management in humid areas. Multiple manifolds are more costly and heavier than single manifold systems. The pulsing of water to a manifold with multiple sprinklers typically has long cycle times and thus requires a large wetted radius to achieve acceptable uniformity for moving irrigation systems.

The advantages of pulsing a group of sprinklers is that the application rate can be varied continuously rather than in incremental steps like in the method described previously. The PLC technologies did a good job of on-site control, but it was expensive to add remote, real-time monitoring and control aspects made possible by wireless sensor networks and the Internet. Moreover, most feedback control systems of the pulsing concept have used centralized control, with sensors and actuators in the field and the controller in a central building, requiring separate wires running to connect individual sensors, devices and actuators to a centrally located controller by point-to-point communication using either direct wiring or radio frequency or infrared links. Depending upon the distance between individual sensors and actuators to a centrally located controller, radio frequency or infrared links could be cheaper than point-to-point wiring. This approach is expensive and difficult to maintain in an environment where mechanical damage and lightning are concerns, especially for site-specific irrigation, which may require the use of a large network of soil moisture sensors and actuators. Also, lack of flexibility is another disadvantage of centralized located controllers, especially for site-specific irrigation control on large irrigated fields. Distributed Irrigation Control (DIC) systems, on the other hand, have autonomous controllers at discrete locations close to sensors and devices (may be covering relatively homogeneous areas in the field). These autonomous controllers have some intercommunication, with each specific zone of the field or a group of sensors or valves having an interconnected controller, which allows the system to prioritize irrigation decisions between site-specific irrigation management units. The advantages of DIC are reduced wiring and piping costs, easier installation and maintenance and lower susceptibility to lightning damage (Torre-Neto et al., 2000). However, since additional controller units are required for DIC, this type of system is viable for site-specific irrigation only if low-cost controllers and sensing/actuating devices with low-power components (sensors, actuators, etc.) are available. Some sort of wireless communication among the controllers is also required in order to optimize the hydraulic operation of the irrigation system. Studies by Sadler and Camp (2005), Ohyama et al. (2005), Coates and Brown (2004) and Rodriguez-de-Miranda (2003) show three major needs:

a) some sort of wireless communication among the controllers is required in order to optimize the hydraulic operation of the irrigation system
b) in-field variable soil water holding capacities demand remote spatial soil moisture monitoring in specific areas within the field, thus requiring an integrated irrigation control and monitoring system (Evans et al., 2000)
c) critical research needs to include improved decision support systems as well as monitoring and feedback to irrigation control in real time (Sadler et al., 2005)

2.2.4 Critical literature analysis for precision irrigation

As more research is conducted using the existing technologies and more site-specific machines are developed, site-specific irrigation functions and other recommendations will be realized. Cost effective and reliable equipment and control systems need to be developed and tested. Techniques for efficient and effective real-time system management need to be developed, field tested and validated. Methodologies for predicting the potential environmental and economic benefit for a particular site are needed to facilitate the adoption and implementation of the technology where appropriate. With due attention to available literature for PI, critical literature analysis for PI includes:

a) Validation and realization of potential benefits of PI through considerable field studies with different soil types or crop characteristics to insure a positive net economic return and more reduction in water and energy consumption
b) Comparison between different sensor-based soil electrical conductivity measurement to delineate irrigation management zones
c) Reduction of wiring of solenoid valves or wireless solenoid valve control
d) Absence of a pump with variable discharge rate under constant pressure
e) Effort for the elimination or reduction of wind drift and evaporation in sprinkler irrigation

Therefore, the development of a remote, real-time monitoring and DIC system for continuous move irrigation systems that would integrate localized wireless sensor networks for the monitoring of soil moisture and weather with the control of individual or group nozzle water application rates and a system design including on-site monitoring and control with wireless access to the computer, which enables water and energy consumption to be reduced, would provide a satisfactory site-specific irrigation system.

3 MATERIALS AND METHODS

The schedule and strategy of the study investigations are divided into two main sections to establish precision irrigation. Firstly the delineation of IMZs based on sensor-based soil EC measurements and secondly, remote real-time and site specific DIC and monitoring system by means of wireless soil moisture measurement and pulsing techniques to deliver variable irrigation depths using programmable logic control.

3.1 Delineation of irrigation management zones

3.1.1 Study field

Data were collected on a 16.6 ha grass field at the Federal Agricultural Research Centre (FAL), Institute of Production Engineering and Building Research, Braunschweig, Germany (Figures 3.1 and 3.2). It was located between latitudes 52°1752, 80"N - 52°1802,41"N, and longitudes 10°2708,39"E-10°27370,27"E, respectively. The physical and chemical characteristics of the soil at the experimental site in Braunschweig are summarised in Table 3.1. By touching, the soil type was identified as cambisol predominantly characterized by a loamy sand soil texture in the upper 40 cm of the soil profile and more a sandy texture at greater depths in agreement with Al-Karadsheh (2003) and Derbala (2003). The pH of low status sulphur of the soil at the experimental site was found to range from highly acid (4.8) to moderately acid (5.5). The average weather conditions in this region are shown in Table 3.2.

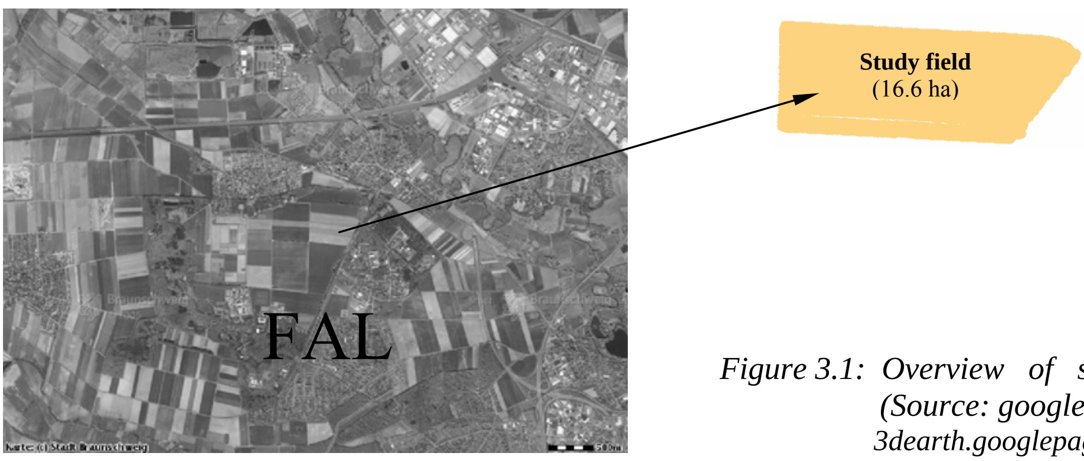


Figure 3.1: Overview of site location (Source: google-earth, http:// 3dearth.googlepages.com)

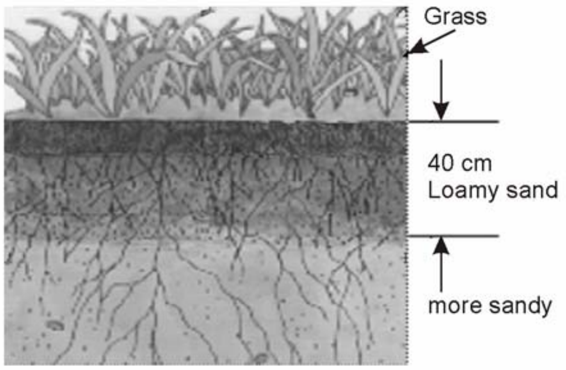


Figure 3.2: Soil profile of the field (Source: www.google.de/search?hl=de&q=soil+profile&meta)

Table 3.1: Description of the soil parameters at the experimental site in Braunschweig (Salac, 2005)

Soil parameters	**Top soil** (0-30 cm)	**Sub soil** (30-60 cm)
pH	5.5	4.8
Organic matter [%]	1.4	0.7
Clay [%]	6.3	5.4
Silt [%]	46.7	47.2
Sand [%]	47	47.5

Table 3.2: Weather conditions during the measuring period in Braunschweig (Source: Deutscher Wetterdienst, www.dwd.de)

Feature	**average from 1961 to 1990**				**2006**			
	May	June	July	August	May	June	July	August
Precipitation [mm]	58	74	58	66	55	52	16	103
Temperature [° C]	12.7	15.8	17.1	17	13.6	16.9	22.6	16.3
Potential evapotranspiration [mm/month]	78	81	84	88	133	152	210	100

3.1.2 ECa sensors and response curves

The two ECa sensors used in this study were the VERIS Model 3100 sensor (VERIS Technologies, Salina, Kansas – www.veristech.com) (Figure 3.3) and the EM38 (manufactured by Geonics Limited of Mississauga, Ontario, Canada – www. geonics.com) (Figure 3.4). ECa data were collected under field capacity soil moisture conditions determined based on the AMBAV climatic water balance model of the German Weather Service (DWD) station. ECa data were collected using each of the two operating modes of each of the two sensors.

The VERIS 3100 and EM38 readings were taken in 1-s intervals corresponding to a 2 to 3 m data spacing on transects spaced approximately 4 to 6 m apart. EM38 and VERIS 3100 measure soil conductivity while being pulled through a field (upper photos in Figures 3.3 and 3.4) in a grid like pattern. The ECa measurement from the EM38 vertical dipole mode was averaged over a lateral area approximately equal to the measurement depth (McNeill, 1992). The EM38 is a lightweight bar approximately 1 m long and includes calibration controls and a digital redout of

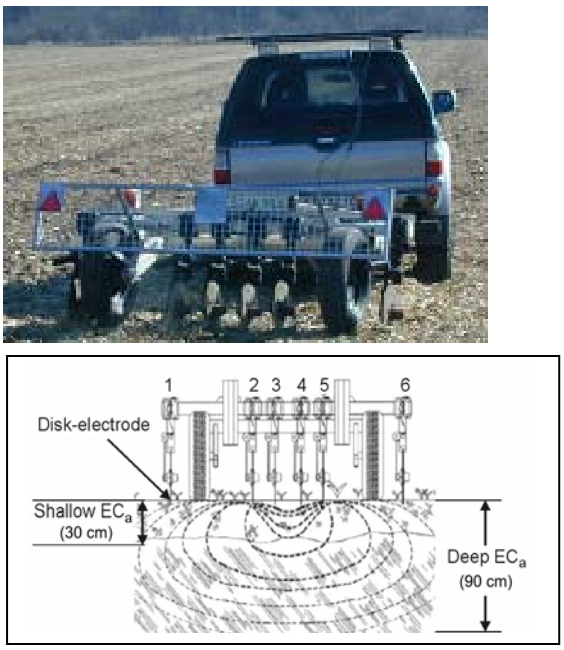


Figure 3.3: VERIS 3100 coulter-based apparent data collection soil electrical conductivity sensor (Source: USDa-ARS water unit, Ft.Collins,CO, www.ars.usda.gov/main /docs.htm?docid =3257). Upper photo is showing VERIS 3100 while being pulled through study field

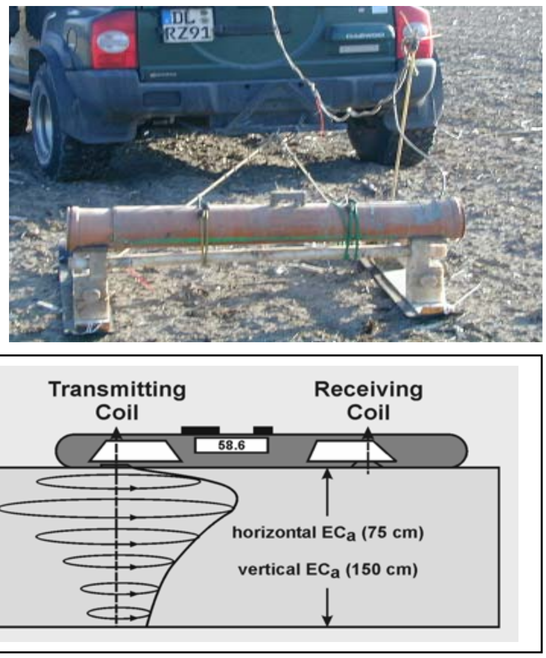


Figure 3.4: EM38 apparent soil electrical conductivity system (Source: USDA-ARS-gallery, Columbia, MO, www. ars. usda. gov/mwa/columbia/cswa). Upper photo is showing EM38 while while being pulled through study field

ECa in milliSiemens per meter [mS/m]. An analog output port was provided to allow data to be recorded on a computer. Data obtained from a Differential Global Position System (DGPS) receiver were integrated with the EM38 data to provide the coordinates of each measurement point with an accuracy in the range of 1-2 m. The theoretical instrument response to soil conductivity varies as a non linear function of depth, as given by Equation 3.1 (McNeill, 1980).

$$R_{em} = 4Z(4Z^2+1)^{3/2} \tag{3.1}$$

Where R_{em} is the relative response of EM38 and Z the distance from the sensor [mm]. Sensitivity in the vertical mode is highest at about 0.4 m below the instrument (Figure 3.4) and sensitivity in the horizontal mode is highest at the instrument (soil surface). The ECa measurement is an integrated response to changes in soil conductivity with depth, as weighted by this instrument response function (McNeill, 1992). The EM38 has an intercoil spacing of 1.0 m with a nominal depth of investigation, defined as the depth to which approximately 70 % of the measured response is generated, of 1.50 m when operated in the vertical dipole mode (EM38_h) and 0.75 m when operated in the horizontal dipole mode (EM38_v) (Mc-Neill 1980). The vertical dipole mode response is less sensitive to near surface material (< ~0.40-m depth) than the horizontal dipole response and more sensitive to deeper material.

In VERIS 3100 measurements, electrodes were configured to provide both shallow and deep readings of ECa. The VERIS 3100 identifies soil variability by means of resistivity metering, which involves applying a voltage into the ground through metal electrodes and measuring the resistance to the flow of the electric current. As the VERIS 3100 is pulled through the field, a pair of coulter electrodes transmits an electrical current into the soil, while two other pairs of coulter electrodes measure the voltage drop. Soil ECa information was recorded in a data logger along with location information. A DGPS transmitted the location information to the data logger. The system georeferences the conductivity measurements using an external DGPS receiver and stores the resulting data in a digital form. The VERIS 3100 records data in 1s intervals and data density can be modified by the operator through changes in travel speed and/or spacing between measurement transects. VERIS 3100 consisted of six aligned rotating coulters on a tool bar (Figure 3.3). Coulters 2 and 5 introduce an alternating current into the soil; the other four coulters measure voltage drop as the current passes through the soil. The voltage drops and the current are used to calculate electrical conductance (i.e., resistance -1) using Ohm's Law. Conductance is multiplied by a geometrical factor to obtain conductivity. The geometrical factor is a function of the electrode spacing and takes soil depth into account. Because the outside coulters (1 and 6) were spaced farther apart than the inside coulters (3 and 4) from the coulters from which the current emanates (2 and 5), the current passing to the two coulters on the outer side passes through a deeper profile of soil. Also VERIS 3100 consisted of a sender and a receiver (Figure 3.3) so that voltage drops and current were used to calculate electrical conductance (i.e., resistance -1) using Ohm's Law. As with the EM38, the VERIS 3100 response to soil conductivity varies as a nonlinear function of depth. The electrodes of the VERIS 3100 are configured in a Wenner array, an arrangement commonly used for geophysical surveys (Milsom, 1996). The theoretical response of the Wenner array is given by Equation 3.2 (Roy and Apparao, 1971).

$$R_W = \left(\frac{8LZ}{3}\right)\left(\left(\frac{L^2}{9} + 4Z^2\right)^{-3/2} - \left(\frac{4L^2}{9} + 4Z^2\right)^{-3/2}\right) \quad (3.2)$$

Where Rw is the relative response of the Wenner array, L the distance between the outermost electrodes [mm] and z is the distance from the sensor [m]. For the VERIS 3100 shallow reading, the value of L in Equation 3.2 is 0.7 m; for the deep reading it is 2.2 m. The graph of these responses shows them to be similar in shape to the response of the EM38, although the two VERIS 3100 responses reach a maximum nearer the soil surface and then decrease more rapidly with depth (Figure 3.5 and 3.6). Integrating the Equations 3.1 and 3.2 with respect to depth clearly shows the different soil volumes examined by the sensors (Figure 3.6). The EM38 was mounted on a PVC beam to avoid the strong response of the EM38 to metallic objects within approximately 1 m. In this configuration, the EM38 was suspended approximately 30 cm above the ground surface during data collection. Therefore, the EM38 curves are situated 30 cm above the ground as shown in Figure 3.7 (Personal communication Dr. Domsch, 2007). With the VERIS 3100_sh, VERIS 3100_dp, EM38_v and EM38_h measurements, 90 % of the response is obtained from the top 0.30 m, 0.91 m, 5 m and 2.2 m of the soil respectively. By integrating Equation 3.1, it can be shown that 90 % of the EM38 vertical response is obtained at depths of less than approximately 5 m. The response curves of Figures 3.5 and 3.6 are based on equations that assume a homogeneous soil volume. Actual weighting functions will vary somewhat due to ECa differences among soil layers, with a highly conductive surface layer reducing response depth (Barker, 1989).

The soil temperature correction of ECa values is essential (McKenzie et al. 1989), requiring the ECa to be standardized to allow a comparison between values monitored at different times. Soil temperature was measured using thermistors at different depths based at the DWD which was located 400 m south of the study site. Apparent electrical conductivity measurements were standardized to 25° C using average correction factors derived from the two equations here under:

$$EC_{25} = ECa(0.4779+1.3801\times EXP(-T/25.654)) \quad \text{(Anonymous, 1954)} \quad (3.3)$$

$$EC_{25} = ECa(0.44633+1.4056\times EXP(-T/26.761)) \quad \text{(Eijkelkamp, 2003)} \quad (3.4)$$

where EC_{25} = ECa standardized to 25° C; and T [°C] = average temperature over a given depth interval. The average temperatures in the top 0.45, 1.20, 0.30 and 0.90 m were used to calculate temperature-standardized EM38_h, EM38_v, VERIS 3100_sh and VERIS 3100_dp readings, respectively (EM38 was applied about 30 cm as suspended above the ground surface).

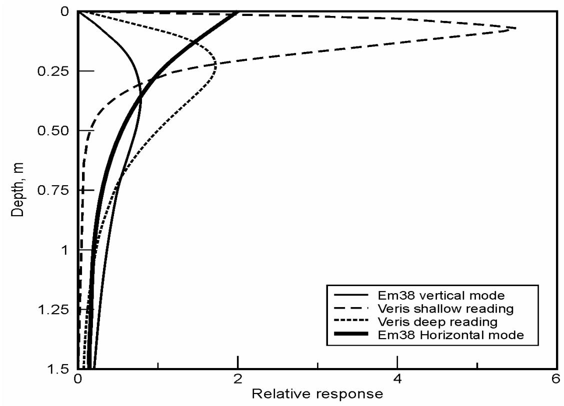


Figure 3.5: Relative response of ECa sensors as a function of depth. Responses are normalized to yield in a unit area under each curve (McNeill, 1992 and 1980)

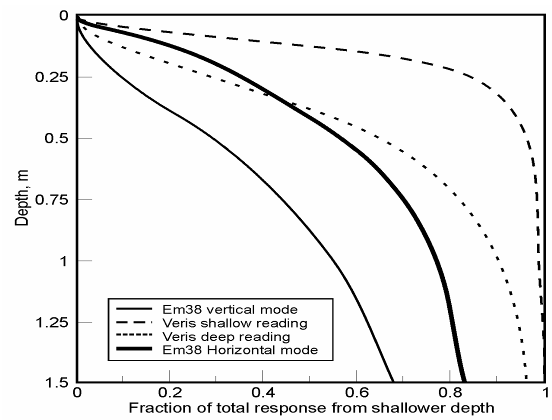


Figure 3.6: Cumulative response of ECa sensors as a function of depth (McNeil, 1992 and 1980)

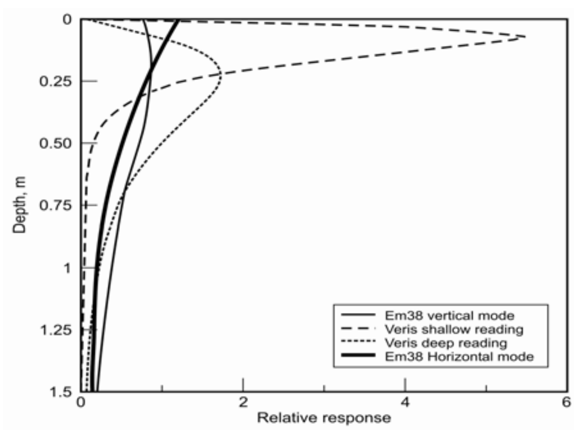


Figure 3.7: Modified relative response of an EM38 sensor as a function of depth. EM38 was 30 cm suspended above the ground (Source: McNeill, 1992 and 1980)

3.1.3 How to create a TAWC map

There are different software programs available on the market that can create maps from datapoint files such as Surfer (GoldenSoftware, Inc.), ArcView (ESRI) and Global Mapper (Global Mapper). An ArcView (ESRI) software program was used to create the ECa and TAWC maps after the readings were logged to a laptop data logger and interpolated using a spherical kriging model. The word "kriging" is synonymous with "optimal prediction". It is a method of interpolation which predicts unknown values based on data observed at known locations. This method uses a variogram to express spatial variation and it minimizes the error of predicted values which are estimated using the spatial distribution of the predicted values.

3.1.4 Soil sampling

Soil sampling was carried out to develop field-specific relationships, calculate the coefficient of determination (R^2) between ECa data and TAWC and to determine the best sensor-based method to monitor TAWC. Twenty-nine monitoring points were located using DGPS (Figure 3.8 a) based on the ECa spatial variability pattern and considering the coverage of the whole range of ECa values present. At each calibration point, an auger boring or a soil sampling machine (Figure 3.8 b,c) were used to take soil samples in 30-cm increments to a depth of 60 cm (common irrigation depth) avoiding the fluctuations of the transition zone in between both layers. Air dried samples were crushed and sieved through a 2 mm sieve and then the water contents at F.C. and P.W.P. were measured three times using a gravimetric method for P.W.P. and a pressure plate (ceramic) method at 1500 kPa for F.C.. In addition, the available data on bulk density at the FAL (ρb = 1.42 [gr/cm^3] was used to calculate the volumetric soil water content.

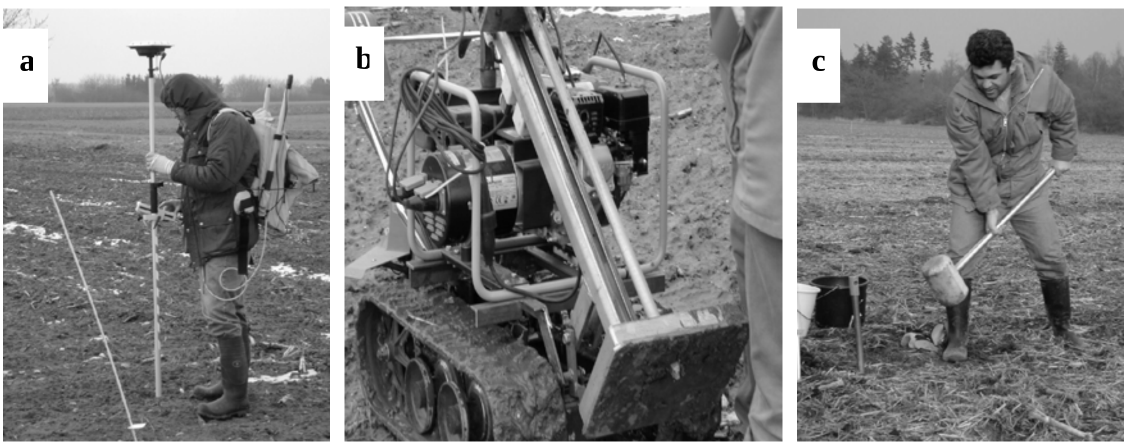


Figure 3.8: a) Locating the sampling point using DGPS, b) Soil sampling by machine and c) Soil sampling by auger

3.1.5 Determination of the optimum number of irrigation management zones

The purpose of this study was the determination of the optimal number of TAWC zones (IMZs). However, where spatial variation is gradual instead of abrupt, disjoint classes poorly match the reality to be described. Therefore an approach with fuzzy classes seems more appropriate. One approach to fuzzy classification, is fuzzy-c-means (Bezdek, 1981), or fuzzy-k-means (De Gruijter & McBratney, 1988). Ideally, the classification system is designed in such a way that it provides an optimal basis for spatial interpolation as well as the prediction of proper ties from class memberships. In this case, FuzMe, a PC Windows program, was used to calculate Fuzzy-k-means with/without extragrades. Fuzzy-k-means minimises the functional within-class sum square errors. It is written in Fortran and compiled using Visual Fortran 6.6 under a PC Windows environment. The program needs a "control file" which details the parameters for the fuzzy-k-means algorithm and a "data file" containing the data. The program works only on a system running under Windows 95/ NT or later. The FuzME interface is a Visual Basic program that helps to create the "control file" and runs the program.

Boydell and McBratney (1999) discuss the use of the fuzziness performance index (FPI) and modified partition entropy (MPE) as measures of cluster performance. The optimum number of classes is established on the basis of minimising these two measures. The FPI is a measure of the degree to which different classes share membership and is limited to values between 0 and 1. As FPI approaches 1, membership sharing increases. As the FPI approaches 0, classes become more distinct with less membership sharing. At a value of 0, classes are no longer fuzzy, but are considered crisp. The MPE is an estimate of the amount of disorganization created by a specified number of classes. Like the FPI, it is also limited to values between 0 and 1. As MPE approaches 1, disorganization predominates while values approaching 0 indicate excellent organization.

3.2 Performance and evaluation of remote real-time and site-specific distributed irrigation control system

The structure of the remote real-time site-specific DIC and monitoring system is shown in Figure 3.9. The performance of site-specific irrigation is divided into six parts:

a) Soil moisture monitoring methods
b) Irrigation scheduling
c) Field tests related to soil moisture monitoring
d) Irrigation system and its modification
e) Calculation of the number of emitters installed on the drop tubes and length of drop tubes
f) Evaluation of emitter performance (laboratory experiments and field tests)

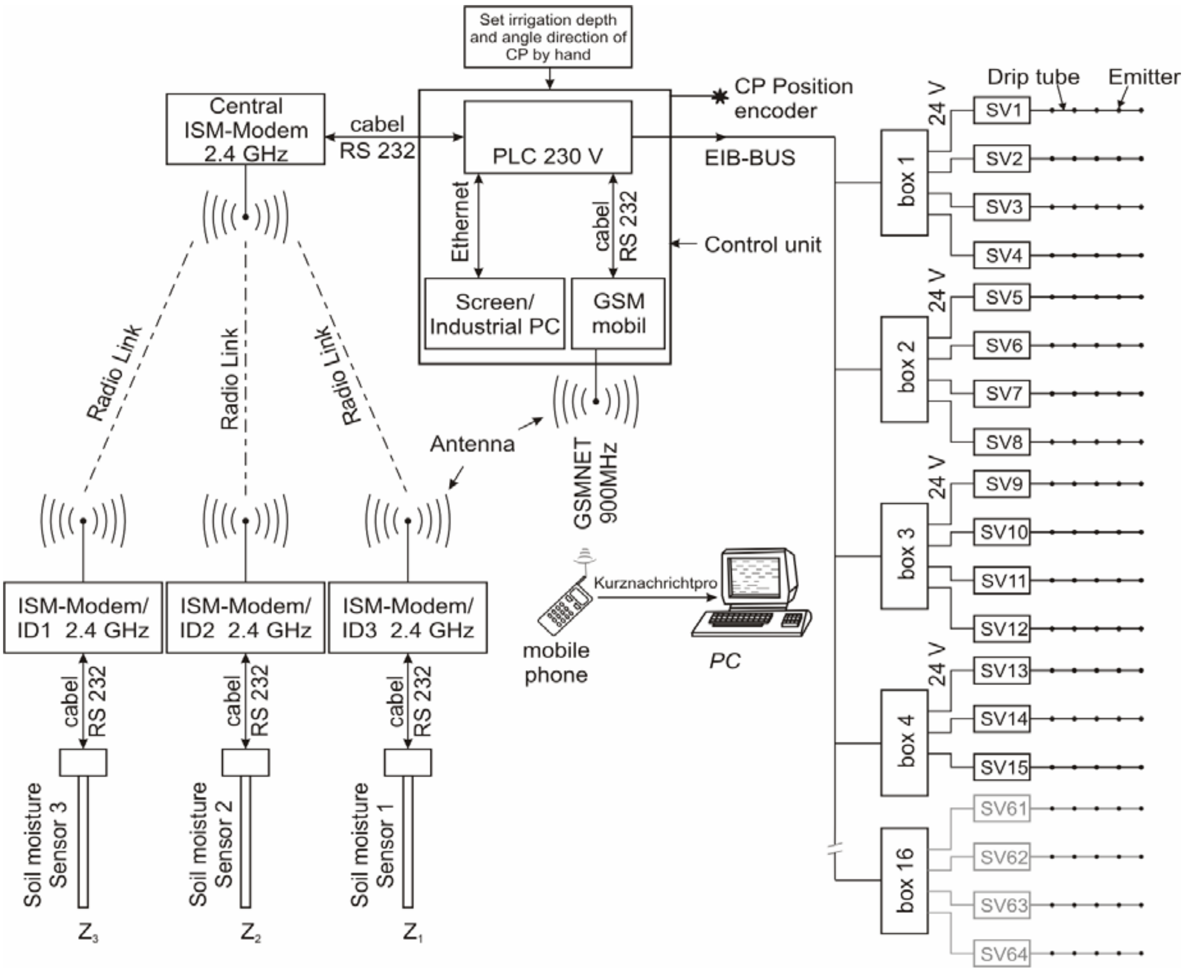


Figure 3.9: Structure of remote real-time site-specific distributed irrigation control and monitoring system

3.2.1 Soil moisture monitoring methods

To determine irrigation depth within IMZs, a) an "EnviroSCAN" soil moisture sensor (www.sentek.com.au) was used to monitor soil moisture within zones which are located inside the sensor-quarter under the 2nd CP segment at angles between 90° to 180° and b) the AMBAV CWB-model was used as an irrigation simulation model to monitor soil moisture within zones which are located in another quarter of the field (CWB model-quarter) under the 2nd CP segment at angles between 180° to 270°. A schematic overview of the experiment is shown in Figure 3.10.

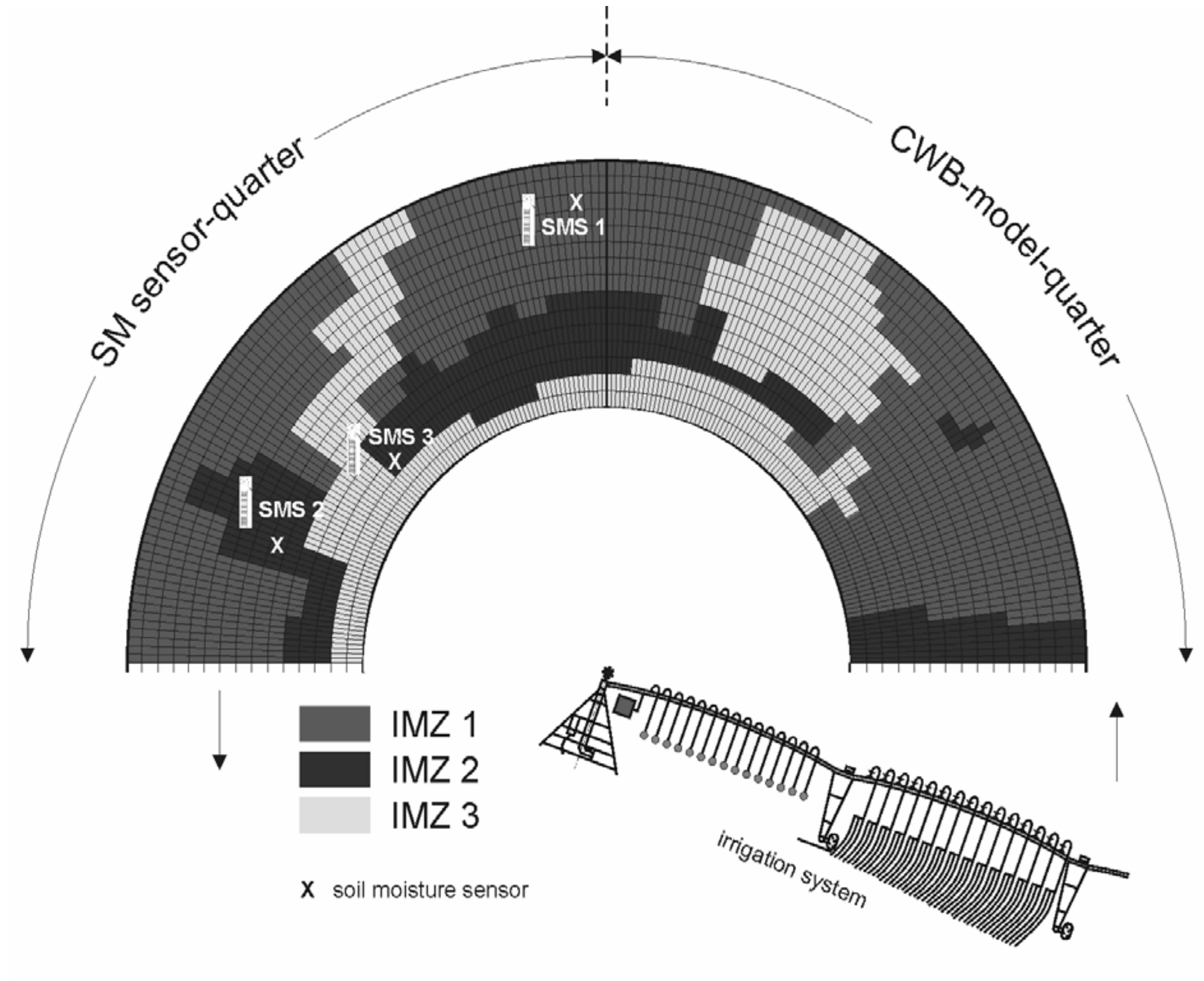


Figure 3.10: Schematic overview of an irrigation plan containing three artificial IMZs, sensor-quarter, CWB-quarter and modified CP

3.2.1.1 Wireless EnviroSCAN soil moisture sensor

Newly developed sensors including the EnviroSCAN capacitance system have the potential to estimate the soil moisture content continuously at various depths. Sentek's inaugural product, EnviroSCAN, developed in Australia, is a complete and stand-alone continuously working soil water monitoring solution over multiple depths in a crop root zone, which determines how often and how much to irrigate. It works based on the capacitance principle, and utilizes Frequency Domain Reflectometry (FDR) to measure soil water (Figure 3.11). In other words, a high frequency electrical field, created around each sensor, extends through the access tube into the soil and then it measures the change in capacitance of the soil depending on the moisture level, as there is a large difference in the dielectric constant of soil, air and water. The EnviroSCAN measures the change in frequency response of the soil's capacitance due to its soil moisture status at each sensor as frequently as every minute. The probes have multiple sensors located at multiple depths (with flexible depth placement in 10 cm intervals), with each probe accommodating up to 16 sensors. Soil water content is determined by the EnviroSCAN capacitance sensor by means of a scaled count (Buss, 1993). Counts were recorded for each sensor inside an access tube suspended in the air. A second set of counts was recorded for each sensor inside a sealed access tube that had been submerged into a container of water. This was done to determine the full scale of counts between no water (air) and 100 % water (Buss, 1993). The scaled count for a given sensor can be thought as a percentage of full scale where the difference between air count (no water) and the measurement count is divided by the full scale of counts for the sensor.

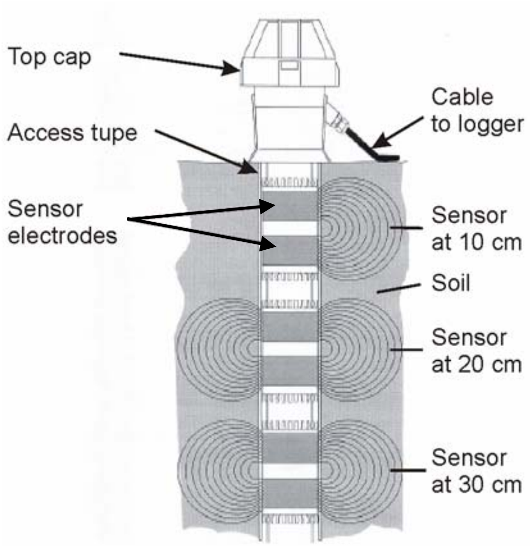


Figure 3.11: EnviroSCAN probe design (Source: www.sentek.com)

The EnviroSCAN software interpolates the frequency readings from the data logger and displays the dynamics of soil water content through time. The following equation described by Buss (1993) was used to convert field frequencies into scaled frequencies, SF:

$$\text{Scaled Frequency (SF)} = \frac{\text{air frequency - field frequency}}{\text{air frequency - water frequency}} \tag{3.5}$$

The default manufacturer's equation (uncalibrated equation) that converts scaled frequency to volumetric water content is:

$$SF = A\theta_v^B + C \tag{3.6}$$

where A is 0.1957, B is 0.404 and C is 0.028520 and θv is the soil water content by volume. Equation 2 can also be written in terms of volumetric water content as:

$$\theta_v = \left[\frac{SF - C}{A}\right]^{1/B} \tag{3.7}$$

The calibration equation used in the software of the EnviroSCAN system is deemed "universal." It is shipped to the user with a default (uncalibrated) equation. Since the soil types determined by sampling the soil around the tubes in order to determine the volumetric water content in wet, moist and dry soil show significant variability, there is some evidence that the equation is not universal. Meanwhile there is concern about the influence of soil salinity and soil temperature on the sensor readings. Thus, if the uncalibrated equations are used to determine the amount and time of irrigation for crops, there is a strong likelihood that the underestimation or overestimation can seriously impact crop yields. However, EnviroSCAN sensors do not automatically produce an accurate estimate of individual soil water content measurements for all soils. Therefore a simple soil calibration of these sensors was done to obtain accurate soil water content. Leib et al. (2003), Fares et al. (2004) and Jabro et al. (2005) found that site-specific calibration of the EnviroSCAN sensor is essential for the most precise soil moisture content measurements as well as for the improvement of the sensor's accuracy and performance because statistical analysis showed considerable discrepancies between soil water contents estimated by site-calibration and uncalibrated equations.

Sensor data transmission: Instrumentation and control standards for the RS232 serial communication protocol has been widely applied and is well documented for the integration of sensors and actuators. The RS232 serial communication protocol was used for communication between EnviroSCAN soil moisture sensors and the ISM-modem, between the central ISM-modem and PLC, and also between the Programmable Logic Control (PLC) and the GSM-mobile phone to transmit soil moisture data by a cable (Figure 3.12). In this study, the RS232 communication protocol was used because of its simplicity and because it is free of charge. Technical specification of 12 volts voltage supply and a 9600 bits per second interface baud rate were used for the soil moisture sensor.

Every ISM-modem had a specific ID number related to every IMZ. Thus, they can not be relocated between zones, but the EnviroSCAN soil moisture sensor did not have any ID and could be relocated between zones. It had a 12 V and 7.2 Ah battery that all 7.2 Ah was useable. The battery was self-recharged by a 24×40.5 cm [972 cm^2] solar panel providing up to approximately 13.7 V (Figure 3.12) with a minimum operation voltage of about 11.2 V. Given the power requirements of 70 to 90 mA, the ISM-modem was able to operate about 3 days from March to October depending on the weather conditions.

The wireless standard used in this study was determined by the major factors of the maximum distance between the soil moisture sensor and the control unit [400 m], data rate transfer (bit/sec) which depends on the number of soil moisture data readings per day needed for this study, compatibility and cost. Based on all factors of our application, a specific 2.4 GHz band of an 8N1

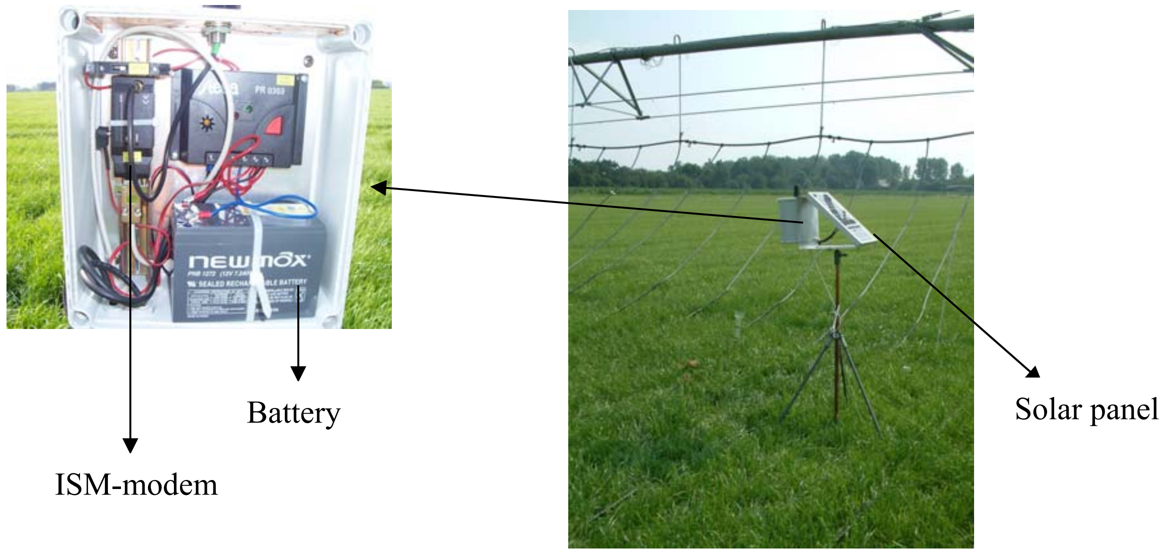


Figure 3.12: Data transmission unit with a solar energy supply

wireless serial protocol that is free and capable of transferring soil moisture data up to 300 m range was selected for wireless data communication from the in-field soil moisture sensing stations to a central unit. The maximum data transfer rate of the 8N1 serial over a distance of a 400 m is 2400 bit/sec. An 8N1 serial was used to transfer soil moisture data from an ISM-modem connected to the soil moisture sensor to a central ISM-modem placed inside a central control unit (about 3 m from pivot point). With due attention to the dimensions of the field under CP, which was 400 m length, a transfer capacity of up to 400 m was needed. In this study, transfer capacity was increased from 300 m to 450 by using two specific antennas with a) an end-fed ½ wave coaxial dipole, model 242451, 1 m tall with 2310-2485 MHz frequency and 175 MHz bandwidth from VIMCOM AG, (www.vimcom.ch) that was installed on the CP and a near position encoder at a height of 5 m and b) a MOBILE MARK model RMM-UMB, BroadBand US Cellular & EU GSM 3 dBi & 750-1250 MHz that was installed on ISM-modem boxes. Three ISM-modems were installed within three IMZ and located about 40, 60 and 90 m away from the central ISM-modem. Under these conditions, soil moisture data were transmitted using a cable and a RS232 communication protocol from the EnviroSCAN sensor to an ISM-modem and from the central ISM-modem to a PLC installed on a CP irrigation system. Soil moisture readings were transmitted to the PLC every 4 minutes. Soil moisture data were also automatically transmitted from the PLC to a mobile phone via the GSM-Net (900 MHz) at 00:00 o'clock every day. Whenever there was no automatically connection to the soil moisture sensor at 00:00 hours, incorrect data was received on the mobile phone as 200.00. In this case, a new SMS from the mobile phone was sent to PLC. Then moisture data were transferred from mobile phone to the computer and exported to an Excel table using the “Kurznachricht Pro 2.2” software (Schmidt, 2003) installed on the office computer. With due attention to the fact that soil moisture data on a mobile phone or in an Excel table can not be readily accessible and useful to the non-professional farmer. Excel data were used to calculate irrigation depth and graphically present its variation by writing a simple Excel program. Sentek’s user-friendly and powerful IrriMAX 6 software is available from the Sentek company, but it costs about € 465.

3.2.1.2 AMBAV model

The AMBAV CWB_model (Agrarmeteorologisches Modell zur Berechnung der Aktuellen Verdunstung) is part of a complex agro-meteorological toolbox of Deutscher Wetterdienst (DWD) (www.agrowetter.de) that separately calculates soil moisture, potential and actual evapotranspiration, effective precipitation (which is more than 2 mm), interception and the soil water balance in the crop-soil-system under different crop covers. It uses the Penman-Monteith formula and synoptic data from a DWD weather station located 1.4 km to the south of the study site. The model which was used by local meteorological advisory services was designed to produce recommendations for irrigation amounts and scheduling for different soil types based on hourly weather data from the meteorological station network (Löpmeier, 1994; Braden, 1995). Soil water dynamics are simulated using a mechanistic model based on the Richards equation that represents the movement of water in unsaturated soils (Richard, 1931). In this model, different soil textures with different F.C. and P.W.P. and also different plant phenology data including the beginning of the vegetation phase and the sleeping phase are considered. The AMBAV model is validated only for a flat field. Thus, this model cannot be used for uneven fields. The model used includes physical processes like infiltration from rainfall or irrigation, redistribution in the soil water zone, plant water uptake in the form of actual evapotranspiration, and percolation out of the soil reservoir. In addition, the model considers the dynamics of the crop root growth model that affect plant water uptake and hence the soil water in the unsaturated zone. In the AMBAV model, the phenological and morphological development of the plants is considered in the form of:

- the partitioning of the radiation absorbed by the plants and the soil surface,
- the aerodynamic transport from the soil surface and the plants and
- resistance against plant transpiration (bulk stomatal resistance).

For these purposes, plant height, leaf area index and bulk stomatal resistance are generated inside AMBAV model for each crop depending on a certain phenological phase. In this model, the calculations of the water budgets of the different soil layers and the hydrological properties of the corresponding soil are parameterized on the basis of Bodenkundliche Kartieranleitung KA4 (AG Boden, 1994).

3.2.2 Irrigation scheduling

Because of different capacities to absorb water between different IMZs, different IMZs will reach t minimum Management Allowed Depletion (MAD) of TAWC at different times. Moreover, in areas where significant rainfall occurs during the irrigation season, the irrigation strategy may have to be adjusted because of the influence of rainfall. The time and the quantity of rainfall is uncontrollable. The amount of water stored in the soil from any rainfall event will vary from location to location, depending on TAWC. Thus, the amount of "effective precipitation" will vary with TAWC since irrigation only needs to supply the difference between crop water needs and effective precipitation. These implied locally variable water amounts may be desired. In Germany, the influence of rainfall is a significant consideration. Average monthly rainfall on the field used for this study (Federal Agricultural Research Centre, FAL, Braunschweig, Germany) in May, June, July and August (irrigation season) is shown in Table 3.2 (P. 46). However irrigation was scheduled based on:

a) Maintaining the maximum and minimum acceptable MAD of the soil water content of three zones. Given no water stress during the growing season and 20 % free capacity to absorb probable rainfall at the study site after irrigation, the minimum and maximum MAD are considered based on Tables 2.1 and 2.2. Moreover, minimum and maximum considered MAD for grass which is planted on the study field match with those found by Rhoads et al. (2000) and Wilamowitz Moellendorff et al. (1985).
b) Limitation of the increase in drop tube length because the length of the drop tube will grow as irrigation depth increases.
c) Watering the grass root zone up to a depth of 60 cm.

Whenever soil moisture measured by sampling indicates the 60 % of TAWC within one of the IMZs, irrigation of all in zones was started (Figure 3.13). In this case, it was expected that IMZ with minimum TAWC will meet 60 % of its TAWC earlier than others IMZs.

3.2.3 Field tests related to soil moisture monitoring

Field tests related to soil moisture monitoring included a) evaluation and soil-specific calibration of the EnviroSCAN sensor, b) field tests of data transmission and power supply of EnviroSCAN soil moisture sensor and c) the validation of the AMBAV model.

3.2.3.1 Evaluation and soil-specific calibration of the EnviroSCAN soil moisture sensor

The installation technique is critical to the performance of devices that use the capacitance technique. Therefore the equipment and techniques developed by the manufacturers of EnviroSCAN that are claimed to eliminate this problem were used.

If care is taken in the installation of the access tubes and the sensors are carefully calibrated and sealed inside the access tube, these potential problems become insignificant (Paltineanu and Starr, 1997). Moreover, the calibration equation used in the software of the EnviroSCAN system is deemed "universal". The system is shipped with a default (uncalibrated) equation to the user. Due to the large variability in soil types found in samples from the soil around the tubes, which were taken in order to determine the volumetric water content in wet, moist and dry soil, there is some evidence that this is not so. In addition, there is concern about the influence of soil salinity and soil temperature on the sensor readings. Thus, if the uncalibrated equations are used to determine the amount and time of irrigation for crops, there is a strong likelihood that the underestimation or overestimation can seriously impact crop yields. However, EnviroSCAN sensors do not automatically produce an accurate estimate of individual soil water content measurements for all soils. Therefore a simple soil calibration of these sensors is required to obtain accurate soil water content. Leib et al. (2003), Fares et al. (2004) and Jabro et al. (2005) found that the site-specific calibration of the EnviroSCAN sensor is essential for the most precise soil moisture content measurements as well as to improve the sensor’s accuracy and performance, because statistical analysis supported considerable discrepancies between soil water contents estimated by the site-calibration and uncalibrated equations. Meanwhile, the software provided with the EnviroSCAN allows the users to enter their own calibration constants/equations.

Soil moisture and its variation within IMZs were measured daily by the EnviroSCAN sensor, and soil samples were taken during the irrigation season for soil-specific calibration and the evaluation of the possibility of using EnviroSCAN sensor as a continuous, multiple depth and reliable method. In this study, soil moisture sensors were located at multiple depths of 10, 20, 30, 50 and 70 cm as shown in the Figure 3.11. The sensors were connected by cable to an ISM-modem, which powers the probes with a solar panel. All sensors in the same access tube shared one electronic measuring circuit, located at the top of each tube. Three EnviroSCAN soil moisture sensors were placed in three IMZs where the locational coordinates of soil moisture sensors (number of solenoid valve, angle) were (8,108 °), (3,127 °) and (13,176 °) as shown in Figure 3.10. Care has to be taken during installation as air gaps can dramatically alter the response. The sensor installation process and operational procedures were carried out according to the manufacturer`s recommendations and instructions (Sentek, 1995; www.sentek.com.au). Soil moisture data at different depths were received on a mobile phone by sending an SMS-message to PLC.

Field evaluation and soil-specific calibration of EnviroSCAN were done at the study site by taking soil samples (as shown in Figure 3.13) and calculating the water contents by mass. Then water contents by mass were converted to volumetric values using soil bulk density values available at the FAL (ρb = 1.42 gr/cm3). Two replications of soil samples were taken at the multiple layers of 0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 40 to 50 cm and 60 to 70 cm. The distance between the EnviroSCAN access tube and the auger sampling points was between 1 and 2 m. Immediately after the soil samples had been e talen, the EnviroSCAN readings were done by sending a mobile-SMS to the control unit and receiving a text message from PLC on mobile phone. Given the nearly uniform soil texture at depths of 0 to 40 cm and 40 to 70 cm at the study site as shown in Figure 3.2, it was decided to find two soil-specific calibration equations for these two layers.

Figure 3.13: Soil sampling for irrigation scheduling and soil-specific calibration of the EnviroSCAN soil moisture sensor

3.2.3.2 The field tests of data transmission and power supply

Wireless communication was tested for different distances between the data transmission unit and the central ISM-modem, such as 100, 200, 300, 350 and 400 m. Given battery voltage dissipation, the minimum battery operation voltage needed to start battery recharging and to ensure that the the solar panel is large enough for the self-recharge of the batteries, battery voltage was measured daily.

3.2.3.3 Validation of the AMBAV model

Obtaining soil moisture information through field practice like soil sampling and using soil moisture sensors is time-consumin, difficult and expensive. Also the validation of soil water balance models and the evaluation of the quality of the model predictions at field-scale and in the active root zone of grass require time-series of in situ measured model outputs. In this case, the validation of the AMBAV CWB_model as a cheap and reliable method to measure the soil moisture content was evaluated by comparing the soil moisture simulated by the AMBAV model with the moisture of soil samples (observed data) which were taken during the measuring period. In order to validate the model, comparisons were made between the simulated and observed values and three statistical tests were performed. These tests are the coefficient of determination (R^2), Mean Absolute Relative Error (MARE) and prediction efficiency (PE) index. The index MARE is computed as:

$$MARE = \left\{ \sum_{i=1}^{N} \frac{(SWC_{i,observed} - SWC_{i,simulated})}{SWC_{i,observed}} \right\} / N \qquad (3.8)$$

Where SWCi, observed and SWCi, simulated are the observed and simulated soil water content in the active root zone of crops on i^{th} time, i the index of the time that is taken as one time in the study and N is the total number of times for which observations are taken. The index PE is computed as:

$$PE = 1 - \left\{ \sum_{i=1}^{N} \frac{(SWC_{i,observed} - SWC_{i,simulated})^2}{(SWC_{i,observed} - SWC_{\underline{observed}})^2} \right\} \qquad (3.9)$$

Where SWC observed is the arithmetic mean of the individual observations of SWC in the active root zone of the crop.

3.2.4 Irrigation system and its modification

A two-span and commercial centre pivot system with an overhang, located at the FAL research field and with a total length of 90 m was used to irrigate an area of 2.54 ha during summer 2006 (Figure 3.10). The irrigation system could be operated in forward or in reverse, with and without applying water, which is pumped from an underlying network. The pressure at the pivot was regulated to 220 kPa. The first step taken was the modification of this present commercial system to a site-specific or Precision Mobile Drip Irrigation (PMDI) system by making some modifications. With due attention to the effect of CP speed on the water application rate, linear CP speed at end of 2nd span that is appropriate to the CP speed stated in percent on the CP control box was measured to calculate an increase and a decrease in the water application rate with CP speed.

The irrigation system had to be modified so that the desired water level could be applied to IMZ (Camp et al., 1998). The basic requirements established for the modified water application system are that the system must apply water depths needed to replace crop evapotranspiration, while it was being moved, to the management zones with different TAWC, based on data stored in a database. The variable-rate application system would be achieved by modifying this commercial centre pivot irrigation system equipped with a computer-aided management system.

A variable rate MDI system was designed and installed on an existing 38-m 2nd CP span. The VRI system used the pulse technique described by Perry et al, (2003) by solenoid valve to apply the desired water application rate. Irrigation system modification was divided into six parts as:

- *Programmable Logic Control (PLC)*
- *Position Encoder*
- *Solenoid valves (SV)*
- *Irrigation segments and drop tubes*
- *Calculating number of emitters required on the drop tubes and length of drop tubes*
- *Evaluation of emitter performance*

3.2.4.1 Programmable logic control

The 2nd span of CP was controlled by the pulsing technique using PLC and SV as DIC by EIB-BUS (Europäischer Installationsbus) for variable-rate water application. EIB-BUS is a free-cost and simple communication protocol that can control many SV together with one cable. All electrical output devices including SV, position encoder, etc., were controlled by a prototype PLC and EIB-Bus communication which were developed by Büro für Steuerungstechnik und

Schaltanlagen (www.schudzich.de). The control unit was mounted on the CP about 3 m from pivot point (Figure 3.9). PLC was programmed to control 64 SV including 16 boxes (every box to control 4 SV). But in this study only four boxes installed on 2nd CP span including fifteen SV were used. The integrative PLC had an on-board PC as data logger, which can read a saved data file and allows changes in the system information and can convert the map of control to on/off setting in the directly-addressable solenoid control registers of the PLC. The main features and flowchart of this PLC are shown in Figure 3.14. When the location had been determined and a zone boundary was crossed, the program checked the expected application map, the appropriate table lookup was performed and the solenoid registers set accordingly. The application rate was varied by different SV pulsing levels from 0 to 100 % of 100 seconds intervals as inserting and removing the pin provided a time-averaged application rate ranging from about 0 to 100 % of maximum sprinkler flow rate. For example for pulsing level of 70 %, SV were 70 seconds opened and 30 seconds closed (1 second for every 1 % pulsing level).

Field tests of PLC validation and uniformity performance: Tests of water distribution were conducted using catch-cups in the direction of system travel (vertical distribution) and along the length of CP (horizontal distribution) a) to examine and evaluate the validation of the PLC and system modifications, b) to ensure that the pulsing technique produces the desired amount of irrigation under different pulsing levels and c) to examine water uniformity over the entire separate IMZ. This water distribution will be used as the comparison baseline for the evaluation of the effectiveness of the PLC for variable-rate water application. To better visualize a comparison of different pulsing conditions, tests were conducted using a sprinkler (NELSON R3000 rotator, U4-8 °, blue plate) before installing drop tubes and under relatively light wind. Seven pulsing levels and two CP speed levels were considered to test PLC validation. The tests were run while the machine was operating under 15 and 30 % of CP speed and programmed on three different pulsing settings of 10-40-70 %, 30-60-90 % and 100-100-100 % of pulsing levels. Three pulsing levels within each setting were considered for IMZ_1, IMZ_2 and IMZ_3, respectively. Uniformity tests are currently being conducted to ensure that the irrigation system is applying an even distribution of water over the entire span of the CP lateral. In this case average uniformity of horizontal and vertical distribution at different pulsing levels and CP speeds were calculated. Uniformity tests were conducted based on a new ASAE standard (2003), which has been updated, and DIN EN ISO 11545 (2001) using the formula developed by Heermann et al (1992):

$$CU_{HH} = 100\left[1 - \frac{\sum_{i=1}^{n} S_i \left|V_i - \overline{V}_m\right|}{\sum_{i=1}^{n} V_i S_i}\right] \tag{3.10}$$

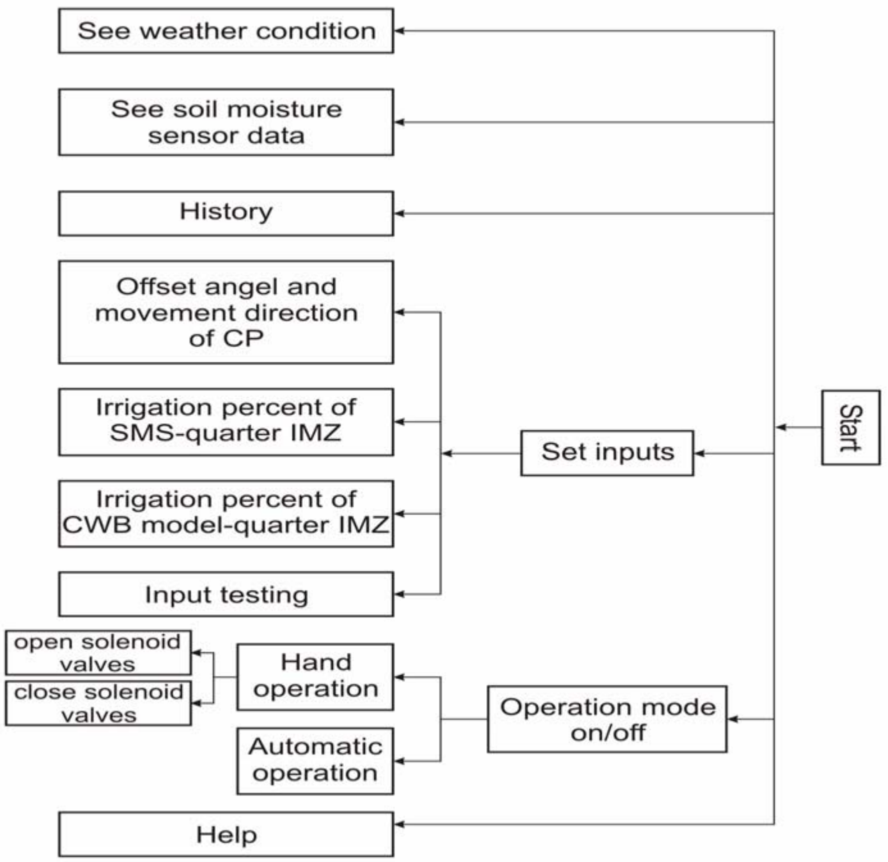


Figure 3.14: Flow-chart of the PLC

where CU_{HH} is the Heermann and Hein uniformity coefficient, n is number of collectors used in data analysis, i is a number assigned to identify a particular collector beginning with i = 1 for the catch cup located nearest to the pivot point and ending with i = n for the most remote catch cup from the pivot point, V_i is the volume (or alternately the mass or depth) of water collected in the i^{th} catch cup; S_i is the distance of the i^{th} catch cup and $\overline{V_m}$ is the weighted average of the volume of water caught by all collectors. The tests were conducted during early morning hours, the wind speed during test time was less than 1.5 m/s and considered to have an insignificant effect on distribution. Water was collected in two horizontal and three vertical rows of 12 catch-cups placed 40 cm from the ground and spaced 1 m between catch-cups with two replications as shown in Figure 3.15. Three catch cup collection arrangements were simultaneously placed on the field as every collection collected water under the different conditions of three zones. Tests were conducted between 90° and 130° where all three IMZ had enough width in both horizontal and vertical distribution.

3.2.4.2 Position encoder

The spatial location of each depth was to be determined based on the system operating parameters: angle of rotation and location along the truss. Target application rates were to be determined from digitised maps stored in a computer file. The location in the field was determined using position encoders from the company HENGSTLER with 12 bit resolution (www.hengstler. de/en/c1002 /Encoder/) by counting the number of teeth, which gives a definite edge in reading the pivot's exact location relative to a 360° circle. The position encoder converts the angular position of a shaft to a digital code. The position encoder was installed at the beginning of the CP mainline and was connected to the control unit (Figure 3.10 and 3.15).

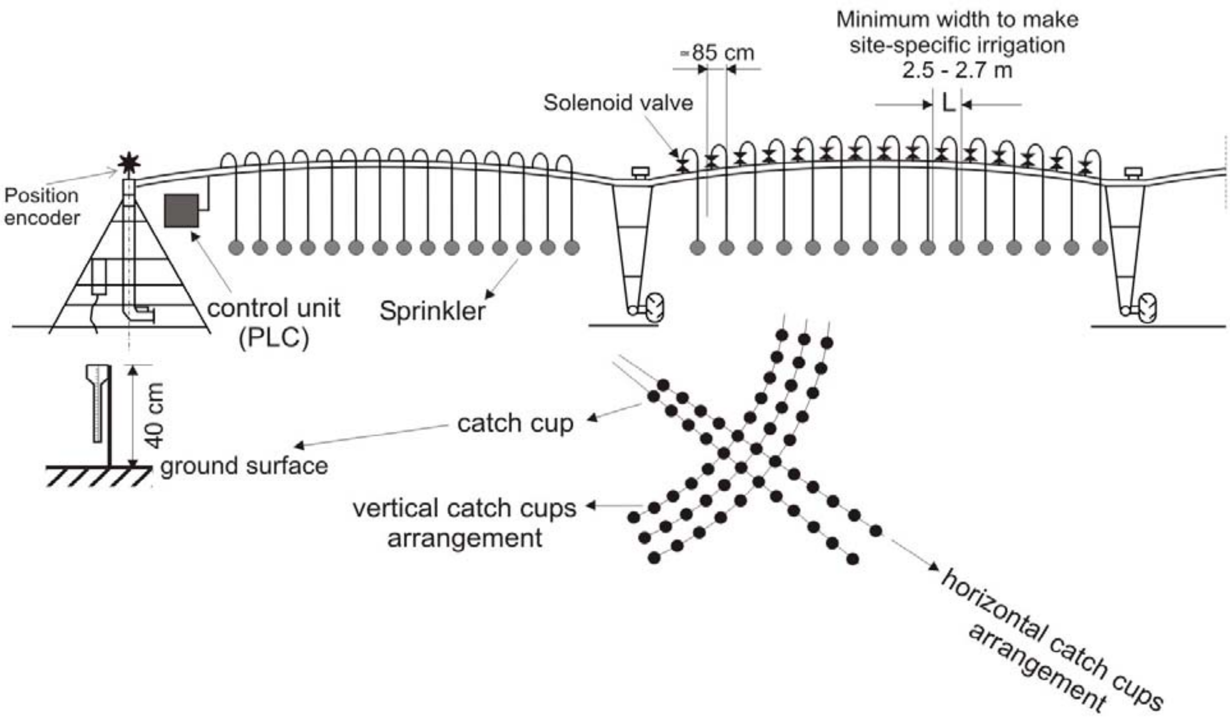


Figure 3.15: Catch-cup arrangement for PLC validation and uniformity test

3.2.4.3 Solenoid valves (SV)

Using valves with minimum pressure loss across the valve will help in minimising the power costs. When valves are subjected to higher discharges, the head loss is independent of diaphragm performance and depends only on the discharge rate and valve construction. In this study, the selection of solenoid valve types was limited because of the necessity to use intelligent and longeval solenoid valves which are appropriate for EIB-BUS communication protocols and allow some of them to be controlled together. Therefore fifteen “Baureihe 82340/82440” solenoid valves, (Figure 3.16) from the Buschjost company (www.buschjost.de) were used and installed at the beginning of each sprinkler vertical tube position subsequently connected to the irrigation segment containing three drop tubes starting from the 2nd span (Figure 3.17). In appendix A, the distance between the solenoid valve and the pivot point and the position of the irrigation blocks supplied by solenoid valves [m] are shown. Solenoid valves were used while pulsing in order to control the depth of water applied along the system radius to each of the individual zones in the system. In this study, every four solenoid valves were wired together in one box by an EIB-Bus communication protocol and connected to the central control box installed 3 m from the pivot point that opened and closed, based on data-base values and the location in the field (using the position encoder).

Valves that are actuated in this way have a combination of direct and indirect actuation. A mechanical coupling between the solenoid core (pilot stage) and the piston (or diaphragm) assists the opening movement of the piston (or diaphragm) that is called forced lifting. “Baureihe 82340/82440” solenoid valves, which were used in this study, are normally open without any electrical energy, and a minimal pressure differential is not necessary with this combined method of operation in order to open the valve and keep it open. This condition causes the valve to be drained of water during the resting position and protected against freezing water in the winter, which is an advantage as compared with other valves.

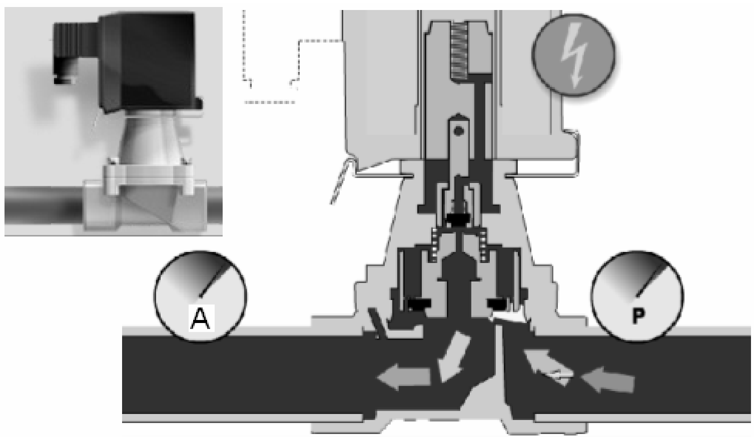


Figure 3.16: Solenoid valves without differential pressure – with forced lifting (Source: www.buschjost.de)

3.2.4.4 Irrigation segments and drop tubes

An MDI system was established by replacing the sprinklers with drop tubes. Because of about 2.5 m spacing between sprinklers installed on the CP mainline (Figures 3.17 and 3.19), the chosen width of the research control element was 2.5 m (LT = 2.5 m). The sprinklers in the 2^{nd} span were replaced by the segments which were subsequently connected to three drop tubes (Figure 3.17).

The 2^{nd} span was located at 39.05 to 77 m from the pivot point. The selection of the 2^{nd} span was based on the recommendation of the American Society of Agricultural and Biological Engineers (ASABE) standards (2001) that inner spans not be tested. This is because they are inherently less uniform due to the limitation of the nozzle size needed to achieve limited flows required in these spans. A pressure regulator (model 0075-PRV produced by NETAFIM - www.netafim.com) was used at the inlet of the drop tubes number 1, 8 and 15 to adapt the operating pressure between 0.5 to 120 kPa. The horizontal PE tube is an additional part that was used for the installation of the drop tubes. In this study, a Mono & Tandem - coextruded type of Siplast drop tube (www.siplast.it) including emitters delivering 15.8 l/h at 120 kPa was used. Moreover, 155 mesh filtration at the pump station was recommended to avoid any clogging. Emitter spacing on drop tubes was 20 cm, while the distance between the drop tubes varied from 76 to 92 cm. Nominal diameter, pipe inside diameter and pipe outside diameter of drop tubes were 20.0, 17.7 and 20.1 mm, respectively.

3.2.4.5 Calculation of the number of emitters installed on the drop tubes (Ne) and the length of the drop tubes

The number of emitters installed on the drop tubes was calculated based on emitter discharge at 120 kPa (q_e = 15.8 l/h), irrigation time (T = 48 h), the maximum irrigation depth required, I_{max}, (that is equal to required irrigation depth at MAD = 55 % for which IMZ has minimum TAWC) and irrigated area covered by drop tubes that was calculated using the distance from the pivot point (r) and narrow spacing covered by the drop tube (dr). Ne was calculated as follows as it was calculated by Chu and Moe (1972):

$$Ne = 2 \times 3.14 \times r \times dr \times (I_{max} / T) / q_e \qquad (3.11)$$

Where:

r = distance between drop tube and pivot point

dr = narrow spacing covered by drop tube

Schematic diagrams of narrow spacing covered by the drop tube located at r meter distance from the pivot point and radios of the area irrigated by the centre pivot (R) are shown in Figure 3.18. With due attention to increasing the water application rate and appearing runoff while decreasing the spacing between emitters as well as increasing the length of the drop tube while increasing the spacing between emitters, an appropriate spacing between emitters should be considered. The length of the drop tubes at any point of the pivot lateral (LT) is dependent upon the number of emitters installed on the drop tube and the spacing between emitters on the drop tube (in this study 20 cm). Thus, LT at any point of the pivot lateral was calculated as follows:

$$LT = Ne \times (0.2) \tag{3.12}$$

Where Ne is number of emitters installed on drop tube. For the connection of the drop tubes to manifolds, a 3 m free emitter tube was used as shown in Figure 3.19.

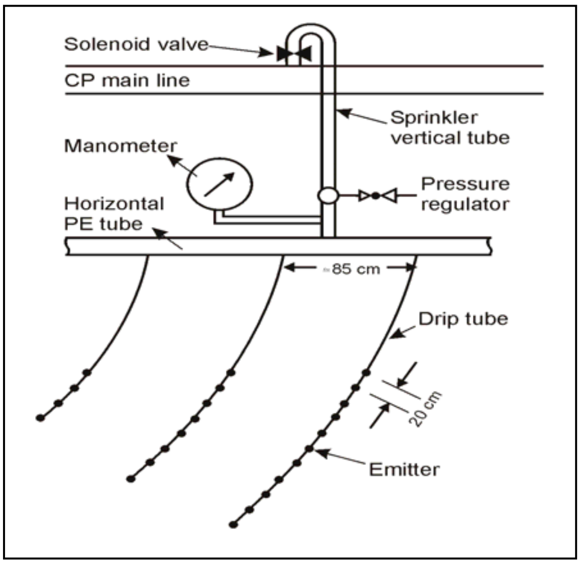


Figure 3.17: Pressure regulator and manometer used to adapt the operating pressure at the inlet of the MDI drop (Derbala, 2003)

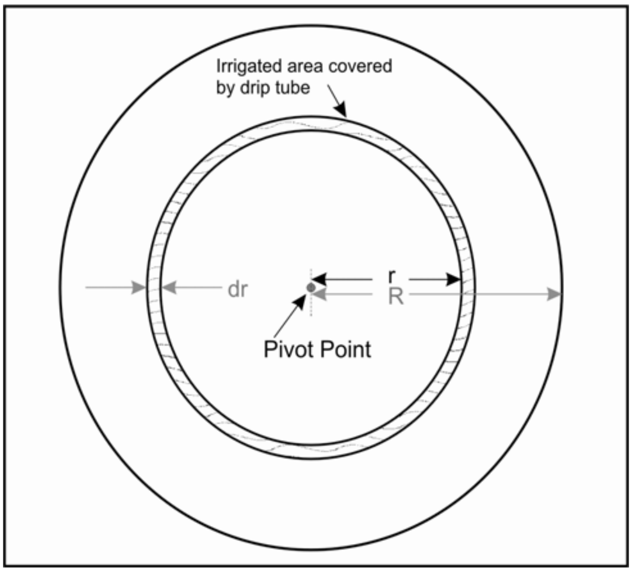


Figure 3.18: Schematic diagram of narrow spacing covered by drop tube located at r meter distance from pivot point (dr) and radios of the area irrigated by the centre pivot (R) (Derbala, 2003)

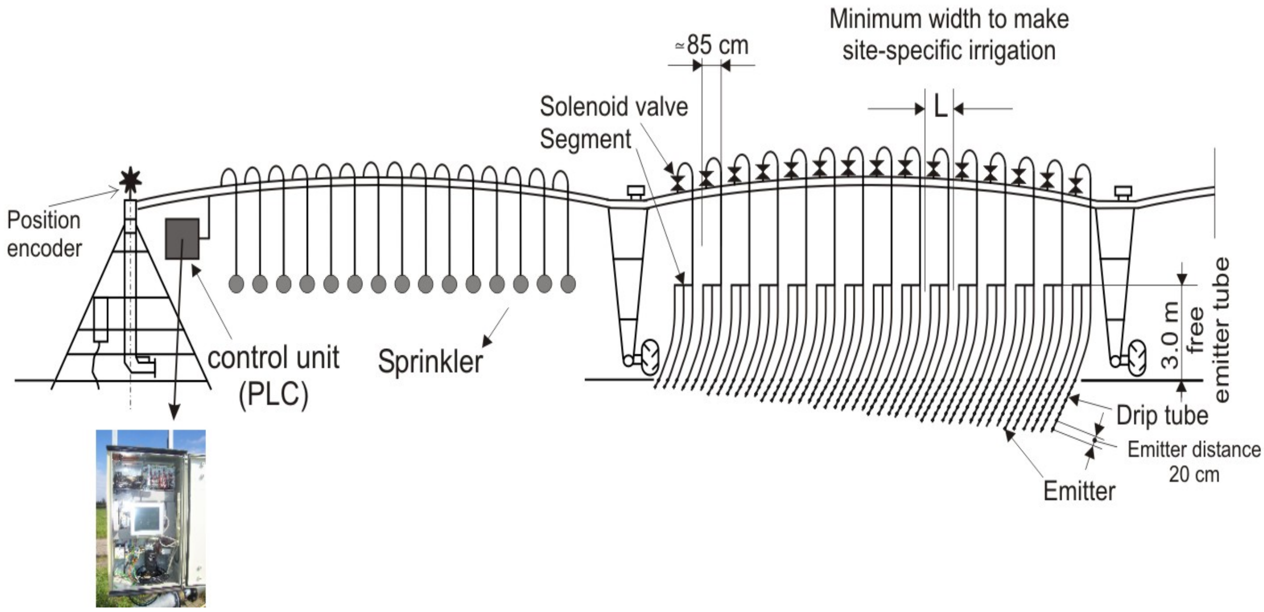


Figure 3.19: Modified centre pivot irrigation system

3.2.4.6 Evaluation of emitter performance

The efficiency of trickle irrigation systems depends directly on the uniformity with which water is discharged from the emission devices throughout the system. Ideally, all emitters in the system should discharge equal amounts of water. One major cause of flow rate difference between two identical emitters from the same manufacturer is the manufacturing variation. Before installing trickle irrigation, the performance of emitters must be evaluated and in this case emitter discharge (q), the emitter discharge exponent (x), the coefficient of variation of the discharge (CV), emission uniformity (EU) and emitter flow variation ($q_{var.}$) are important parameters:

Emitter discharge: Keller and Karmeli (1974) and Howell et al. (1980) calculated the relationship between emitter discharge and operating pressure in the design of drop irrigation systems given by the following equation:

$$q_e = KeH^X \qquad (3.13)$$

Where q_e is emitter discharge, in l/h, Ke is the emitter discharge coefficient that characterises the emitter dimensions, H is operating pressure at the emitter, in kPa and x is the emitter discharge exponent which is a characteristic of the emitter flow regime.

Coefficient of variation of the discharge: CV is one of the significant parameters related to the uniformity and efficiency of the system. It could be obtained by taking a random sample of emitters and measuring the discharge rates at the same temperature and pressure. It was calculated as follows:

$$CV = (S_q/q_{av}) \times 100 \quad (3.14)$$

Where CV is the discharge coefficient of variation, in %, S_q = the standard deviation of discharge rates of the emitters in the sample, in l/h and $q_{av.}$ = mean of emitter discharge rate, in l/h. The standard deviation values were calculated in the same manner using the following equation given by Wagenführ (1974) :

$$S_q = \frac{\sum_{i=1}^{N} (x_i - x_m)}{N} \quad (3.15)$$

Where Sq is the standard deviation of discharge, in l/h, N is the sum of samples, x_i is the measured discharge value in l/h and x is mean of discharge. Classifications of the coefficient of discharge variation values according to ISO standards are given in the International Standard Organisation (1991) as indicated in Table 3.3.

Table 3.3: Classifications of coefficient of variation values (ISO standard, 1991)

Category	CV	details	Classification
A	0 to +/- 5 %	higher uniformity of emission rate and smaller deviations from the specified nominal emission rate	Good
B	+/-5 to +/- 10 %	medium uniformity of emission rate and medium deviations from the specified nominal emission rate	Medium
C	>10 %	lower uniformity of emission rate and greater deviations from the specified nominal emission rate	Poor

Emission uniformity: EU was also calculated by Keller and Karmeli (1974) as follows:

$$EU = (q_n / q_{av}) \times 100 \quad (3.16)$$

Where EU is the emission uniformity of emitters, in %, q_n is average discharge from emitters in the lowest 25 % of the discharge range, in l/h and qav is average discharge of all emitters, in l/h. They recommended that EU values of 94 % or more are desirable and in no case should the designed EU be below 90 %.

Emitter flow variation: q_{var} can be shown by comparing maximum and minimum emitter flows and was expressed by Wu and Gitlin (1983) as follows:

$$q_{var.} = (q_{max.} - q_{min.}) / q_{max.} \times 100 \quad (3.17)$$

where q_{var}. is emitter flow variation, in %, q_{max}. is maximum emitter discharge, in l/h and q_{min}. is minimum emitter discharge, in l/h.

Manufacturer values of the Siplast emitter discharge exponent, Ke, CV and EU were 0.444, 14.4, 0.03 and 90 %, respectively. The manufacturing pressure-flow rate relation of Siplast with a nominal diameter of 20 mm is shown in Table 3.4.

Table 3.4: Pressure flow rate relation of Siplast emitters (Source: www.siplast.de)

Pressure [kPa]	50	100	120	150	200
Flow rate [l / h]	11.1	14.5	15.7	17.1	19.4

The laboratory experiments: In this study, two drop tubes (drop tube number 10 including 19 emitters and LT = 3.8 m and drop tube number 35 including 35 emitters and LT = 7.0 m) were tested to measure q_{av}, the emitter discharge exponent, CV, EU and $q_{var.}$ .In these tests, the operating pressures were 50, 100, 120, 150, 200 and 250 kPa with an accuracy of 5 kPa measured by a manometer. The water temperature measured by a mercury thermometer was adjusted to 22 °C by using an electrical heater to compare different pressure (ISO 9260, 1991). Two-litre measuring cylinders with 20 ml divisions were used with three replications to collect the water from the emitters as shown in Figure 3.20. When the chosen pressure was reached, pressure in the drop tube was controlled using a pressure regulator. Emitter discharge was measured over a range of six pressures to determine the manufacturing variation of emitters. The discharge of the emitters was measured volumetrically and a stopwatch was used to measure the flow times. The water volumes were collected in the graduated cylinders and manually read and recorded.

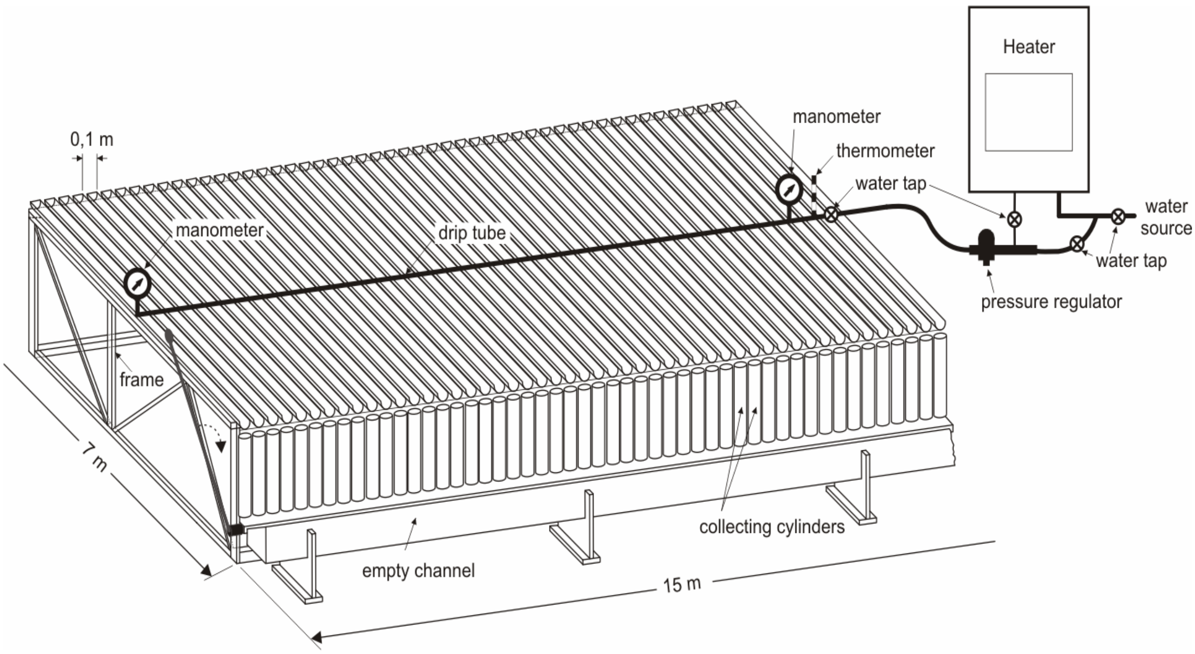


Figure 3.20: Measurement of the emitter discharge rate in the laboratory (Derbala, 2003)

The field tests of MDI: Discharged water from two drop tubes (drop tube number 10 and 35) were collected using a 20-litre measuring pail during 30 minutes with 2 replications as shown in Figure 3.21. After water pressure had been adjusted to 120 kPa using a pressure regulator installed before the drop tube, the water application rate of the MDI at different CP speeds and ten different pulsing levels including 10, 20, 30, 50, 60, 70, 80, 90 and 100 percent was calculated. The volume of the water collected in the pail was converted to the depth of water with due attention to the area irrigated under drop tubes that is given in appendix B. In addition, the quantity of water discharged from the drop tubes including Ne = 19, LT = 3.8 m and Ne = 35, LT = 7.0 m during 30 minutes at maximum and minimum pressure at the pivot point and at the beginning of the drop lateral are given in appendix B.

Then variation in irrigation depth against different amounts of pulsing level was calculated and drawn for different CP speeds. It was tested under motionless condition, but irrigation depth was calculated for different CP speeds with due attention to linear CP speed, length of drop tube and the area irrigated under the drop tube.

Figure 3.21: Field measurement of the drop tube water application rate

4 RESULTS AND DISCUSSION

At first IMZs were delineated on a 16.6 ha field using sensor-based ECa measurements and then a wireless communication and modified CP were developed to apply site-specific amounts of water to a grass field. The system was tested and run in the months of June, July, August and September of 2006. The results and discussion are divided into three main sections. 1) the delineation of IMZs using sensor-based soil EC measurements with the aid of EM38 and VERIS 3100; 2) remote real-time site specific DIC and monitoring by means of wireless soil moisture measurement and pulsing techniques for the delivery of variable amounts of irrigation depth using programmable logic control and 3) potential economic implications.

4.1 Delineation of irrigation management zones

4.1.1 Data collection

Individual ECa measurements of 8383, 8304, 7967 and 7967 were obtained respectively for EM38-h, EM38-v, VERIS 3100-sh, VERIS 3100-dp on different dates during the winter 2005 experimentation period on the 16.6 ha field. The average soil temperature at the site ranged from 0 to 10° C over different depth intervals at different times. Therefore ECa data were standardized to 25° C (EC_{25}).

EC_{25} collected in each of the two operating modes with each of the two sensors were mapped (Figure 4.1). Within each map, an equal number of readings were represented within each classification interval. The conductivity readings provided by each sensor (in mS/m) were considerably different in magnitude even though the range was within the trends observed at the field level on a map based on one single EM38 measurement. These results are in agreement with those found by Sudduth et al. (1999). However, similar trends were not found in a map based on one single VERIS 3100 measurement and EM38 and VERIS 3100 measurements in contrast to the results found by Sudduth et al. (1999).

4.1.2 Comparison of the EM38 and VERIS 3100 readings

Because of unequal measurements of transect locations between EM38_v, EM38_h, VERIS 3100_sh and VERIS 3100_dp readings, a combined data set (about 300 points) was created at different ECa to allow ECa readings to be compared. Based on DGPS coordinates the closest EM38_v, EM38_h, VERIS 3100_sh and VERIS 3100_dp readings were combined. If a match was not found within a 3 m radius, that point was removed from the data set. Coefficient of determination values (R^2) were calculated between the various ECa measurements. Alongside these, the comparison of coefficients of determination between ECa measurements showed that there was not any good coefficient of determination between ECa measurement methods. The highest coefficient of determination (R^2 = 0.55) was generally found between EM38_h and EM38_v as shown in Figure 4.2 and from visual comparison between maps in Figure 4.1.

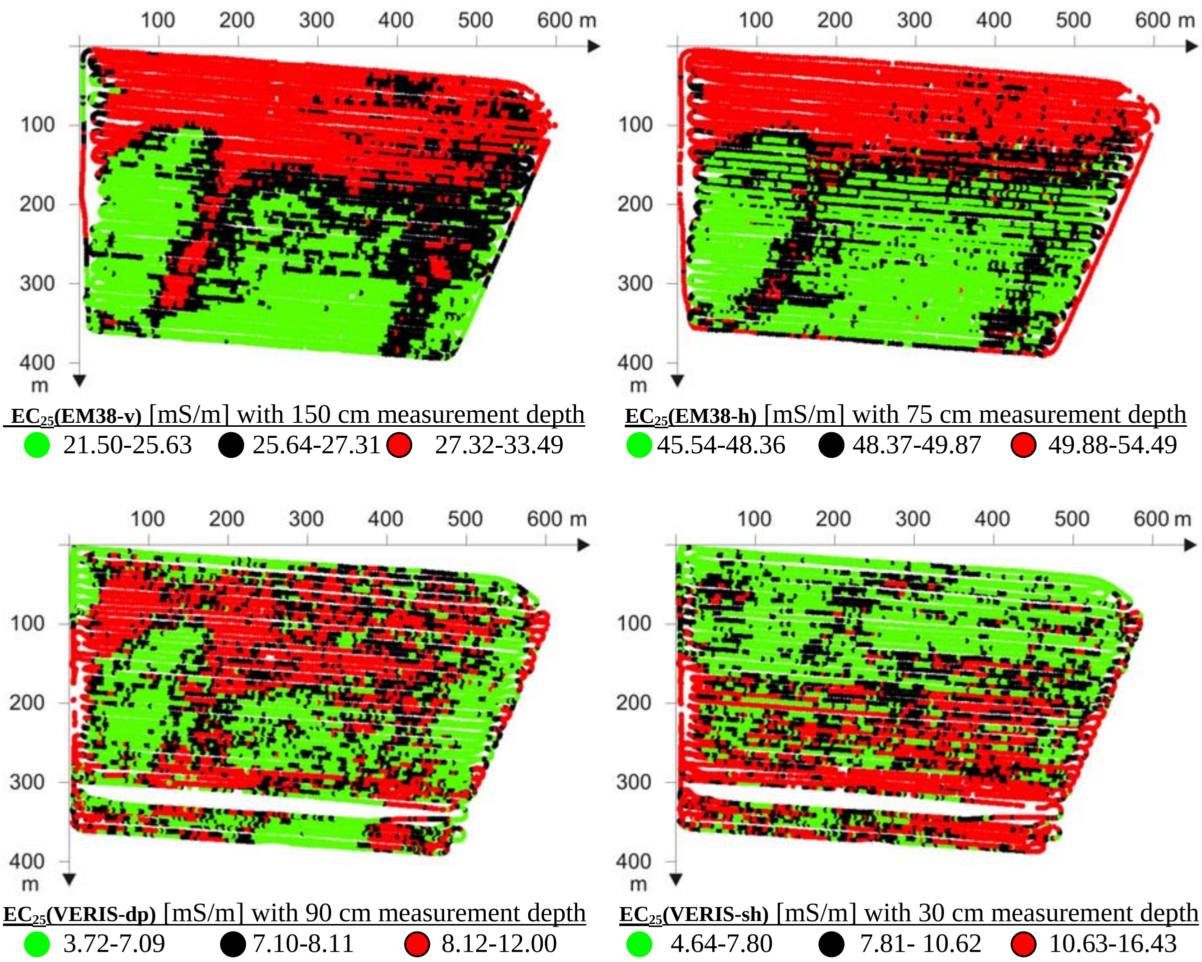


Figure 4.1: Comparison of the different EC_{25} obtained with VERIS 3100 (shallow and deep) and EM38 (horizontal and vertical). Within each map, an equal number of readings are represented within each classification interval

Sudduth et al. (2002b and 2003), Triantafilis and Lesch (2005) and Doolittle et al. (2005) also came to a same conclusion. This result can be discerned from the EM38_h and EM38_v curves in Figures 3.6 and 3.7 (P. 50) where these two curves lie closer together than other curves (EM38 was applied suspended 30 cm above the ground surface). However, lower coefficients of determinations were obtained between VERIS 3100_dp and EM38_h (R^2 = 0.29) and VERIS 3100_dp and VERIS 3100_sh (R^2 = 0.26) and very low coefficients of determination between VERIS 3100_sh to EM38_h, VERIS 3100_sh to EM38_v and VERIS 3100_dp to EM38_v (Figure 4.2). These results also can be discerned from Figures 3.6 and 3.7 (P. 50) where related curves were found to lie further away from the other curves. These results are contrary to the high coefficient of determination between EM38 and VERIS 3100 found by Malo et al. (2000), Sudduth et al. (1999 and 2003), Bramley (2002) and Lück (2002).

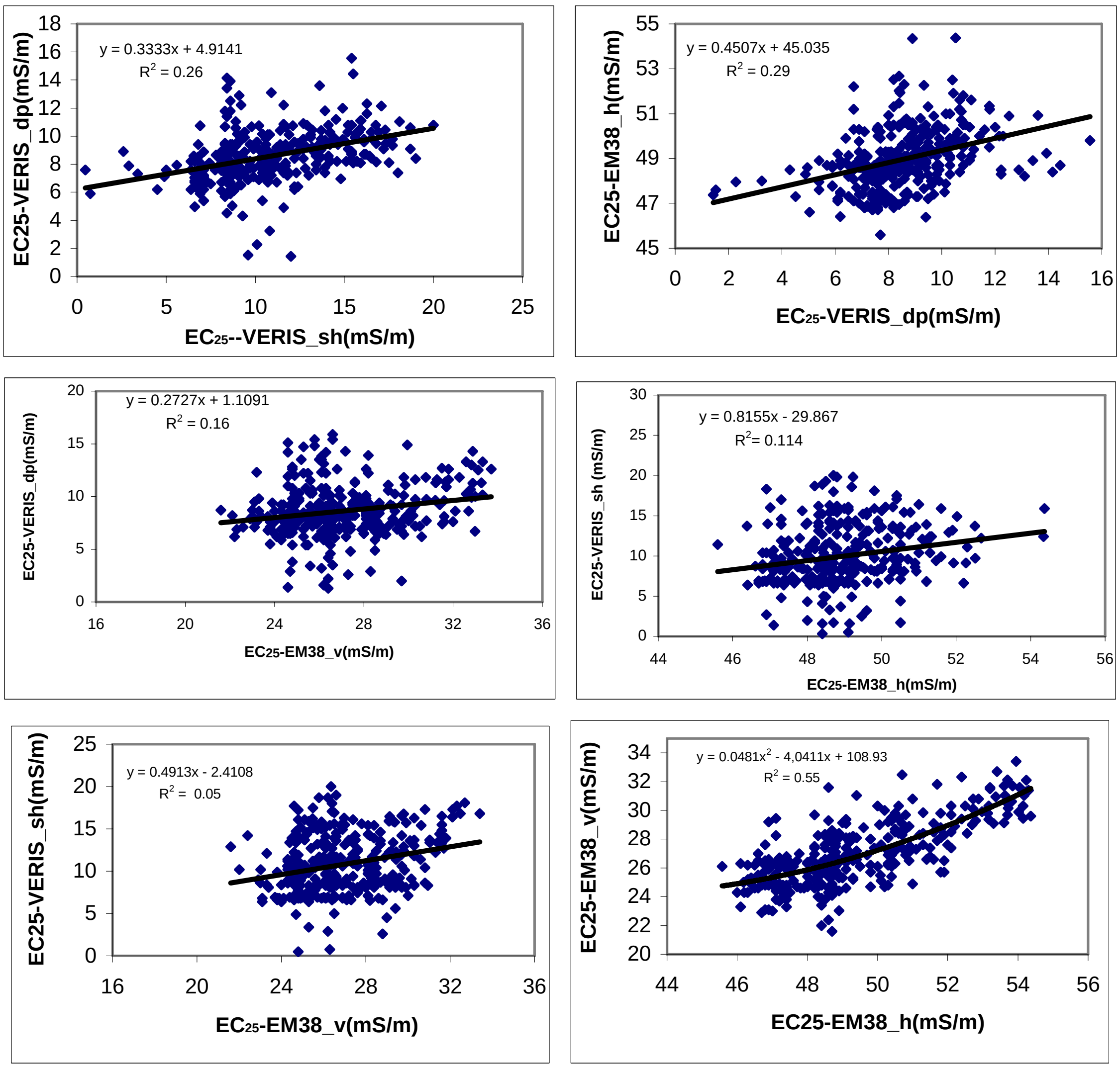


Figure 4.2: Relationships between different ECa readings standardized to 25° C obtained with VERIS 3100 and EM38

A statistical summary of the different apparent soil electrical conductivity (ECa) readings standardized to 25° C obtained with VERIS 3100 and EM38 data for each measurement after limitation of the unreasonable values, is shown in Table 4.1. Maximum and minimum ECa readings were found in the EM38_h and VERIS 3100_dp readings, respectively compared with other sensor- based ECa readings. However, the VERIS 3100_sh and VERIS 3100_dp readings were somewhat equal. In general, there was a large difference between EM38 and VERIS 3100 readings. The ECa readings of the EM38 were higher than the ECa readings of VERIS 3100, though variations among VERIS 3100 readings were significantly higher than among EM38 readings as shown by the measured CV values listed in Table 4.1 ($CV_{(VERIS\ 3100\_sh)}$ = 26.0 % and $CV_{(VERIS\ 3100\_dp)}$ = 16.1 %). These results are in agreement with soil-depth variation on the study field that is more variable in the upper 40 cm (mix of loam and sand) and more uniform at greater depths (mostly sandy) and can be found in Figure 3.2 (P. 46) and in particular in Figure 3.6 (P. 50) where about 94, 56, 40 and 24 % of the cumulative response of the VERIS 3100_sh, VERIS 3100_dp, EM38_h and EM38_v, respectively, are found in the upper 40 cm. That means the major variability in the soil properties that affect ECa may be in the upper layers of the study field, which are weighted more in the VERIS 3100 ECa measurements. Moreover, more uniformity in the soil properties that affect ECa may be at greater depths, which are less heavily weighted as shown in Figures 3.6 and 3.7 (P. 50). Sudduth et al. (2002b) came to a similar conclusion.

Differences between maps were attributed to the differences in sensing depth of the different sensors (EM38 and VERIS 3100) and different data collection modes (vertical vs. horizontal or deep vs. shallow, respectively). However, VERIS 3100-sh readings were not able to measure soil ECa at deeper layers than about 30 cm, which is the appropriate sensing depth for this device, as stated by the manufacturer.

Table 4.1: Statistical values of the different ECa readings standardized to 25° C obtained with VERIS 100 and EM38 based on based on a combined data set (300 points)

EC_{25} [mS/m]	**count**	**Minimum** [mS/m]	**Maximum** [mS/m]	**Sum**	**Mean** [mS/m]	**Standard** Deviation	**CV** [%]
EC_{25} (EM38-h)	300	45.6	54.4	16280.5	49.3	1.7	3.5
EC_{25} (EM38-V)	300	21.6	33.7	8891.1	26.9	1.8	6.7
EC_{25} (VERIS-sh)	300	0.3	20.0	3565.4	10.8	2.8	26.0
EC_{25} (VERIS-dp)	300	1.3	15.6	2821.1	8.6	1.4	16.1

4.1.3 Soil samples and the best sensor-based methods of ECa measurements for the delineation of TAWC variability

To determine the best sensor-based method for the delineation of TAWC variability and the development of field-specific relationships between ECa data and TAWC, twenty nine monitoring points (black points in Figure 4.4) were located using DGPS based on the ECa spatial variability pattern and considering the whole range of ECa values present. Average P.W.P., F.C., TAWC, ECa readings and the latitude-longitude of the sampling calibration points are shown in Table 4.2.

Linear calibration equations for the TAWC as a function of ECa were developed separately for each of the two operating modes with each of the two sensors (Figure 4.3), since the effect of operating mode and sensor were found to be statistically significant. However, a better coefficient of determination was found between TAWC and the VERIS 3100 readings (in both shallow and deep modes). These results can be discerned from the VERIS 3100_sh and VERIS 3100_dp curves as shown in Figures 3.5 and 3.7 (P. 50) where VERIS 3100 curves have bigger relative responses in the upper layers (near the surface) than the other curves. About 97, 68, 55 and 32 % of the cumulative response of the VERIS 3100_sh, VERIS 3100_dp, EM38_h and EM38_v, respectively, came from the upper 60 cm of the soil as described by McNeill (1992; 1980). These results are in agreement with the soil-depth variation of the study field where there is more variability on soil texture in the upper 40 cm (mix of loam and sand) and more uniformity in the more deeper layers (mostly sandy). The estimation of TAWC from VERIS 3100_sh data showed that the data matched well and had a high coefficient of determination (R^2 = 0.77), whereas calibrations to EM38 data (both vertical and horizontal orientation) were low and apparently could not adequately reflect the spatial variability of the TAWC due to the greater influence of the EM38 on deeper layers, which are more uniform.

The VERIS 3100_sh data exhibited the highest coefficient of determination and apparently could adequately reflect the spatial variability of the TAWC. Thus, the VERIS 3100_sh method was selected as a technique of sensor-based soil electrical conductivity measurement to develop a TAWC map that will be used for decision making to create an irrigation application map showing different irrigation depths for different management zones. Figure 4.4 shows an interpolated ECa map standardized to 25° C (EC_{25}) obtained with VERIS 3100 (shallow) and an interpolated TAWC map (TAWC was calculated with the aid of an equation similar to the one used for the calculation of the coefficient of variation between VERIS 3100_sh readings and TAWC at twenty nine soil sampling points).

Table 4.2: Average P.W.P., F.C., TAWC, ECa readings and latitude-longitude of the sampling calibration points

NO of sample point	Geographical position		Soil water content			Soil electrical conductivity [mS/m]			
	Longitude	Latitude	F.C. [%W]	P.W.P. [%W]	TAWC [cm/60cm]	EM38-h	EM38-v	VERIS 3100-sh	VERIS 3100-dp
6	10.4521856	52.3008423	13.6	2.9	9.08	36.3	21.1	4.6	5.4
23	10.4528086	52.2990774	17.0	4.7	10.59	44.0	29.9	7.1	6.4
19	10.4540946	52.3011483	15.4	3.0	10.62	47.9	24.8	5.8	6.4
5	10.4535433	52.3001776	15.8	3.1	10.77	50.6	28.7	7.1	7.3
12	10.4525315	52.3004647	15.8	3.2	10.82	52.1	30.3	6.1	7.1
18	10.4545495	52.3008132	15.8	3	10.96	49.3	28.1	8.6	7.6
21	10.4554904	52.3010982	16.0	3.1	10.97	53.1	22.0	6.1	7.9
17	10.4559177	52.3010160	16.4	3.5	11.00	51.7	30.3	5.6	7.4
2	10.4557382	52.2988216	16.8	3.8	11.09	52.6	31.9	7.8	8.6
24	10.4572069	52.3004510	16.6	3.5	11.16	50.2	28.7	7.8	8.3
16	10.4549903	52.3005991	17.1	3.9	11.18	47.5	23.9	6.5	8.3
11	10.4571022	52.2999910	16.5	3.2	11.28	52.3	31.9	10.6	8.6
27	10.456513	52.298718	17.0	3.7	11.33	49.3	22.5	7.8	7.3
22	10.4552880	52.3009359	16.8	3.4	11.36	46.4	34.2	7.6	8.1
10	10.4564437	52.3006691	17.1	3.4	11.7	50.4	27.8	7.0	7.6
1	10.4567739	52.2987210	16.8	3.0	11.75	46.8	23.2	7.8	6.4
15	10.4539019	52.3007334	17.1	3.1	11.89	51.9	30.8	7.5	6.8
4	10.4531331	52.2996885	17.7	3.5	12.07	47.5	24.4	8.8	6.9
20	10.4561360	52.2983884	16.2	1.4	12.64	48.8	27.3	8.1	6.8
9	10.4540553	52.2994025	18.1	3.3	12.65	47.5	25.1	7.3	8.8
7	10.4581784	52.2994835	18.7	3.8	12.66	48.0	25.8	8.8	8.2
25	10.4563245	52.2992208	18.6	3.6	12.83	53.8	36.7	10.0	7.9
3	10.4528688	52.2992744	17.4	2.3	12.91	53.8	36.0	9.1	8.8
28	10.452198	52.300891	15.9	0.7	12.96	50.1	37.4	10.1	9.0
14	10.4573551	52.2984173	17.2	1.9	13.04	53.8	35.1	12.1	11.1
8	10.4554557	52.2994951	19.1	2.8	13.90	53.7	35.9	14.9	10.2
26	10.4564054	52.2989562	20.2	3.4	14.34	53.9	36.0	11.8	10.3
13	10.4576453	52.2990727	19.3	2.4	14.37	54.0	37.9	10.8	11.2
29	10.4567443	52.2994572	24.3	5.6	15.89	39.8	38.2	16.4	12.0

% w = Soil moisture content on a dry-weight basis

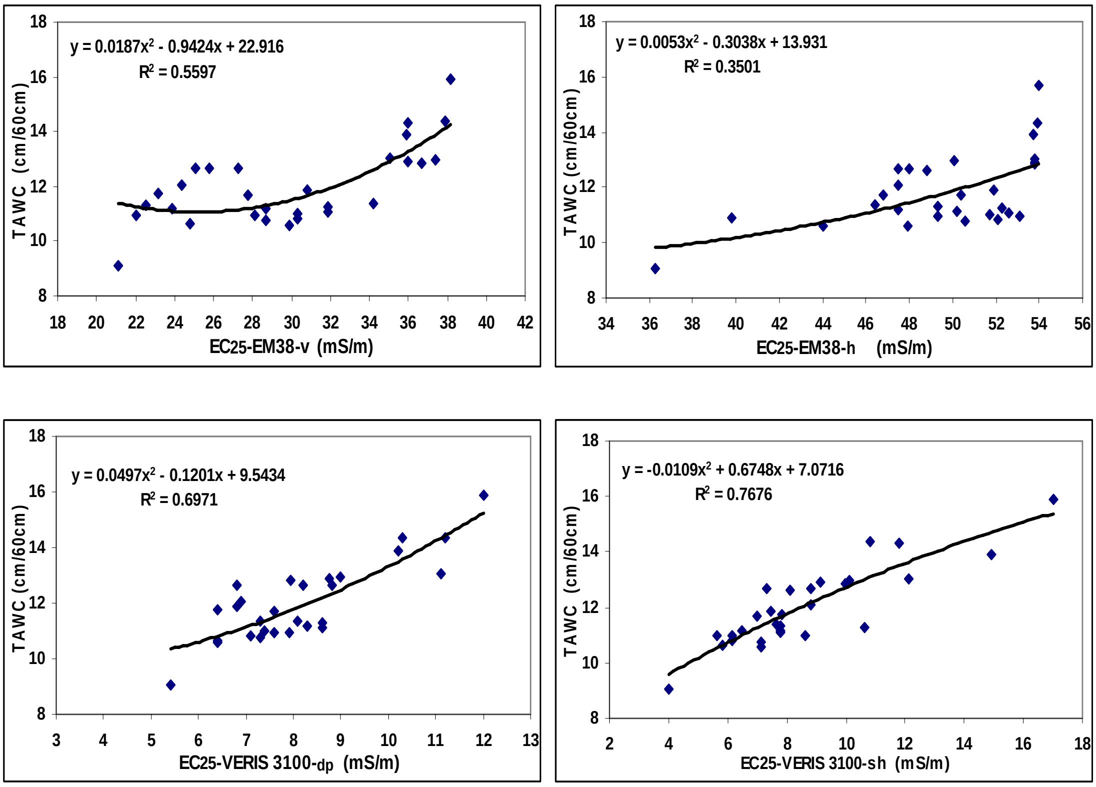


Figure 4.3: TAWC calibration from different ECa readings standardized to 25° C (EC_{25}) obtained with VERIS 3100 (both shallow and deep readings) and EM38 (both horizontal and vertical orientations)

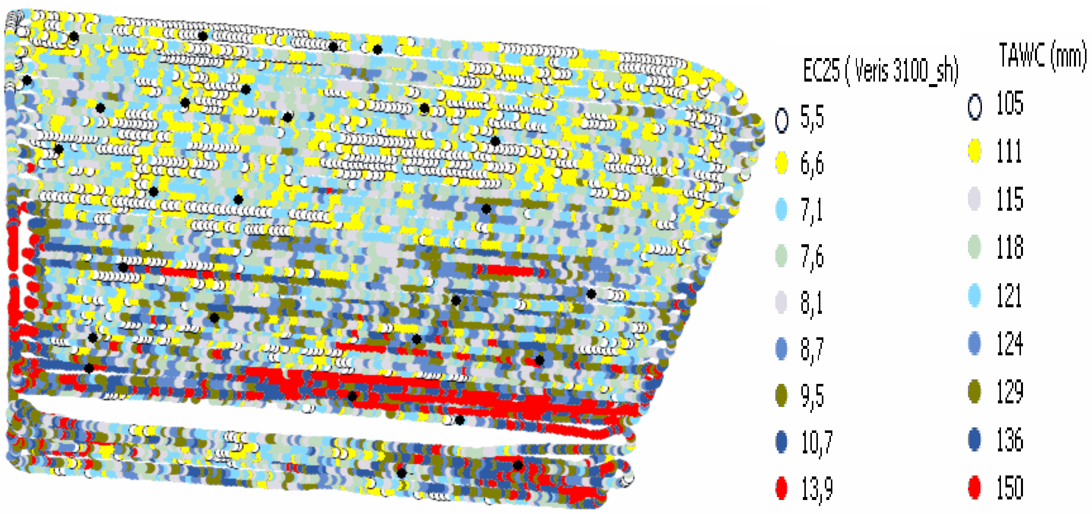


Figure 4.4: Interpolated apparent soil electrical conductivity (ECa) map standardized to 25° C (EC_{25}) obtained with VERIS 3100_sh and interpolated total available water content (TAWC) map. Within each classification interval, an equal number of readings is represented as well as 29 samples (calibration points) located using DGPS (black points)

4.1.4 Optimum number of irrigation management zones

Six TAWC zones were identified based on the number of classes that minimize two cluster validity indices: (the FPI and the MPE) at a fuzziness exponent value of 1.3 (Boydell and McBratney, 1999). Euclidean distance was used to enhance the influence of the highly variable TAWC. The FPI and MPE values plotted against the number of management zones are shown in Figure 4.5. The FPI indicates very good initial segregation of the data in two zones and reaches a minimum value in two zones. The MPE indicates a large amount of initial disorganization in two zones. However, as the number of zones increases, both cluster validity indices (FPI and MPE) indicate that the degree of membership sharing between zones also increases until four zones and then two cluster validity indices are reduced to six zones. However, with equal weight given to both indices, a classification into six zones would be optimal for the study field.

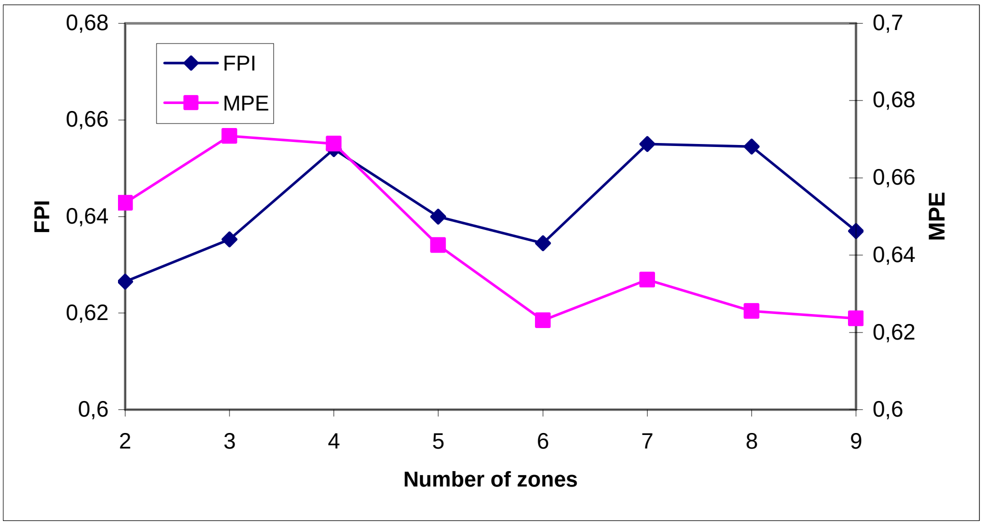


Figure 4.5: Plots of clustering performance (FPI = fuzziness performance index; MPE = modified partition entropy) against the number of zones

4.1.5 Features of irrigation management zones

Based on standard deviation, these six TAWC classes were identified as IMZ_1: 99 to 105 mm/60 cm, IMZ_2: 105 to 116 mm/60 cm, IMZ_3: 116 to 127 mm/60 cm, IMZ_4: 127 to 138 mm/60 cm, IMZ5: 138 to 149 mm/60 cm, IMZ6: 149 to 152 mm/60 cm just as within field variation of field capacity in volumetric percent was IMZ_1: 20.6 to 21.5, IMZ_2: 21.5 to 23.6, IMZ_3: 23.6 to 25.5, IMZ_4: 25.5 to 27.5, IMZ_5: 27.5 to 29.6, IMZ_6: 29.6 to 33.7 (Figure 5.8). Zones 1, 2, 3, 4, 5, 6 accounted for: 0.13 ha (1.6 %), 2.77 ha (33.8 %), 3.23 ha (39.4 %), 1.30 ha (15.9 %), 0.55 ha (6.7 %) and 0.21 ha (2.6 %) of the 16.6 ha study field, respectively (Figures 4.6 and 4.7). IMZ_1 and IMZ_3 are the smallest and the biggest irrigation zones including 39 and 2 % of the entire study field, respectively (Figures 4.6 and 4.7). Moreover, Figure 4.7 shows that about 50 % of the area (median TAWC) had TAWC values of 118 mm/60 cm or less. Therefore the average TAWC of the study field are equal to 121.6 mm on this field:

$$(1.6\times 102+33.8\times 110.5+ 39.4\times 121.5+15.9\times 132.5+6.7\times 143.5+150.5\times 2.6) /100 = 121.6 \text{ mm/60 cm}$$

Given the similarity of the physical soil characteristics of zone 3 (including 121.5 mm average TAWC) and the average physical characteristics considered under conventional uniform irrigation (normal irrigation), it could be concluded that no water could be saved by using site-specific irrigation instead of conventional uniform irrigation on this study field (because deficit and over-irrigation are similar in volume) as stated by Oliveira et al. (2003), but that irrigation water application and energy consumption are optimized and yield increases (King et al., 2006; Camp et al., 2000). Under conventional uniform irrigation, IMZ_1 and IMZ_2 (about 35.4 % of area) were over irrigated whereas IMZ_4, IMZ_5 and IMZ_6 (about 25.2 % of the area) showed an irrigation deficit. It is possible to optimize water consumption and to increase water use efficiency in irrigated zones by reducing water consumption within over-irrigated zones and increasing the irrigation water volume in zones which show an irrigation deficit. Oliveira et al. (2003) found that the difference between average water application depth in site-specific irrigation (PI) and uniform application was significant (approximately 90 %). Depending on the site-specific irrigation schedule, the distribution of water applied in the field varied in each irrigation zone over the years but the annual averages were not statistically significant ($p > 0.73$). It is a logical conclusion that PI can not necessarily save water because zones showing an irrigation deficit (areas with high amounts of TAWC) will receive more water with PI than under conventional, uniform irrigation and over irrigated zones (areas with low amounts of TAWC)

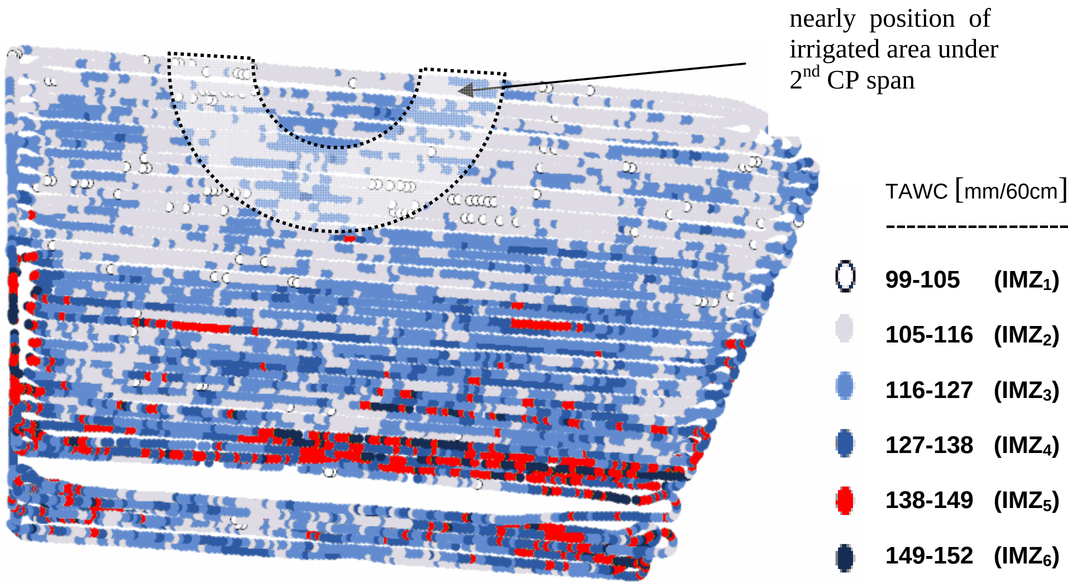


Figure 4.6: Six optimum management zones delineated on the basis of TAWC map (classification is represented on the basis of standard deviation)

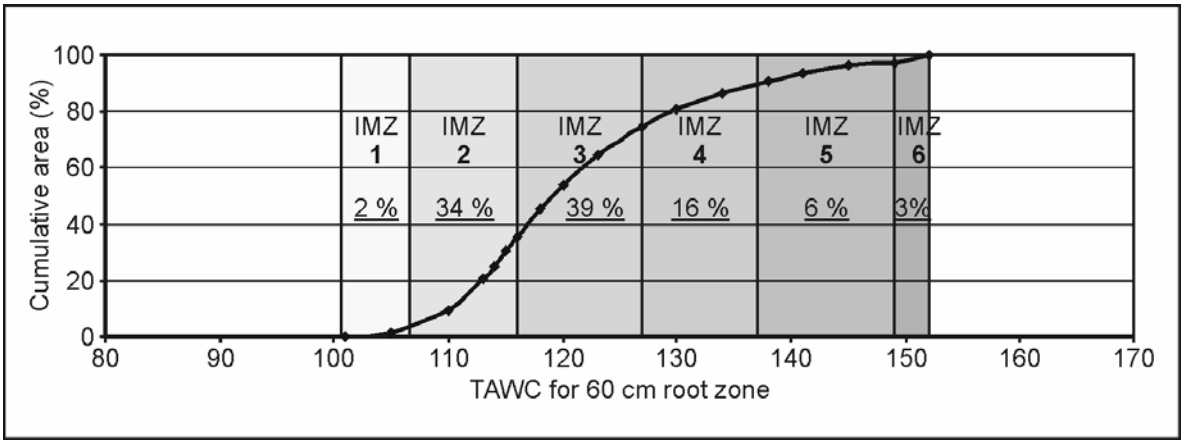
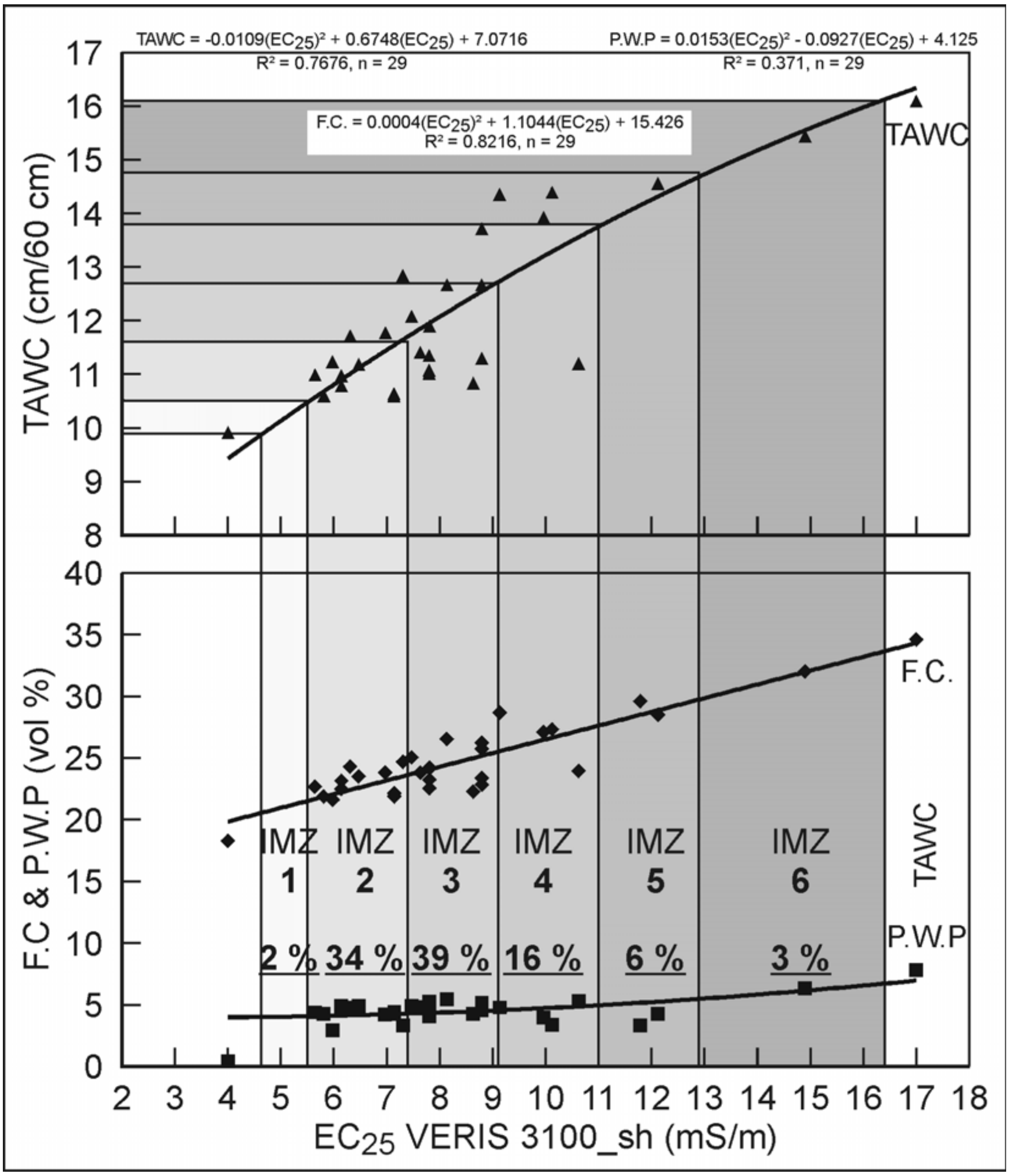


Figure 4.7: Variation of cumulative area against TAWC

will receive less water with PI than under conventional, uniform irrigation. Thus, with due attention to the overlapping of over and deficit consumption of water (similar deficit and over irrigated water volume), the quantity of water supplied is not necessarily reduced.

The appropriate EC_{25} variation of IMZs can be calculated using the calibration equation based on TAWC and EC_{25} (Figure 4.8). More details and the features of zones (F.C., P.W.P. and EC_{25}) and the relationship between these features are shown in Figure 4.8. There was a good coefficient of determination between EC_{25} readings by VERIS 3100_sh and the volume percent of field capacity at twenty nine monitoring points. However, a low coefficient of determination between the volume percent of the permanent wilting point and EC_{25} readings by VERIS 3100_sh was found. Using Figure 4.8 and based on measurements of soil moisture within each management zone in the upper 60 cm, it is possible to realize different irrigation depths by calculating the soil moisture deficit in order to reach 80 percent of field capacity in the upper 60 cm of each management zone. Figure 4.8 shows that there is an obvious difference in TAWC between minimum TAWC and maximum TAWC in study field. Although this significant difference could not save and decrease the water consumption, a big advantage and an obvious potential for the optimization of water application based on site-specific TAWC variation could be derived.

With due attention to uniform area under the 2nd span of the CP (Figure 4.6), an artificial TAWC map including three IMZs (IMZ_1, IMZ_2, IMZ_3) and the whole extent of real variation of field TAWC was created (Appendix C). To decrease the cost of purchasing six soil moisture sensors for the six IMZs defined in Figures 4.6, three IMZs were considered within the new TAWC map as shown in Figure 4.8. Appendix C indicates details and also the variation of irrigation depth including the volumetric soil moisture of three artificial IMZs. The artificial zones of IMZ_1, IMZ_2 and IMZ_3 had a TAWC variation from 99 to 116 mm/60 cm, from 116 to 130 mm/60 cm and from 130 to 152 mm/60 cm. These TAWC variations were attributed to an EC_{25} variation of 4.64 to 7.8 mS/m, 7.8 to 10.62 mS/m and 10.62 to 16.43 mS/m, respectively.



IMZ₁:
EC_{25} = 4.64-5.5 mS/m
FC = 20.6-21.5 %
PWP = 4.0-4.1 %
TAWC = 99-105 mm/60cm

IMZ₂:
EC_{25} = 5.5-7.4 mS/m
FC = 21.5-23.6 %
PWP = 4.1-4.3 %
TAWC = 105-116 mm/60cm

IMZ₃:
EC_{25} = 7.4-9.1 mS/m
FC = 23.6-25.5 %
PWP = 4.3-4.5 %
TAWC = 116-127 mm/60cm

IMZ₄:
EC_{25}=9.10-11.0 mS/m
FC=25.5-27.6 %
PWP=4.5-4.9 %
TAWC=127-138 mm/60cm

IMZ₅:
EC_{25}=11.0-12.8 mS/m
FC=27.6-29.6 %
PWP=4.9-5.4 %
TAWC=138-149 mm/60cm

IMZ₆:
EC_{25} = 12.8-16.43 mS/m
FC = 29.6-33.7 %
PWP = 5.4-6.7 %
TAWC = 149-161 mm/60cm

Figure 4.8: Calibration and relative changes of TAWC, F.C. and P.W.P from EC_{25} VERIS 3100_sh for the organization of management zones and the creation of an irrigation application map

4.2 Performance and evaluation of a remote real-time and site-specific distributed irrigation control system

This section is covers: field tests related to irrigation scheduling, soil moisture monitoring and irrigation system modification.

4.2.1 Irrigation scheduling

The maximum and minimum MAD values chosen for this study were equal to 80 % and 60 % of TAWC, respectively. The range was reasonable and in agreement with Tables 2.1 and 2.2 (very fine sandy loam soil texture on the study field and 60 cm root depth). I_{max} was considered with due attention to:

a) 20 % (100-80 = 20) free soil water capacity for the absorption of rainfall to be expected after irrigation and for the maintenance of soil moisture between an acceptable maximum and minimum MAD. Frequent rainfall during the irrigation season (285 mm from 17 May until 30 September) showed that the consideration of free capacity for the absorption of rainfall to be expected after irrigation is a logical decision and could save water and energy.
b) Limitation of the length increase of the drop tube
c) Watering the grass root zone up to a depth of 60 cm

Net irrigation depth: It is irrigation depth that must be stored in the root zone. Normally irrigation depth is bigger than net irrigation depth because of some water losses (infiltration and runoff, for example). The irrigation amounts of three IMZs in Appendix C are calculated based on soil sample data at different soil moisture levels before irrigation as shown in the following equation:

$$In = (80\text{-}SML) \times (F.C. - P.W.P.) \times 6 \qquad (4.1)$$

Where In is the net irrigation depth [mm] required to increase the soil water content of the upper 60 cm to 80 percent of TAWC, SML is the soil moisture level before irrigation [%] that is variable between 60 and 80 percent, F.C. and P.W.P are the volumetric soil water content at field capacity and the permanent wilting point, respectively. I_{max} was calculated 21.7 mm for IMZ_1 which has minimum TAWC (soil moisture deficit of IMZ_1 from 60 % TAWC to 80 % TAWC) which is equal to 63 % and 70 % of TAWC in IMZ_2 and IMZ_3, respectively. The comparison of irrigation depth variation and soil moisture variation inside three IMZs is shown in Figure 4.9. It is shown as well that when the soil moisture content and soil drought are reduced, the soil needs more water to reach the 80 % of field capacity. Moreover, Figure 4.10 shows the variation of irrigation depth and also the variation of soil moisture in percent of TAWC against average soil moisture in the upper 60 cm inside IMZ_1. The values in Figure 4.10, which can be used in practice during the irrigation season, show that the soil moisture content of IMZ_1 in percent of TAWC (right axis) is reduced when the soil water content decreases and that the irrigation depth of IMZ_1 (left axis) grows.

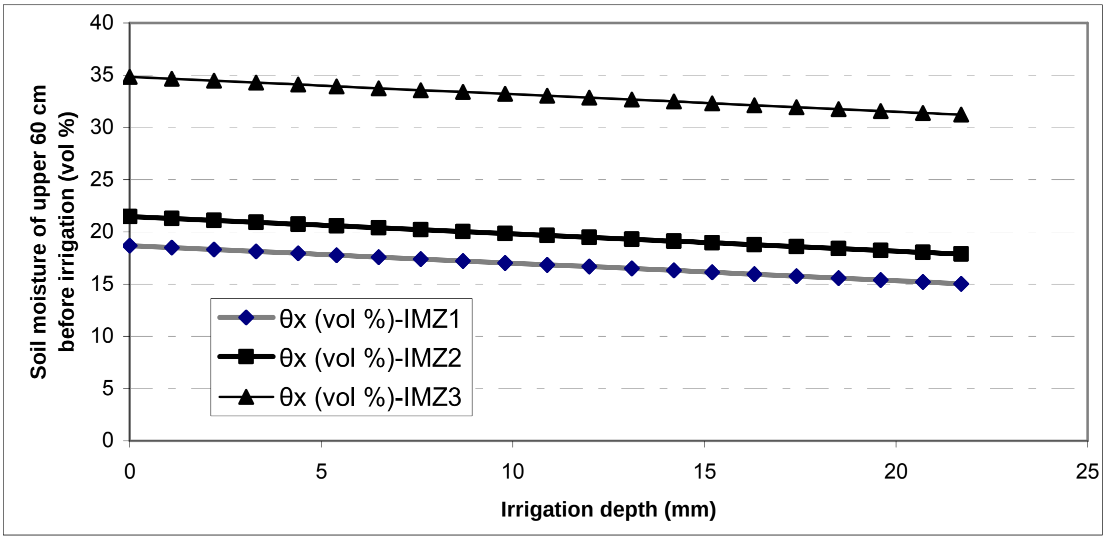


Figure 4.9: Comparison of the irrigation depth variation against soil moisture variation inside three IMZs

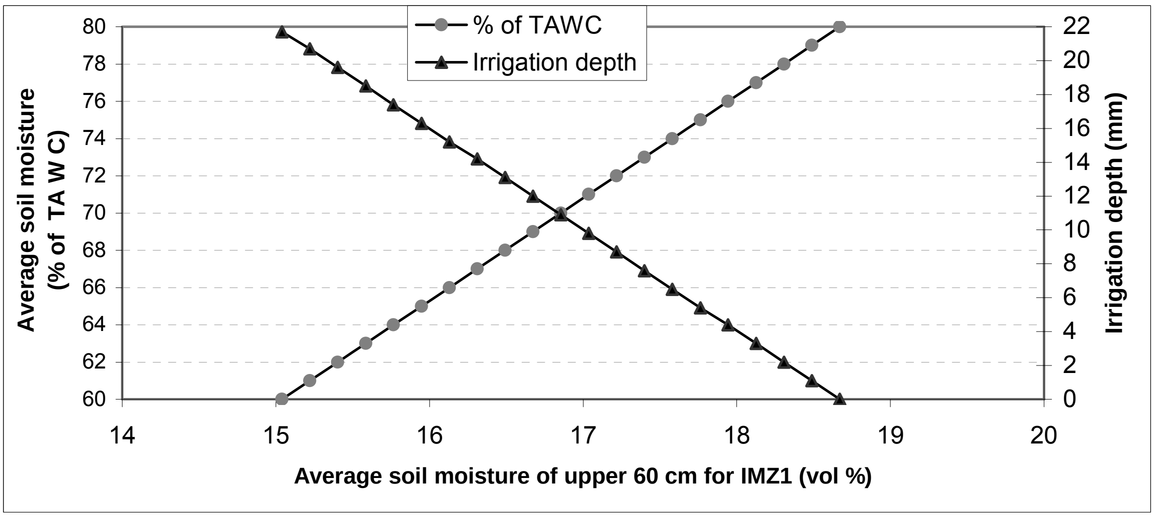


Figure 4.10: Variation of irrigation depth and soil moisture as percent of TAWC with average soil moisture of the upper 60 cm for IMZ_1

Soil moisture within IMZs was measured using the EnviroSCAN soil moisture sensor and the AMBAV-CWB-model every day. It was decided to irrigate all three IMZs whenever the soil moisture content inside IMZ_1 decreased to 60 % of TAWC, but this was not realized because the soil in the study field was homogeneous, water supply was limited, and some technical and mechanical problems occurred during the irrigation season. Thus, as shown in Figure 4.11 (c), it was not possible to maintain the soil moisture content between 60 and 80 % of TAWC during the irrigation season.

However, this study (like PI) is in the development phase and practical experience and the results of this work can be used for the next step in PI development. Figure 4.11 (a, b and c), also shows the variation of the soil moisture content in samples and sensor readings and the variation of ´irrigation + rain´ during the data collection period. The results suggest that sensors were able to follow the general trend successfully as soil water content measured by sampling changed during the growing season, but EnviroSCAN sensors were not able to reliably repeat moisture conditions on sandy soils (under 40 cm depth).

4.2.2 Field tests for soil moisture monitoring

Field tests related to soil moisture monitoring include the evaluation and soil-specific calibration of the EnviroSCAN soil moisture sensor, the field tests of data transmission and power supply as well as the validation of the AMBAV model.

4.2.2.1 Evaluation and soil-specific calibration of the EnviroSCAN soil moisture sensor

Soil moisture is a direct indicator of soil water content and must be accurately observed for irrigation decision support. Moisture contents were measured and transmitted to central control every four minutes during the measuring period. The results evidenced that the universal calibration equation used in the software of the EnviroSCAN system has been generated based on varying soil types. It shows a significant difference as compared with equations developed from soil sample data (Figure 4.11). Therefore, soil-specific calibration was found to be essential for precise soil moisture content measurements as well as for the improvement of the sensor's accuracy and performance in accordance with the findings of Jabro et al. (2005), Mead et al. (1995), Paltineanu and Starr (1997) and Morgan et al. (1999). Thus, equations have been developed during the measuring period on the study field to relate and calibrate sensor readings to the actual moisture content and to an amount of irrigation for future application using sub-surface soil samples (from a depth of 40 to 70 cm) gained under different moisture condition as shown in Figures 4.12 and 4.13.

The results exhibited an underestimation of the uncalibrated sensor-based soil moisture content in comparison with data from both the surface surface and the subsurface in agreement with Mead et al. (1995) in sandy loam, Morgan et al. (1999) in fine sand and Paltineanu and Starr (1997) in mattapex silt loam. These results were in contrast to those found by Jabro et al. (2005), which consistently overestimated soil water content by a magnitude of nearly 10 % of the volume in silt loam soil. Meanwhile, Kelleners et al. (2004) in saline silty clay and Fares et al. (2004) in clay soil found both underestimation and overestimation of the soil water content in an uncalibrated equation. Although the general trend of sensors installed at different depths were similar, visual and statistical analyses indicated that the actual measured values varied significantly between the sensors and soil sampling measurements.

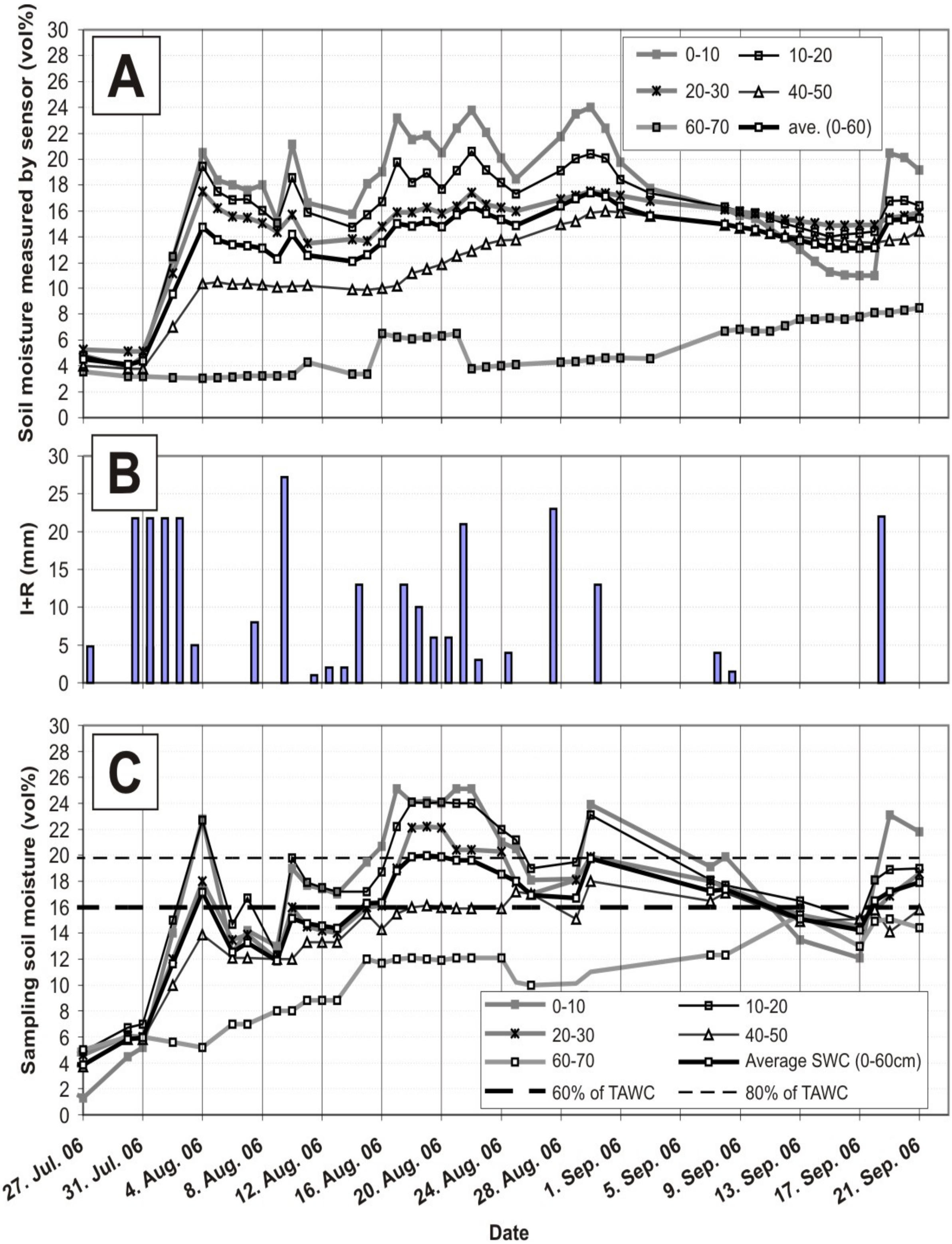


Figure 4.11: Variation of A) Soil sample moisture at different depths of IMZ_1, B) "Rain + irrigation" depth during measuring period and C) Uncalibrated sensor-based soil moisture measurement at different depths of IMZ_1. Variation of SWC due to soil watering. The same trend of SWC variation in A and C can be discerned in a visual comparison between curves

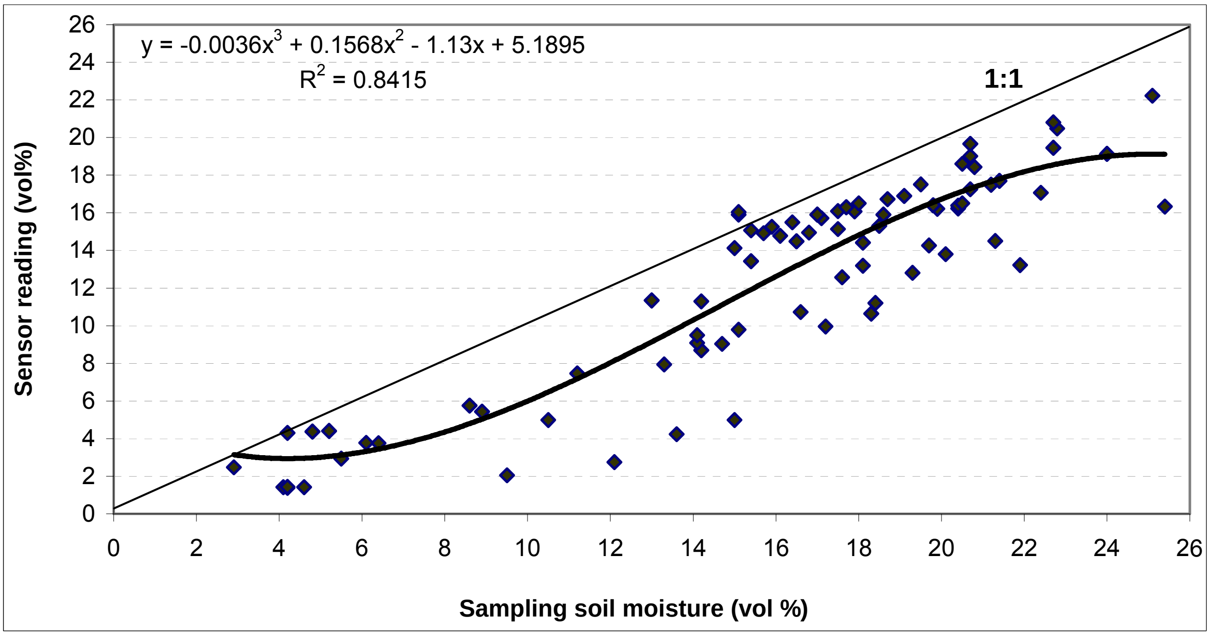


Figure 4.12: Soil-specific calibration curve of the EnviroSCAN sensor installed at different layers of 0 to 10 cm,10 to 20 cm and 20 to 30 cm

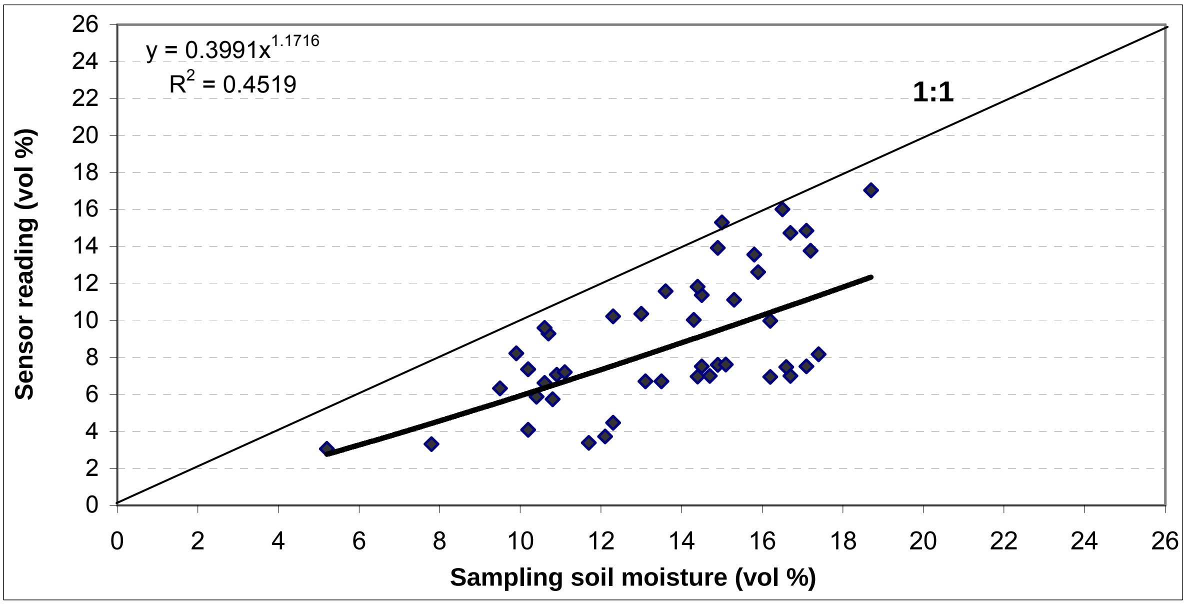


Figure 4.13: Soil-specific calibration curve of the EnviroSCAN sensor installed at different layers of 40 to 50 cm and 50 to 60 cm

The results shown in Figures 4.12 and 4.13 indicated that EnviroSCAN sensors installed at depths between 40 and 70 cm (where soil texture was more sandy) were not able to repeat the soil moisture conditions ($R^2 = 0.45$) because the soil moisture content variation shown by them was not similar to the values gained from soil samples. But a good calibration coefficient of $R^2 = 0.84$ was found for sensors installed in loamy sand layers (upper 40 cm). Thus, uncalibrated EnviroSCAN-based soil moisture measurements in the upper 40 cm must be modified by using the calibration equation of Figure 4.12, where x is uncalibrated EnviroSCAN-based soil moisture measurement by content and y is soil-specific modified or calibrated EnviroSCAN-based soil moisture reading by volume. Therefore, a soil specific calibration of each sensor would have been necessary to obtain a high degree of absolute accuracy in soil water content measurements. Thus, it could be concluded that the expensive EnviroSCAN sensor is not a reliable sensor to repeat moisture conditions on sandy soils and it could not be applied in an effective way to measure soil water content. However, the sampling water content method as a witness measurement may not be correct. Therefore, the distance between the sampling points and the installation point of the sensor must be reduced and more sampling and calibration points are needed in order to improve accuracy.

4.2.2.2 The field tests of data transmission and power supply

Communication from the EnviroSCAN sensors to the central ISM modem and PLC worked as expected. The 2.4 GHz band of 8N1 wireless serial protocol combined with two specific antennas from VIMCOM AG (model 242451) and MOBILE MARK (model RMM-UMB) was found to be a wireless solution for the in-field wireless sensor used in this study. It was found that the maximum data transfer rate of 2400 bit/sec reached by 8N1 serial over a 400 m distance is significantly bigger than the data transfer rate needed for this study, because soil moisture data were transferred every 4 minutes. However, it could be reduced to every one hour in real-time PI.

The field tests showed that soil moisture data can be transferred between two ISM modems as well without any problem as it was tested for different distances of 50, 100, 150, 200, 250, 300, 350 and 400 m. Field observation showed that the VIMCOM antenna (model 242451) installed at a height of 5 m, which had a frequency of 2310-2485 MHz and a bandwidth of 175 MHz enabled the transfer range for soil moisture data to be increased from 300 m to 400 m. Moreover, soil moisture data measured at 00:00 o´clock (the same time when weather data measurement by DWD begins) were easily received on a mobile phone and then transferred to a programmed Excel table on a computer using “Kurznachricht Pro 2.2” software to calculate irrigation depth and draw its variation.

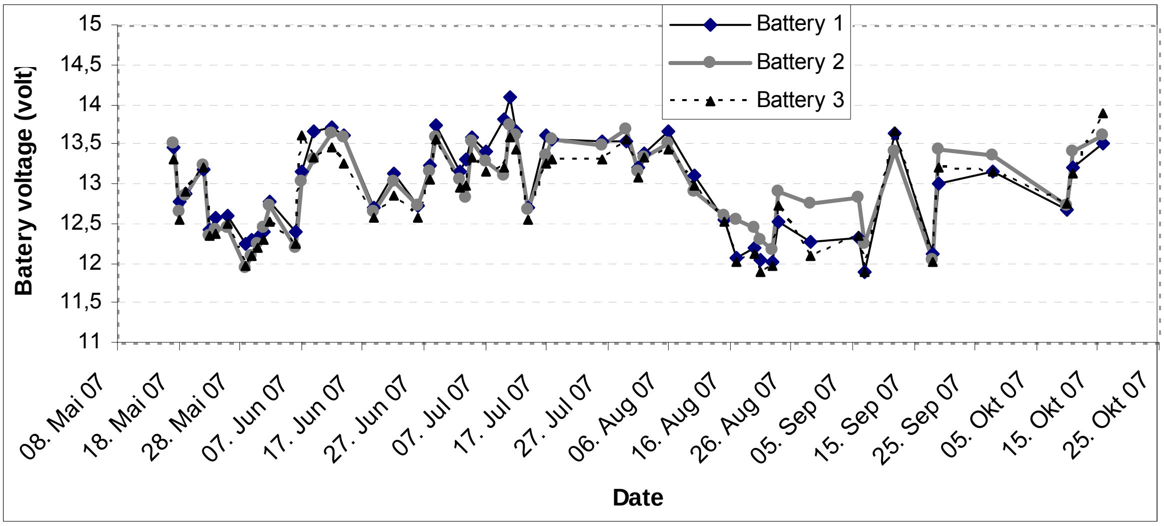


Figure 4.14: Variation of battery voltage during measuring period

The “Kurznachricht Pro 2.2” software and the simple Excel program for the calculation of irrigation depth and the drawing of its variation were found to be easy and suitable to use and to improve application. The battery voltage dissipation of the EnviroSCAN sensor was often observed on rainy or cloudy days, but it did not get below minimum operation voltage (11.2 V) during the measuring period. Therefore there was not any necessity for battery recharging to avoid lower voltage dissipation. This is an indication that the solar panel size was adequate for the self-recharging of batteries. Figure 4.14 shows the variation in the voltage of three batteries placed inside three IMZs during the measuring period with a minimum battery voltage of 11.9 V.

4.2.2.3 Validation of the AMBAV model

A comparison between the observed soil water content using sampling and simulated values of soil water content in the upper 60 cm (root zone) of grass crops during the measuring period reveals close variation, and the model satisfactorily simulated the SWC (Figure 4.15) like in a conceptual model eveloped by Panigrahi and Panda (2003) where SWC was simulated reliably in the root zone of crops. The results suggest that AMBAV model is a cheap method that can be used instead of expensive and nonereliable EnviroSCAN soil moisture sensors for irrigation decision support. Simulated values of SWC during the measuring period gained using the AMBAV model are shown in Appendix D in millimetres of water available in the root zone. The simulated SWC in the root zone of grass can be calculated as follows:

$$\text{SWC [vol \%]} = ([\text{available water in root zone [mm]} + (\text{P.W.P.} = 24\text{mm})]/\ 600) \times 100 \qquad (4.1)$$

In some cases, discrepancies between the observed and simulated values of soil water contents are noticed. The reason might be due to spatial variation in soil water content. In the simulation model, it is also assumed that all the soil water in excess of soil storage capacity percolates out of the active root zone of the crop instantaneously, which is not true under actual field conditions. Downward flux in the soil profile below the root zone actually continues for several days after redistribution. Because of the aforementioned reasons, some discrepancies are noticed in some cases between the observed and simulated values of soil water content in the active root zone.

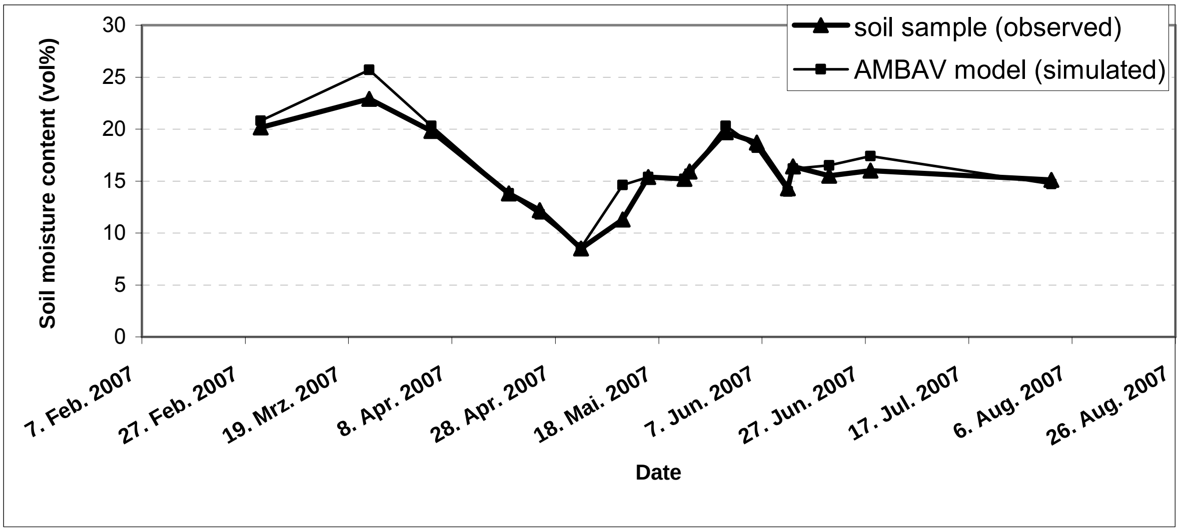


Figure 4.15: Observed and simulated SWC in the upper 60 cm of grass on different days

However, a significant finding observed in the present study is that the trend of variation of soil water content throughout the growing season remains constant for both observed and simulated cases. The soil was watered many times due to irrigation and rainfall as is shown in Figure 4.11b. During the periods when there was neither rainfall nor any supplementation by irrigation, the soil water content in the root zone was depleted gradually. This is due to the loss of water by the grass in the form of evapotranspiration. However, if during the crop-growing season there was any rainfall or irrigation, then water content in the root zone was observed to increase as shown in Figure 4.11a and c.

To strengthen the model`s predictive performance, the values of the coefficient of determination (R^2) of the observed and the simulated root zone soil water content were estimated. The R^2 value was 0.94 (Figure 4.16). Since the R^2 value was close to one, it could be concluded that the AMBAV model performance was satisfactory in simulating the root zone soil water content under field conditions. In addition to the graphical presentation, statistical tests were carried on to investigate the model´s predictive performance. The MARE value was found to be 0.11. The low values of MARE (according to the methods outlined in Equation 4.8) of the simulated and observed data signify that the AMBAV model can be safely used for the simulation of the root zone soil water content. Furthermore, the PE index was estimated using the methods outlined in Equation 4.9. It was found out that the value of the PE index is 0.999 (99.9 %). Low MARE values and high values of PE and R^2 indicate that the soil water balance simulation model as presented in the paper can be used safely to simulate the soil water content in the root zone.

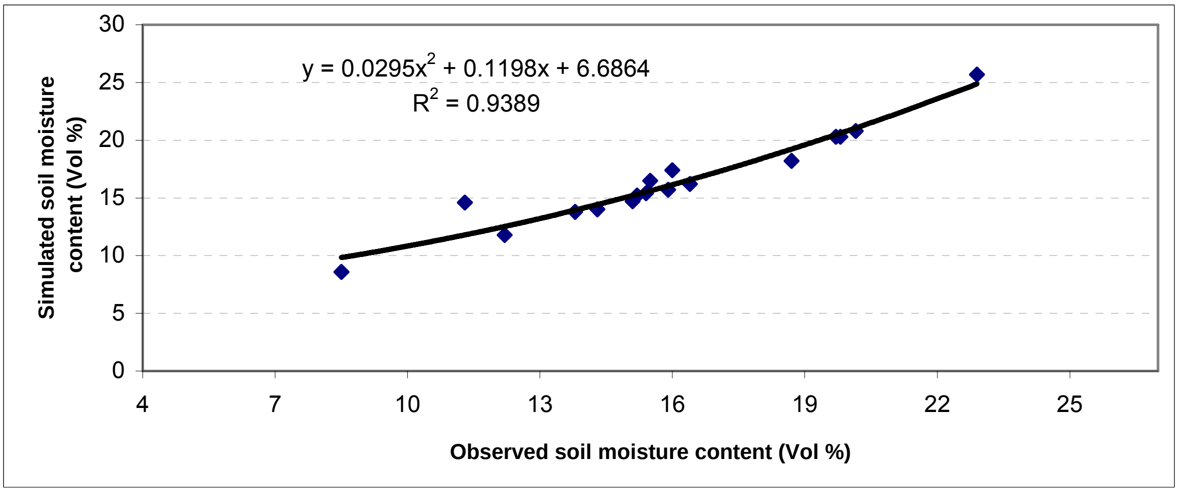


Figure 4.16: Relationship between observed and simulated SWC

4.2.3 Evaluation of the modified centre pivot irrigation system

The results of the evaluation of the modified centre pivot were divided into three parts of field tests, in which PLC performance, the number of emitters installed on the drop tubes, the length of the drop tubes and the laboratory and field tests of drop tubes were assessed.

4.2.3.1 Field tests for the evaluation of programmable logic control performance

The PLC and the solenoid valve functioning (open and close) was able to pulse the water on and off for any given application rate at a programmable pulsing level from 0 to 100 % in a pulsing interval of 100 seconds and at 15 to 30 % of the given CP speed. Field observation showed that the opening and closing time of the SV depended on the pulsing level at a rate of 100% (nozzle on for 100 seconds, off for 0 seconds), at a rate of 90 % (nozzle on for 90 seconds, off for 10 seconds), at a rate of 70 % (nozzle on for 70 seconds, off for 30 seconds), at a rate of 60 % (nozzle on for 60 seconds, off for 40 seconds), at a rate of 40 % (nozzle on for 40 seconds, off for 60 seconds), at a rate of 30 % (nozzle on for 30 seconds, off for 70 seconds), at a rate of 10 % (nozzle on for 10 seconds, off for 90 seconds). Figures 4.17 and 4.18 show the pulsing effect on nozzle irrigation depth. The results show that the pulsing technique operated successfully while providing a flexible means of applying variable water treatments (Fraisse et al., 1995 and Duke et al., 1997). Although the control system was firstly programmed on a pulsing interval of 20 seconds but field observation showed that a 20 second pulsing interval is short because of water hammering due to valves being turned on and off at various pre-planned locations in the field (changes in flow rate and then changes in pressure). Therefore the pulsing interval was increased to 100 seconds, but it is proposed to apply pulsing intervals longer than 100 seconds. In order to solve the problem of water hammering in the variable rate linear move irrigation system, Moore et al. (2005) installed a variable frequency drive (Zentac America, Madison, CT) on the pump that was manufactured by Franklin Electric to slow down the motor as flow decreased to the system. The variable frequency drive operates in the range from 60 Hz at full capacity to about 40 Hz. When the pump motor turns at a rate below 40 Hz, it will automatically shut down the motor to prevent overheating of the shaft and bearings. A high pressure cut-off switch was also installed at the pump to shut it down if line pressure exceeds 550 kPa.

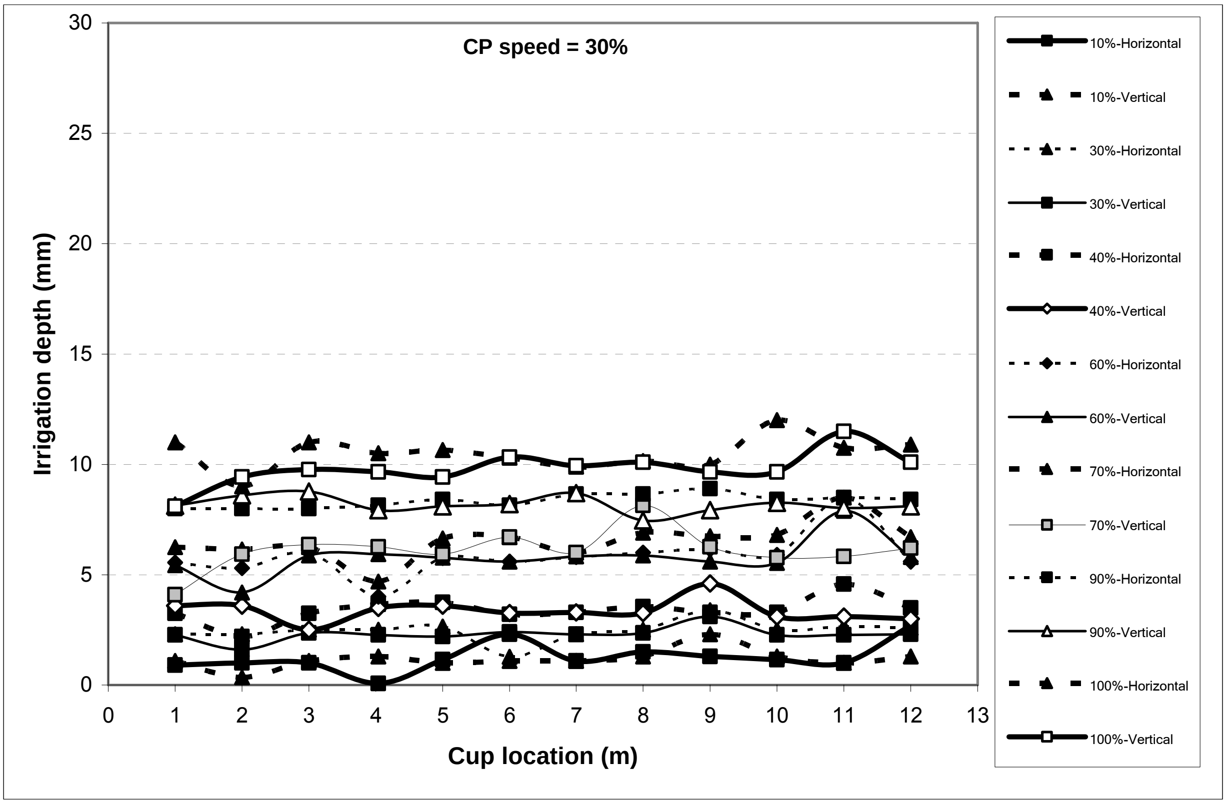


Figure 4.17: Pulsing effect on nozzle irrigation depth under 30 % CP speed

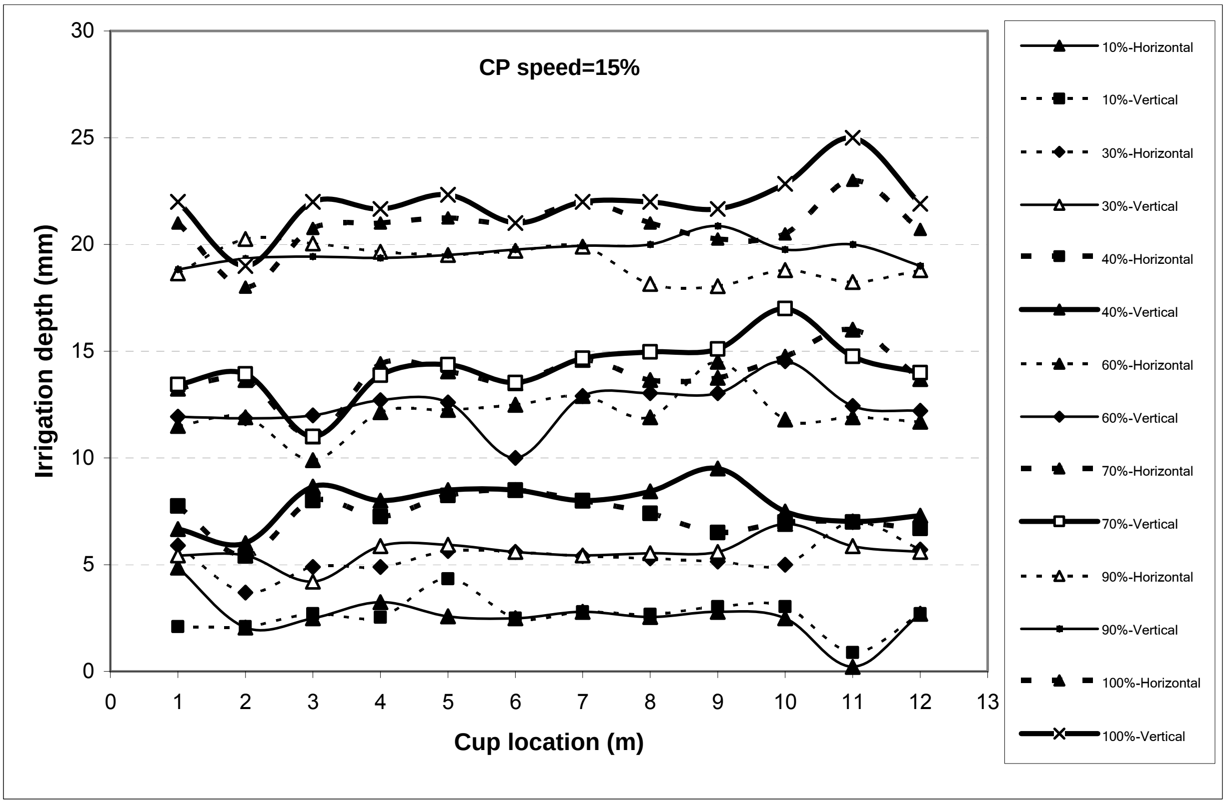


Figure 4.18: Pulsing effect on nozzle irrigation depth under 15 % CP speed

Table 4.3: Average irrigation depth and error produced at different pulsing rate and CP speed

Pulsing level [%]	**CP speed 15** [%]			**CP speed 30** [%]		
	Measured Irrigation depth [mm]	Theoretical irrigation depth [mm]	Error [%]	Measured Irrigation depth [mm]	Theoretical irrigation depth [mm]	Error [%]
10	2.6	2.15	20.9	1.1	1.02	7.8
30	5.5	6.45	14.7	2.4	3.06	21.6
40	7.7	8.6	10.5	3.4	4.08	16.7
60	12.3	12.9	4.7	5.7	6.12	6.9
70	14.1	15.05	6.3	6.3	7.14	11.8
90	19.4	19.35	0.3	8.3	9.18	9.6
100	21.5	21.5	0.0	10.2	10.2	0.0

Generally measured irrigation depths reached the target depths, but there was significant difference between measured and target irrigation depths for low pulsing levels as shown by Table 4.3. This difference was reduced by increasing the pulsing level and decreasing CP speed. These results are in agreement with field observations and also in agreement with Fraisse et al. (1995) since the valves had a discrete response time for opening and closing (valves open quickly, but require a longer time to close) and can have a greater effect on water distribution during short time irrigation than during long time irrigation (irrigation time is short when CP speed is high and pulsing level is low). However, it could be concluded that irrigation depth determination must be based on field measurement instead of theoretical calculation. Nozzle irrigation depth at other CP speed dial settings was determined with due attention to the nozzle irrigation depth of 15 to 30 % and the relationship between the speed dial setting on the CP control box and the linear speed at the end of the 2nd CP span (Figure 4.19).

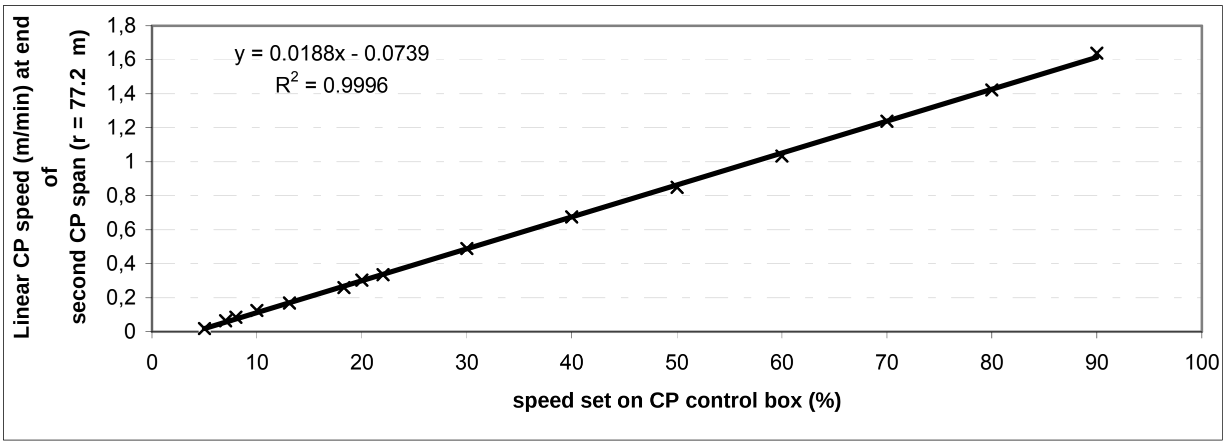


Figure 4.19: Relationship between speed dial setting on CP control box and linear speed at the end of 2nd CP span

The measurements indicated some deviations at the management zone’s border with more/less irrigation depth than the target depths. The error is considered very small when compared to typical sizes of irrigation zones and when considering that in the border area (where the irrigation zone receives water from sprinklers which are installed inside overlapping neighbouring irrigation zones) water application depth or rate blending will occur. This is because the sprinklers used in the package had a relatively large wet radius, which indicates the importance of using sprinklers with a smaller wet radius to reach depths much closer to the target depths. Moreover, the selection of the proper sprinkler packages also has an effect on the size of the management unit or the zone in the application map, which depends mainly on the ability to measure and manage it (Blackmore, 1994). Therefore, as suggested by Omary and Sumner (2001), the throw radius of the spray nozzle should not be larger than three times the spacing between the spray nozzles. The contrasts between the target and measured depths at the border area is decreased and increased when the required change in water depth is small and big, respectively. This indicates that this variable rate irrigation system is appropriate for applying variable target amounts step-wise. Otherwise some deviations in the applied amount are expected. In this study, however, sprinklers were actually replaced by drop tubes. Therefore, they could not cause deviations in the management zone’s border with more/less irrigation depth than the target depths, which can be considered one of the advantages of PMDI.

With due attention to linear the CP speed at the end of the 2^{nd} span at 30 % and 15 % of the programmed CP speed, which was 0.489 and 0.208 m/min, respectively, irrigation depth produced under 15 % has to be 2.35 times more that irrigation depth produced under 30 %, but field tests showed that the proportion was about 2.21 times greater than the small deviation between measured and target irrigation depth (Figure 4.20). Although some deviation could be caused by wind that exceeded the maximum velocities described by the ASAE Standard S436.1 (2003) for a short time, it can be concluded that the determination of irrigation depth must be based on field measurements instead of theoretical calculation. This suggests that wind was a factor in this study for a short time. This was important to prevent any other factor affecting water distribution except the open/close time of the solenoid valves.

Because the system pulses water on and off to produce the desired amount of irrigation, the uniformity of water application along the system is a concern. In site-specific irrigation, the distribution uniformity within each IMZ must be as uniform as possible. Therefore water distribution uniformity was also considered to be a vitally important aspect of the performance of the system using sprinkler outlets before installing drop tubes. The insignificant deviation in

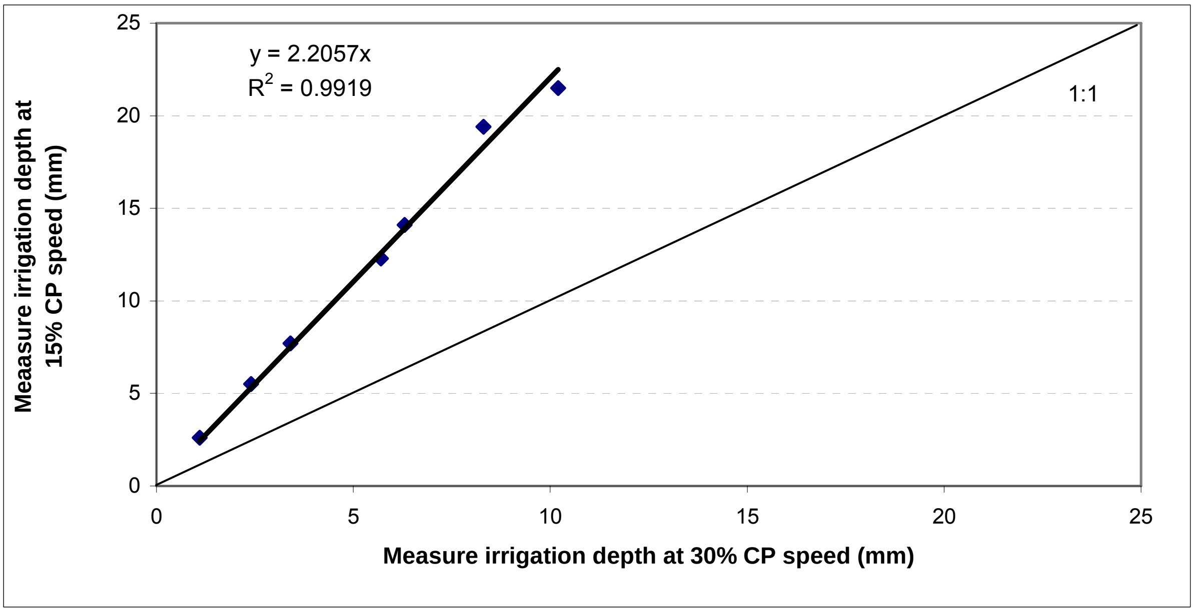


Figure 4.20: Comparison between irrigation depths produced under 15 % and 30 % of programmed CP speed

water distribution patterns could be attributed to the small loss in pressure due to the solenoid valve installation which has a low impact on the distribution patterns (Fraisse et al., 1995). The coefficient of uniformity for conventional CP irrigation systems ranges from 0.85 to 0.95 (Scherer et al., 1999).

The coefficients of uniformity at different pulsing levels and CP speeds in this study can be seen in Table 4.3. The solenoid valve functioning (open and close) had no effects on the CU and the uniformity of the nozzle output was not adversely affected by using the pulsing technique for water application as compared to the uniformity of a conventional CP system.

In this study and based on equation 4.10 (Heermann et al. 1992), the CU was between 72.8 and 97.2 % as shown in Table 4.4. Michael et al. (2006) came to a similar conclusion that tested uniformity of variable-rate irrigation control systems and measured CU equal to 93 and 84 % for modified centre pivot and linear move systems, respectively. Also Moore et al. (2005) and King and Wall (2001) obtained a high quantity range of CU from 79 to 95 % for irrigation depths between 6 to 25 mm for a variable rate linear move system and from 87 to 92 % for relative application rates of 33 to 100 % and mean water application depths within 10 % of the target depths of modified CP, respectively, that are in agreement with current results.

Table 4.4: Coefficient of uniformity at different pulsing level and CP speed

Pulsing level [%]	**CU_{HH} at 15 % of CP speed**	**CU_{HH} at 30 % of CP speed**
10	76.3	72.8
30	89.9	91.8
40	90.8	89.5
60	94.4	89.9
70	94.1	90.8
90	96.2	96.9
100	97.2	94.7

There were no observed system failures or malfunctions that would affect its performance, except that the pressure in the system inlet at the pivot point was significantly changed (increased or decreased) when a section of CP was arriving to the new IMZ or while simultaneously opening or closing all the solenoid valves. Since no system failures or malfunctions occurred it could be concluded that the position encoder can help PLC to find the spatial location of each irrigation depth as well.

One of the most important advantages of MDI is decreased operation pressure around 100 kPa because drop tubes were used instead of sprinklers. But field observation has shown that although about 100 kPa operation pressure was enough for drippers it was not able to open and close the "Baureihe 82340/82440" solenoid valves and that the inertia of the solenoid valve must become better. Thus, operation pressure was obligatorily increased to 120 kPa in the SV position. Therefore it is proposed to select SV with good inertia, which are able to provide the minimum required dripper operation pressure.

In this study, besides simplicity and flexibility, the risk of system failure caused by mechanical damage or electrical storms and wiring costs was reduced for an EIB-BUS or DIC system in comparison to centralized control systems. Although the cost of multiple control units required by a DIC control system used in this study could be greater than the cost of a central controller required by a centralized control system, the wiring costs for the distributed control system would be significantly reduced.

4.2.3.2 Number of emitters installed on the drop tubes and length of drop tubes

The number of Siplast on drop tubes emitters installed on 2nd span was calculated based on Equation 4.11 and Siplast emitter discharge at 120 kPa (q_e = 15.8 l/h), the irrigated area covered by the drop tubes (the distance from the pivot point and narrow spacing covered by drop tube), irrigation time (T = 48 h, that was equal to CP dial set of 14 %) and the maximum irrigation depth required within IMZ_1 (I_{max} = 21.7 mm) as indicated in Appendix E. The number of drop tubes installed on the CP, drop tube position, distance between drop tubes, narrow spacing covered by the drop tube, irrigated area covered by the drop tube, volume of water which has to be discharged by the drop tube for I_{max} = 21.7 mm, discharge of water by the drop tube for I_{max} = 21.7 mm and CP speed = 30 % and the related number of emitters installed on the drop tube and the length of the drop tube are shown in Appendix E. According to the number of emitters installed on each drop tube and the spacing between emitters on the drop tube (20 cm), the length of the drop tubes at any point of the pivot lateral was calculated using equation 4.12. The water quantities at the drop tubes increased with growing the distance from the pivot point. Thus, the length of the tubes and the number of emitters installed on each drop tube were increased with growing distance from the pivot point. The shortest drop tube, which was located at a distance 39.67 m from the pivot point, and the longest drop tube located at a distance 77.02 m from the pivot point had lengths of 1.4 and 3.0 m, respectively. The minimum number of emitters installed on the shortest drop tube and the maximum number of emitters installed on the longest drop tubes of the 2nd CP span were 7 and 15 respectively. For a CP 400 m in length, the number of emitter installed on the last drop tube and the length of the last drop tube will be 80 and 16.0 m, respectively. Although a pressure of 170 kPa on the pressure manometer was used at the beginning, it was decreased to 120 kPa as a suitable operation pressure at the beginning of the drop tubes and before the pressure regulator (Figure 3.17), because of the possibility to save energy. In Figure 4.21, the lengths of the drop tubes are calculated at two pressures of 120. To show the effect of water pressure on the length of the drop tube, it is also calculated for 170 kPa. The calculated length of the drop tube at 120 kPa was longer than at an operating pressure of 170 kPa because of less emitter discharge. With due attention to increasing drop tube length with growing distance from the pivot point, it is better to calculate the friction force between the drop tube and the grass in particular for the last span of the CP as it was calculated by Derbala (2003).

Field observations showed that the drop tube was tangled into the CP drive mechanism when the CP changed its direction. Thus, a metallic bar was installed at a distance of 0.5 m and parallel to the CP wheel to solve this problem (Appendix G).

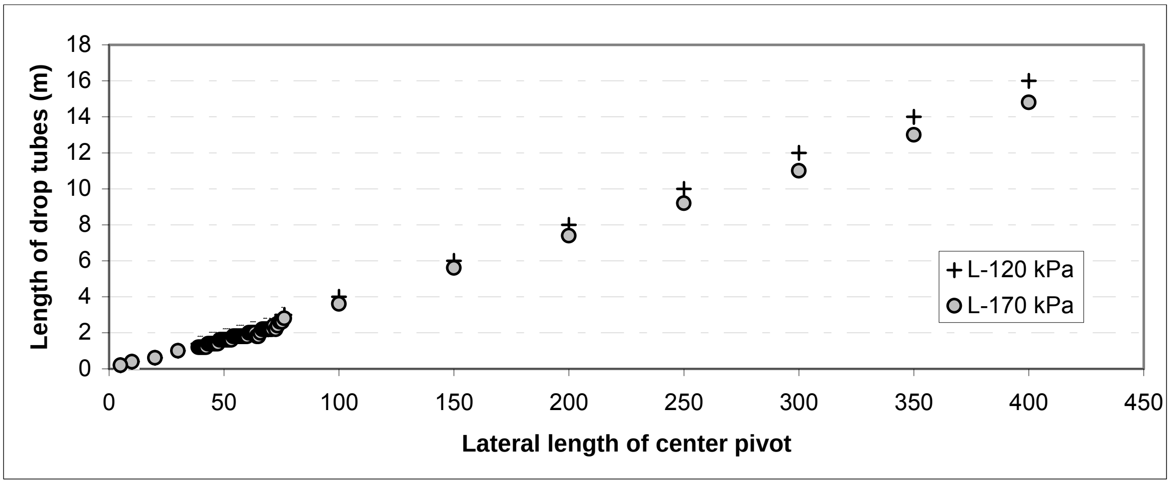


Figure 4.21: Length of drop tubes at two pressures under the conditions of MDI with a centre pivot irrigation system

4.2.3.3 The laboratory and field tests of drop tubes

Different performance parameters were calculated in the laboratory to illustrate the relationship between the operating pressure and discharge rate, the emitter discharge exponent, the coefficient of variation, flow variation and emission uniformity. The pressure-discharge relationships of emitters are expressed by equation 4.13. The Siplast emitter discharge was very uniformly distributed for all emitters at all operating pressures as shown in Figure 4.22. At the same time, the discharge increased linearly as the operating pressure grew because this type of emitters is a non-pressure compensating (NPC). The effect of operating pressure on the emitter discharge was highly significant and the emitter discharge was strongly influenced by the operating pressure. The discharge was about 10 l/h and 19.4 l/h at 50 kPa and 200 kPa, respectively.

Means of the measured discharge rates at different operating pressures are illustrated in Figure 4.23. The results indicated that the emitter discharge rate increased linearly with operating pressure. Except at 200 kPa, measured discharge flow rates at other pressure levels and in particular at 50 kPa did not reach the design flow rate claimed by the manufacturer. These variations are presented in Table 4.5.

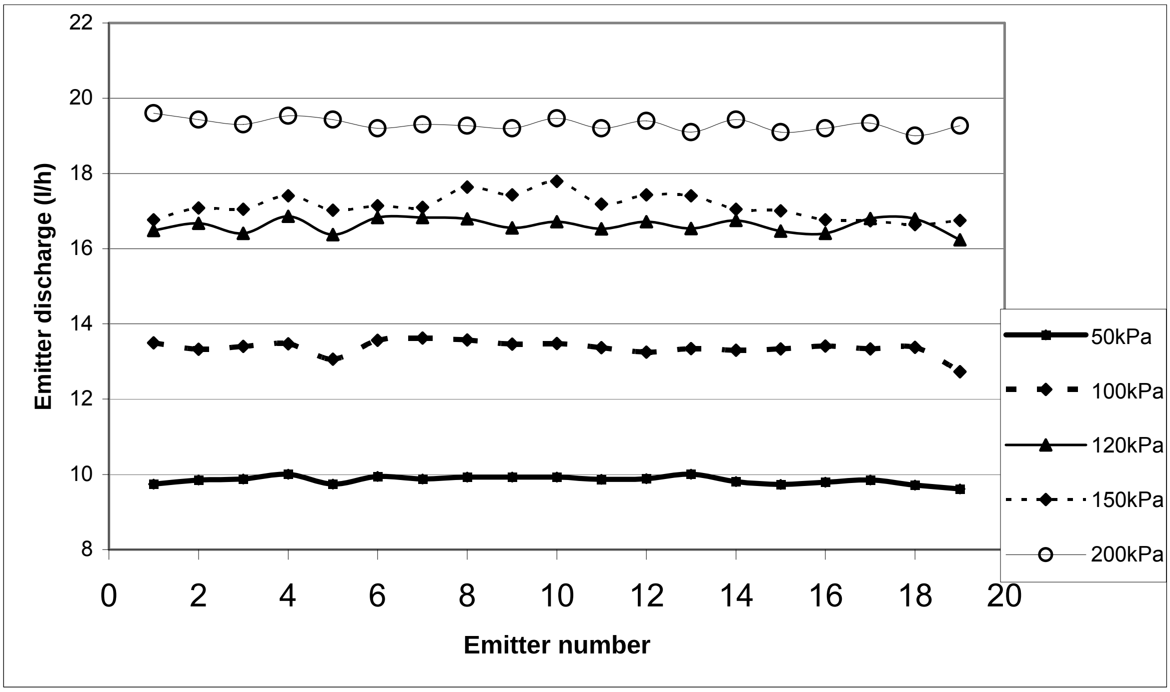


Figure 4.22: Emitter discharge rate at different operating pressures for drop tube including 19 emitters under laboratory condition

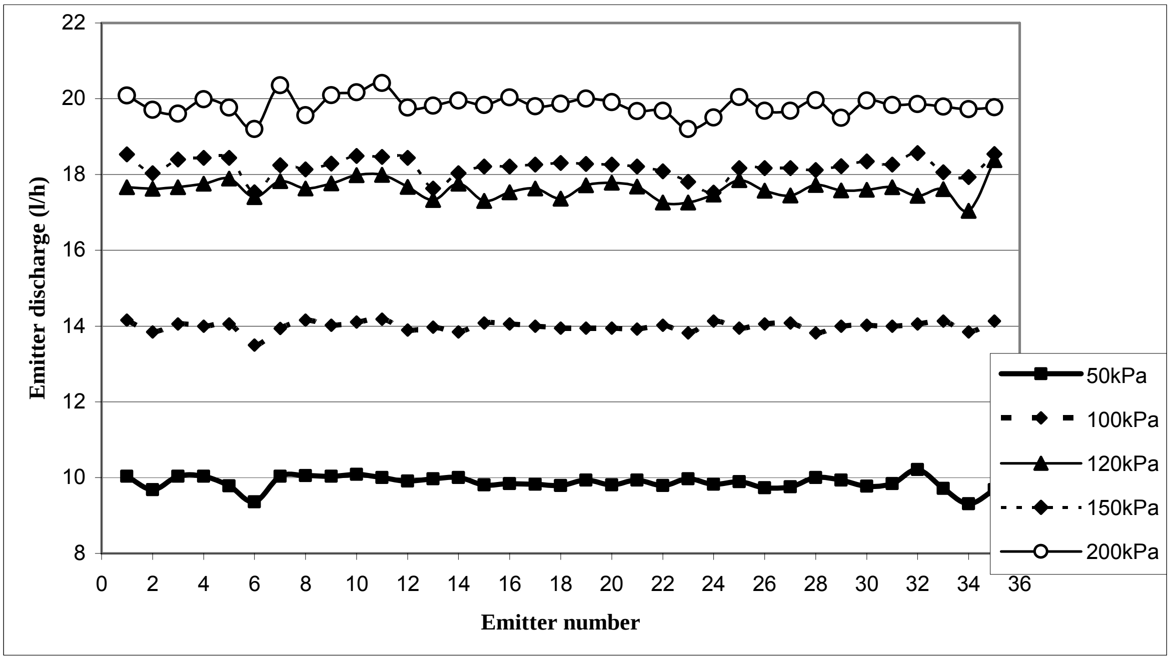


Figure 4.23: Emitter discharge rate at different operating pressures for drop tube including 35 drippers under laboratory conditions

Table 4.5: Average difference between the nominal discharge indicated by manufacturer and measured discharge in laboratory

Emitter pressure [kPa]	Nominal discharge by manufacturer [l/h]	Measured discharge in laboratory [l/h]	Difference [%]
50	11.1	9.9	- 10.8
100	14.5	13.7	- 5.5
120	15.7	17.1	+ 8.9
150	17.1	17.7	+ 3.5
200	19.4	19.4	0.0

In addition, the hydraulic characteristics of emitter were calculated based on estimated coefficient of determination values. Ke and x were 1.3444 and 0.5128, respectively as shown in Figure 4.24. With due attention to the turbulent flow type when the emitter exponent values is higher than 0.5, the Siplast emitter is classified as NPC. The coefficient of determination (R^2) is also reported. When the R^2 value is very close to 1, equation 4.13 is an appropriate model for the description of the relationship between the discharge and the pressure of these emitters, but low R^2 values either indicate considerable data scattering or that the model used was not appropriate. The coefficient of determination for the Siplast emitter was 0.96 (given by Figure 4.24). Thus, equation 4.13 is an appropriate model for the description of the relationship between the discharge and the pressure of Siplast emitters.

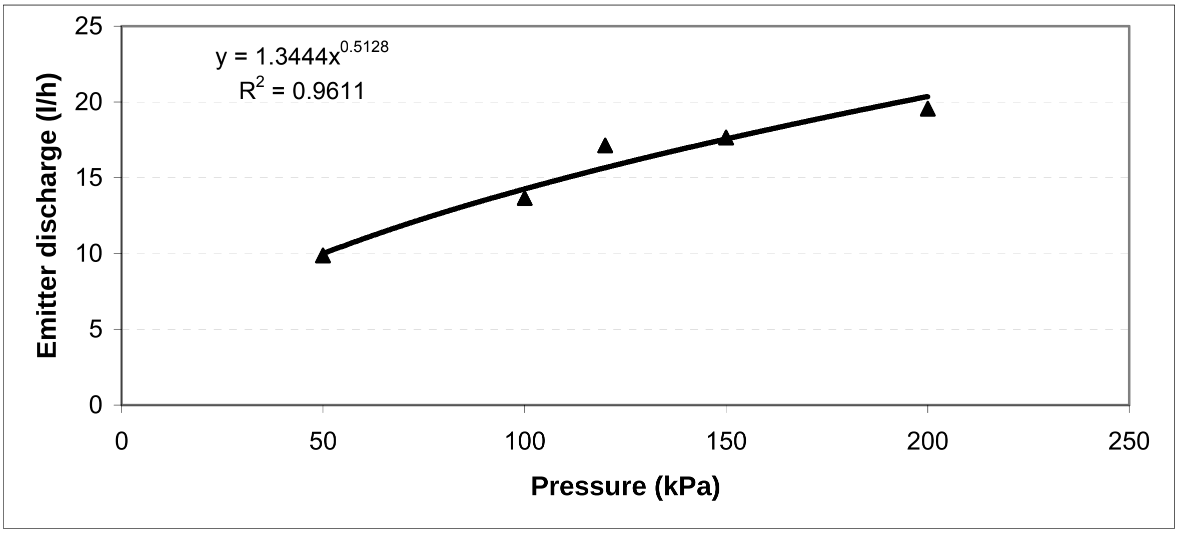


Figure 4.24: Means of measured discharge rates for all tested emitters at different pressures under laboratory conditions

The coefficient of discharge variation of emitters in the sample falling within a given deviation from the mean discharge was calculated using equation 4.14. The results indicated that the coefficient of discharge variation value was followed by a normal distribution at each operating pressure. Emitter performance was classified as good based on the coefficient of variation in Table 4.2, according to ISO standards (1991). Emission uniformity was calculated using equation 4.16. The relationship between operating pressure and both emission uniformity discharge and the coefficient of variation is illustrated in Figure 4.25. The emission uniformity value was higher than 95 % at all operating pressures. At the same time, results indicated that the measured CV value at 100 kPa was less than the design CV (3 %) claimed by the manufacturer as shown in Figure 4.25. The fluctuation of the coefficient of variation with pressure may be used to define emitter discharge sensitivity to pressure. The manufacturer coefficient of variation should be 15 % or less to achieve reasonable uniformity of water application (Solomon, 1977). The results showed that an increasing value of the coefficient of discharge variation CV leads to decreasing emission EU uniformity.

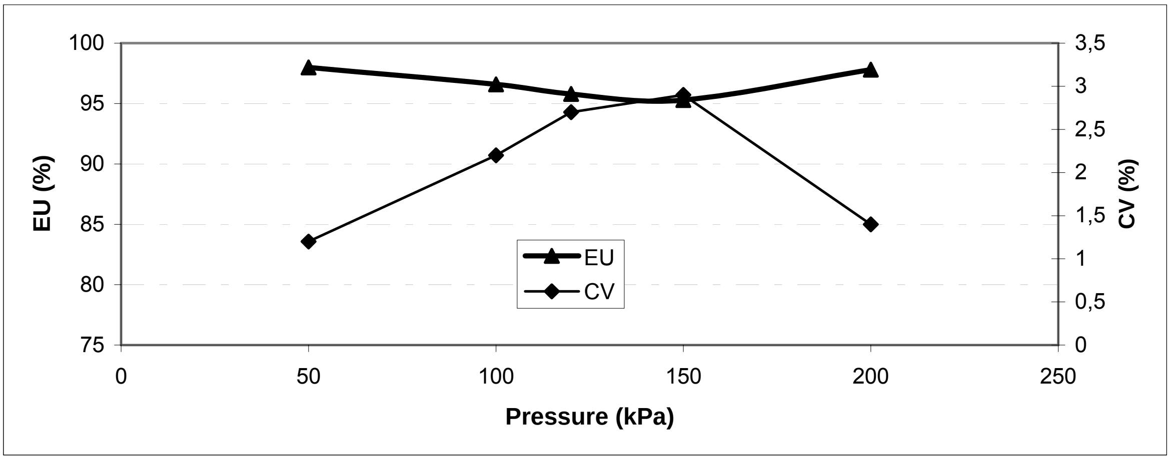


Figure 4.25: Relationship between the operating pressure and both the coefficient of variation and emission uniformity of Siplast drop tube

The calculation of emitter flow variation using equation 4.17 showed that the mean value of emitter flow variation was about 10.9 % at operating pressures ranging from 50 kPa to 200 kPa and that the maximum value of emitter flow variation was reached at 120 kPa. These results are presented in Figure 4.26.

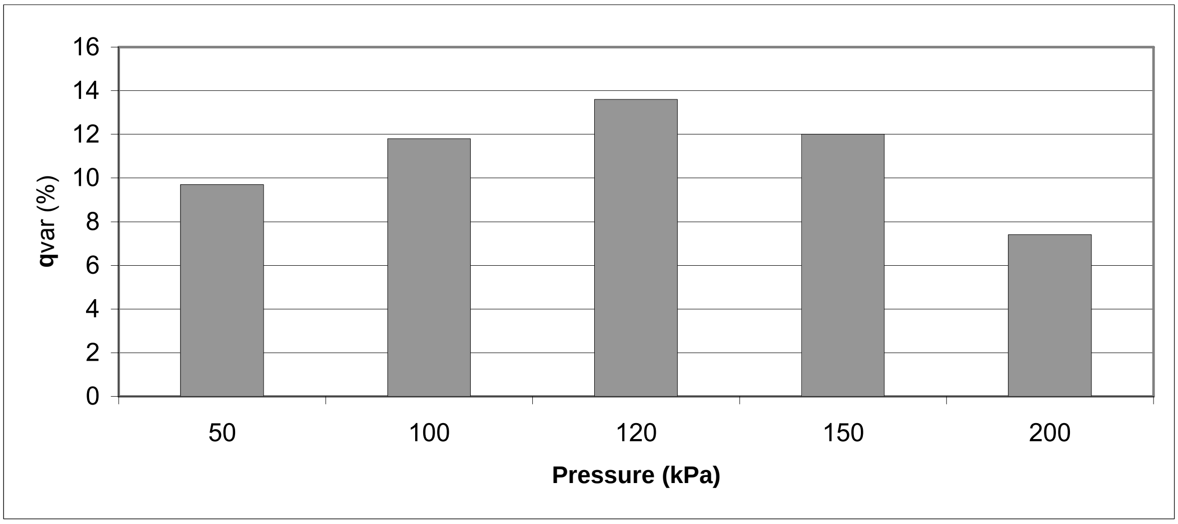


Figure 4.26: The relationship between different operating pressures and emitter flow variation

The calculation of water application rates by MDI and two drop tubes (Ne = 19, LT = 3.8 m and Ne = 35, LT = 7.0 m) at different CP speeds and different pulsing levels under field conditions showed the expected results. These tests were the suggested solution which would provide variable rate water application in the radial direction as stated in the hypothesis upon which a strategy for precision irrigation is based. These test cases represented different locations in the application map (different angles in the field). The field tests of the drop tube show:

a) The variation of the drop tube flow output is proportionate to the number of emitters installed on the drop tube
b) The variation of the drop tube flow output is proportionate to the pulsing level

Field tests of MDI depth variation were done against pulsing level under different CP speed. An example of this variation for 20 % of CP speed is shown in Figure 4.27. In Appendix F, same curves for 10, 30, 40, 50, 60, 70, 80 and 90 % of programmed CP speed are drawn. In practice, one of these curves can be selected for each irrigation time based on irrigation duration and the maximum available flow rate for pumping.

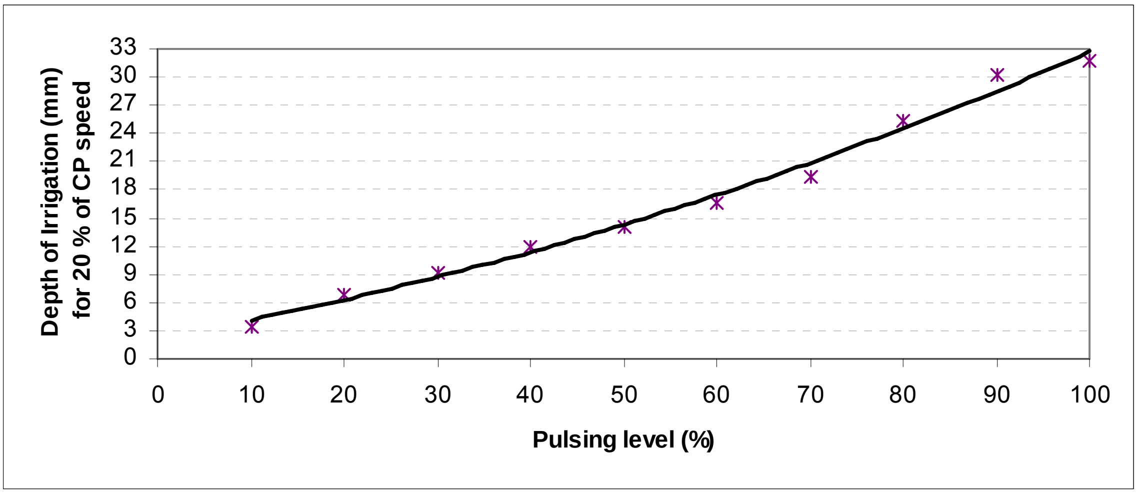


Figure 4.27: Field test variation of MDI depth against pulsing level for 20 % of programmed CP speed

With due attention to different irrigation rates needed to cover different irrigation depths, it is very important to consider that the maximum irrigation rate used within IMZs must be below the soil infiltration rate to avoid runoff. Since saturated infiltration rates on the study field are 48 mm/h according to measurements by Seibold et al. (1998), the minimum speed set at the CP control box [%] for the avoidance of runoff was calculated for different pulsing levels. This minimum speed can be calculated based on the water application rate at different pulsing levels, lengths of the drop tube and a saturated infiltration rate of 48 mm/h. CP speed must be reduced by decreasing the pulsing level as shown in Table 4.6.

The results showed that at a pulsing level of 100%, the speed set at the CP control box to avoid runoff must be more than 34.3 %. But the minimum speed set at the CP control box to avoid runoff can be improved by increasing distance between emitters on drop tubes. The results showed that the maximum pulsing level used at 10 % CP speed setting can be 68 % to avoid runoff, but at 20 % of CP speed or more, the maximum pulsing level of 100 % can be used without any runoff as shown by Figures 4.27. The average manufacturer value of discharge and the average values of emitter discharge under laboratory and field conditions at 120 kPa were 15.8, 17.1 and 15.3 l/min, respectively.

Field observation showed that in spite of some advantages of the Siplast drop tube, it has hard and inflexible material and was difficult to install and to work with. Moreover, a metallic horizontal tube was found to be better than a horizontal tube of out polyethylene shown in Figure

3.17 because of the ard sliding of two tubes out of different materials which lay one on top of the other.

Although this system had not experienced any clogging problems even though no filtration system had been installed in the summer of 2006, a DN-150 filter from the company Hüdig (www.huedig.de) was installed between the supply and the pivot point for future applications of mobile CP drip irrigation.

Table 4.6: Minimum allowed speed set at the CP control box to avoid runoff at different pulsing levels

Pulsing level [%]		10	20	30	40	50	60	70	80	90	100
Minimum allowed CP speed to avoid runoff	speed set on CP control box [%]	7.1	10.5	12.6	15.9	17.9	20.0	22.5	28.2	33.0	34.3
	Linear speed at the end of 2^{nd} CP span [m/min]	0.12	0.30	0.49	0.68	0.85	1.03	1.24	1.42	1.64	1.81

4.3 Potential economic implications

The cost of irrigation per hectare varies from system to system, but they all have different economic returns. The primary extra costs in the PI technology are the costs of modification of conventional irrigation systems to PI systems as well as the acquisition of data and their conversion to information. The general introduction of PI will not take place for several years until the field data for irrigation control are available in manageable forms (Sourell and Sommer, 2002). While this management system is in its early stages, it could be expected in the coming years with regard to technological improvements in industry that these extra costs of industrial accessories could be minimised. Thus, a full economic analysis cannot be conducted until full results from research programmes are available.

The potential benefits of a PI system include increased crop yield (King et al., 2006; Camp et al., 2000 and Oliveira et al., 2003), cost-efficient usage of inputs via variable-rate application (Kenneth, 1988), water and energy optimising or saving, reduced contamination of water supplies by deep percolation of agrochemicals or runoff (Beckie et al., 1997; Lindquist et al., 1998) and increasing yield quality (King et al., 2004 and 2006; Nijbroek et al., 2000 and 2003).

In this study, the economic analysis is followed by conclusions based on the model that is presented in Equations 4.1 and 4.2. By this model allows the irrigation costs and farming benefits of different irrigation systems for different crops to be compared.

Total irrigation cost [€/(ha×year)] = fixed costs [€/(ha×year)] + variable costs [€/(ha×year)] (4.1)

Fixed costs are including the repairing, waiting and depreciation costs and the variable costs are including the labour, water and energy costs.

Farming benefit [€/(ha×year)] = (yield [kg/(ha×year)]×yield price [€/kg])–total irrigation cost [€/(ha×year)] (4.2)

4.3.1 Capital requirement and fixed costs

A very expensive prototype irrigation control system (€ 12.900) was used in this study, but for economic analysis, a market price of € 8000 was considered (market price includes cost of development phase). Moreover, although a very expensive "Baureihe SV" (€ 162) from the Buschjost company was used in this study, many other cheaper SV which could be used were found on the market. Some of them are Elektro-Magnetventil and AVS-GAMMA-Ventil at € 74 and € 88, respectively (www.magnetventile-shop.de) and SV from the ESSKA company (www.esska.de) at € 61. Therefore, normal market prices of control systems and solenoid valves were used for the economic analysis of the work carried out in this study. Capital requirements for CP modification and annual fixed cost of different irrigation system per hectare in Germany and Iran are given in Tables 4.7, 4.8 and 4.9. In this study, the costs of ISM modems and wireless soil moisture data transference is neglected, because a CWB-model is considered to be more economical than wireless data transfer with due attention to the fact that the AMBAV-model was developed as a safe and cheap method instead of the expensive and wireless EnviroSCAN soil moisture sensors for irrigation decision support (Each ISM modem and EnviroSCAN soil moisture sensor cost about € 006). A promising hardware low-cost Bluetooth wireless solution (€ 766), which cost 1000 and € 1257, respectively was used, although Kim et al. used five in-field sensing stations to measure soil moisture and soil temperature. The fixed costs determined in the current study are comparable with those found by:

a) Evans and Harting (2005) that a total PLC system costs approximately € 178 per hectare on wiring, while a 370 meter long CP or about € 18 per sprinkler and a pivot control system including PLC, valves, air lines, labour, etc installed directly on the CP machine come to about € 4444 with a GPS compared to € 3333 for the current version of commercially available digital control systems (based on 2004 prices).
b) Miranda et al. (2005) that hardware construction cost for one irrigation controller unit was approximately € 136 (based on 2003 prices), including the solar panel and the battery. With sensors and the latching solenoid valve, the total cost was € 222, but for a production scale of 1000 units, the estimated unit cost would be € 86 for the irrigation controller, and € 150 including sensors and valve and
b) Al-Karadsheh (2003) that a total PI control system including PLC, SV, wiring and technical works costs approximately 194 [€/(ha×year)] (based on 2001 prices).

A comparison between PI costs determined in this study and the expenses for a PI system found in the above mentioned three studies shows that the PI system of the current study is expensive and can be reduced especially for the control system and SV. In the coming years, when this new management system establishes itself, it is expected that these costs will go down to a level that does not make the additional costs an obstacle to the application of such a management system. Capital requirements in Iran are lower than in Germany, particularly in the development phase. Capital requirements per hectare in Iran are considered to be about € 250 (Personal communication, Golestan Agricultural and Natural Resources Research Centre, 2007).

Table 4.7: Details of capital requirements for the modification of a CP with 400 m radius (50.2 ha) and mapping cost for PMDI in Germany (Personal communication, Sourell and Schudzich, 2007)

Item	**No. of units**	**Price per unit [€]**	**cost [€]**
Control System	1	9000	9000
Solenoid valve	33[4]	100 (61-162)	3300
CWB-model	1	70	70
Cables and boxes	------	-------	4350
Pressure sensitive drop tube	4691 m for 120 kPa,	0.25	1173
Fitting	500	1.5	750
EM38(1)- VERIS 3100(2)	50.2 ha	9.5 - 12	540
Soil sampling[3]	50.2 ha	2.7	154
Total			19337
Capital requirements per hectare [€/ha]			385

[1] Service from company Agricon
[2] Service from company Arndt Kerkenpass
[3] Service from laboratory of German Weather Station
[4] Although 3 m distance between sprinklers on the conventional CP irrigation system was considered as minimum width of control zone, but economic analysis of the study was done based on 12 m minimum width of control zone (400/12 = 33).

Table 4.8: Capital requirement of different irrigation systems per hectare in Germany and Iran from hydrant on the ground surface including head station without pump (Enciso et al. 2004; Personal communication, Sourell, 2007; Personal communication, Golestan Agricultural and Natural Resources Research Centre, 2007)

Factors	**Surface irrigation for 50.2 ha**	**Centre pivot with 400 m radius**	**Drip irrigation for maximum lateral length of 200 m and 50.2 ha**	**PMDI with 400m radius CP**
Capital requirement in Germany [€/ha]	---	1077	1451	1462 [1]
Capital requirement in Iran [€/ha]	0	1000	1300	1250 (2)

[1] 1077+385 = 1462
[2] 1000+250 = 1250

Table 4.9: Annual fixed cost of different irrigation systems per hectare in Germany and Iran including repairs, maintenance and depreciation (Personal communication, Sourell (2007), Teichert (2007), Personal communication, Golestan Agricultural and Natural Resources Research Centre (2007). In this table, labour, water and energy cost are not included

Factors	Surface irrigation for 50.2 ha	Centre pivot with 400m radius	Drip irrigation for maximum lateral length of 200 m and 50.2 ha	PMDI with 400 m radius CP
Fixed cost in Germany [€/(ha×year)]	---	143 (1)	306 (2)	195 (1)
Fixed cost in Iran [€/(ha×year)] (3)	0	180 (3)	353 (4)	225 (3)

Amortization of drop tube by Morris (1999), Wade and Boman (2003), Fereres and Meyer (1978), Teichert (2007) and Netafim company (www.netafim.com) were considered 10, 8-12, 7-8, 2, and 5 years, respectively. With due attention to these references, amortization of drop tubes in this study were considered 5 and 4 years for Germany and Iran, respectively.

(1) Interest rate = 3 % of capital requirement per ha, "repair + maintenance" cost = 2 % of capital requirement per ha, depreciation = 8.33 % of capital requirement per ha with 12 years amortization. Although amortization of drop tube under PMDI is also 5 years, but it is neglected because of low proportional cost of drop tube than PMDI.

(2) It is including 570 [€/ha] for head station, chemigation requirement and distribution system with 10 years amortization (10 % of capital requirement depreciation), interest rate = 3 % of capital requirement, "repair + maintenance" cost = 2 % of capital requirement and 881[€/ha] for drop tubes with 5 years amortization (20 % of capital requirement depreciation), interest rate = 3 % of capital requirement, "repair + maintenance" cost = 2 % of capital requirement [(570× 15 %) + (881× 25 %) = 306].

(3) Interest rate = 5 % of capital requirement per ha, "repair + maintenance" cost = 3 % of capital requirement per ha, depreciation = 10 % of capital requirement per ha with 10 years amortization.

(4) It is including 507 [€/ha] for head station, chemigation requirement and distribution system with 10 years amortization and 10 % of capital requirement depreciation, interest rate = 5 % of capital requirement per ha, "repair + maintenance" cost = 3 % of capital requirement per ha and and 793 [€/ha] for drop tubes with 4 years amortization and 25 % of capital requirement per ha depreciation, interest rate = 5 % of capital requirement per ha, "repair + maintenance" cost = 3 % of capital requirement per ha (507× 18 % + 793 × 33 % = 353)

4.3.2 Variable costs

The variable costs of different irrigation systems include labour, water and energy costs. In this study and in agreement with Feinerman and Voet (2000) and the field study of Oliveira et al. (2003), it was found that increasing flexibility of water application (via subdivision of the field into some IMZs) does not necessarily involve a reduction in total water use. As seen in Section 4.1.5, no water could be saved under PI in this study, but it can increase yield quantity and quality with due to optimised water consumption (improving soil moisture and soil aeration conditions). In this study, and because of soil homogeneity of the study area under the second span of the PMDI system, it was not possible to compare the volume of water applied under uniform irrigation and PI. But in this study and in agreement with Perry et al. (2004), water savings of 10 % were seen in the PMDI as compared with drip irrigation. Perry et al. (2004) found the potential water savings from four modified CP at, about 7, 0, 8 and 36 percent water savings compared to a “normal” application based on application maps and soil variability on four fields. Table 4.10 shows irrigation water requirements, yield and yield price of different irrigation systems and crops in Germany and Iran that were derived by the German Ministry for Food, Agriculture and Consumer Protection, 2006; Tognetti et al., 2000; Erdem et al., 2006; Krüger et al., 1999; Kalle and Salo, 2007; Personal communication, Sourell, 2007; Farshi, et al., 1996 and Personal communication, Golestan Agricultural and Natural Resources Research Centre, 2006.

Moreover, total energy use can be calculated based on power input integrated over the time (McCann et. al, 1996). Therefore, the various flows and pressure as reflected in energy use must be identified, because the rate of energy use at any time is a function of flow rate and pressure. However, when PI includes the use of a drop tube instead of a sprinkler, a significant quantity of energy can be saved because of low operation pressure of emitters. If a drop tube is used instead of sprinkler, water could also be saved by converting sprinkler irrigation to drip irrigation. In this study, kWh/m^3 needed for surface irrigation, sprinkler irrigation, drip irrigation and PMDI were considered about 0.0, 0.5, 0.2 and 0.2 kWh/m^3 (Personal communication, Sourell, 2007), for both Germany and Iran. Therefore it could be concluded that energy consumption can be reduced by about 70 % under PMDI as compared with CP if it is possible to use a variable-rate pumps or multiple staged pumps which are expensive. The energy required to discharge one cubic meter of water under PMDI and drip irrigation is reduced by about 0.3 kWh ($[(0.5-0.2)/0.5] \times 100 = 70$ %). Moreover, water consumption is reduced by about 10 % because CP irrigation is replaced with PMDI. Therefore energy saving for different irrigation system and crops in Germany and Iran can be calculated as shown in Figure 4.28. Figure 4.28 shows that although energy saving and consequently cost reduction by PMDI is not too much in comparison to drip irrigation, but in comparison to CP irrigation a high amount of 575.4, 378.0, 462 and 588 kWh energy can be saved per hectare for different crops, such as lettuce, sugar beet, potato and strawberry, respectively. Also the energy and water cost of different irrigation system and different crops are calculated in Table 4.11. Table 4.11 showed that in addition to perceptibly lower annual fixed cost of PMDI than drip irrigation (Table 4.9), it also has less labour, water and energy costs also in both of Germany and Iran.

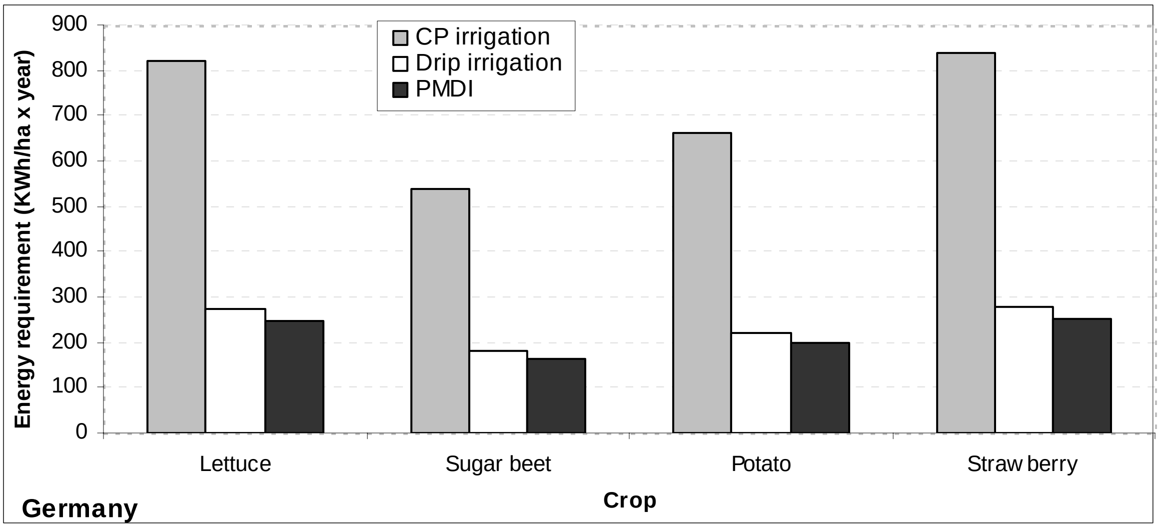


Figure 4.28: Energy requirement of different irrigation systems and some crops in Germany

Table 4.10: Irrigation water requirement, yield and yield price of different irrigation systems and some crops in Germany and Iran

Item	Germany				
	Irrigation system	**crop**			
		Lettuce	Sugar beet	Potato	Strawberry
Irrigation water requirement [m³/ha]	CP irrigation	1644	1080	1320	1680
	Drip irrigation	1370	900	1100	1400
	PMDI (1)	1233	810	990	1260
Yield [kg/ha]	CP irrigation	43000	60000	43000	15500
	Drip irrigation	48000	70000	46000	19000
	PMDI	50400	73500	48300	19950
Price [€/kg] (2)		0.60	0.05	0.37	1.65
	Iran				
	Irrigation system	**Crop**			
		Cotton	Lettuce	Potato	Strawberry
Irrigation water requirement [m³/ha]	Surface irrigation	11340	12650	9407	12650
	CP irrigation	5965	6655	4949	6655
	Drip irrigation	4930	5500	4090	5500
	PMDI (1)	4437	4950	3681	4950
Yield [kg/ha]	Surface irrigation	2050	30000	23000	11000
	CP irrigation	2700	40000	34000	13000
	Drip irrigation	3600	47000	40000	16000
	PMDI	3780	49350	42000	16800
Price [€/kg] (2)		0.45	0.12	0.085	0.45

(1) It this study and in agreement with Perry et al., (2004) 10 % water saving is considered with PMDI in comparison with drip irrigation.

(2) Yield price in field is to be considered about 66 % of wholesale selling prices (Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz, 2006)

Table 4.11: Required labour, water and energy cost of different irrigation systems and some crops in Germany and Iran

Germany					
Item	Irrigation system	Lettuce	Sugar beet	Potato	Strawberry
Required labour cost related to irrigation [€/(ha×year)]	CP irrigation(3)	0	0	0	0
	Drip irrigation(4)	245	245	245	245
	PMDI (3)	0	0	0	0
Energy and water cost [€/(ha×year)](1)	CP irrigation	123+8.2	81+5.4	99+6.6	126+8.4
	Drip irrigation	41+6.9	27+4.5	33+5.6	42+7.0
	PMDI	37.8+6.3	24.3+4	29.7+5	37.8+6.3(2)
Iran					
Item	Irrigation system	Cotton	Lettuce	Potato	Strawberry
Required labour cost related to irrigation [€/(ha×year)]	Surface irrigation(5)	25	25	25	25
	CP irrigation(3)	0	0	0	0
	Drip irrigation(6)	15	15	15	15
	PMDI(3)	0	0	0	0
Energy and water cost [€/(ha×year)](1)	Surface irrigation	0+68	0+75.9	0+56.4	0+75.9
	CP irrigation	63+35.8	6.7+39.9	5+29.7	6.7+39.9
	Drip irrigation	2+29.6	2.2+33	1.6+24.5	2.2+33
	PMDI	1.8+26.6	2+29.7	1.5+22.1	2+29.7

(1) Water cost in Germany and Iran were 0.005 and 0.006 [€/m^3], respectively. Cost of electricity in Germany and Iran is 0.15 and 0.002 [€/kWh], respectively. In this study, kWh/m^3 needed for surface irrigation, sprinkler irrigation, drip irrigation and PMDI were considered about 0.0, 0.5, 0.2 and 0.2 kWh/m^3, for both of Germany and Iran.

Water cost = Volume of consumed water × Water cost

Energy cost = (Cost of electricity per kWh) × (Required kWh electricity per 1 m^3 volume of consumed water)

(2) Energy cost + water cost = (0.15×0.2×1260) + (1260×0.005) = 37.8 + 6.3

(3) It is calculated by considering 0.04 and 0.01 [hr/(ha×year)] of man work time for CP and PMDI in Germany. Salary was considered 12 and 0.8 [€/h] in Germany and Iran, respectively (Teichert, 2007; Sourell, personal communication, 2007; and Personal communication, Golestan Agricultural and Natural Resources Research Centre, 2007). Therefore required labour cost related to CP irrigation and PMDI will be near zero (0.04*12 = 0.48 [€/(ha×year)] for Germany and 0.01*0.8 = 0.008 [€/(ha×year)] for Iran).

(4) It is calculated by considering 20.44 [hr/(ha×year)] of man work time and 12 [€/ha] salary in Germany (Teichert, 2007 and Rosegger et al., 1977).

(5) It is calculated by considering 32 [h/ha] man work time and 0.8 [€/ha] salary (32×0.8 = 25).

(6) It is calculated by considering 20.44 [hr/(ha×year)] of man work time and 12 and 0.8 [€/h] salary (Personal communication, Golestan Agricultural and Natural Resources Research Centre, 2007 and Rosegger et al., 1977).

4.3.3 Total irrigation cost

Based on Equation 4.2, the total irrigation cost of different irrigation system was calculated (Table 4.12). A comparison between total the irrigation cost of different irrigation systems (Table 4.12) showed that the PMDI system is not the most expensive system with regard to capital requirements in spite of its novelty and the extra installation on CP. Table 4.12 shows that drip irrigation and PMDI systems are the most expensive and cheapest irrigation system in Germany, respectively and drip and surface irrigation systems are the most expensive and cheapest irrigation systems in Iran, respectively. Moreover, PMDI is mainly more expensive than CP for different crops. Under PMDI in Germany, annual irrigation costs are 360.7, 359.2, 359.9 and 360.9 [€/ha] less than drip irrigation for different crops, such as lettuce, sugar beet, potato and strawberry, respectively. These differences show the advantage of PMDI over drip irrigation. Moreover, from Table 4.12 it is concluded that under German conditions, PMDI is cheaper than CP irrigation systems, because of lower energy and water costs. in addition, the economic returns of PI methods need to be improved before wide-range acceptance can be reached (Domsch and Giebel, 2001). By distributing capital costs for mapping over more land and time and using the skills of PI specialists, the costs could be reduced, and precision irrigation would gain wider acceptance.

Figure 4.29 which is derived from Tables 4.10 and 4.12, shows that although the cost of each millimetre of irrigation water depth for different crops in PMDI is somewhat more than in CP, it is significantly less than in drip irrigation. The results show that with increasing irrigation depth, the cost of each millimetre of irrigation depth will be reduced because the expenses for greater irrigation depth would be distributed. The irrigation costs of 1.7, 2.1, 1.9 and 1.7 [€/mm] determined in this study for different crops (lettuce, sugar beet, potato and strawberry) in Germany, respectively, are comparable with the irrigation cost of 2.5 [€/mm] established by Fricke (2004) for different crops irrigated by sprinkler irrigation.

Under Iran´s conditions, except for cotton, annual farming costs of PMDI are generally higher than the costs of a CP irrigation system. Annual farming costs of PMDI in Iran are 344.2, 344.5, 343.5 and 344.5 [€/ha] less than drip irrigation for different crops, i.e. cotton, lettuce, potato and strawberry, respectively.

Table 4.12: Total irrigation cost (including fixed and variable costs) under different irrigation systems and crops in Germany and Iran [€/(ha×year)]

	Irrigation system	Lettuce	Sugar beet	Potato	Strawberry
Germany	Centre pivot	274.2	229.4	248.6	277.4
	Drip irrigation	598.9	582.5	589.6	600
	PMDI with 400 m CP radius	238.2	223.3	229.7	239.1 [(1)]
Iran	Irrigation system	Cotton	Lettuce	Potato	Strawberry
	Surface irrigation	93	100.9	81.4	100.9
	Centre pivot	278.8	226.6	214.7	226.6
	Drip irrigation	399.6	403.2	394.1	403.2
	PMDI with 400 m CP radius	253.4	256.7	248.6	256.7

[(1)] (37.8 + 6.3) + 0 + 195 = 239.1

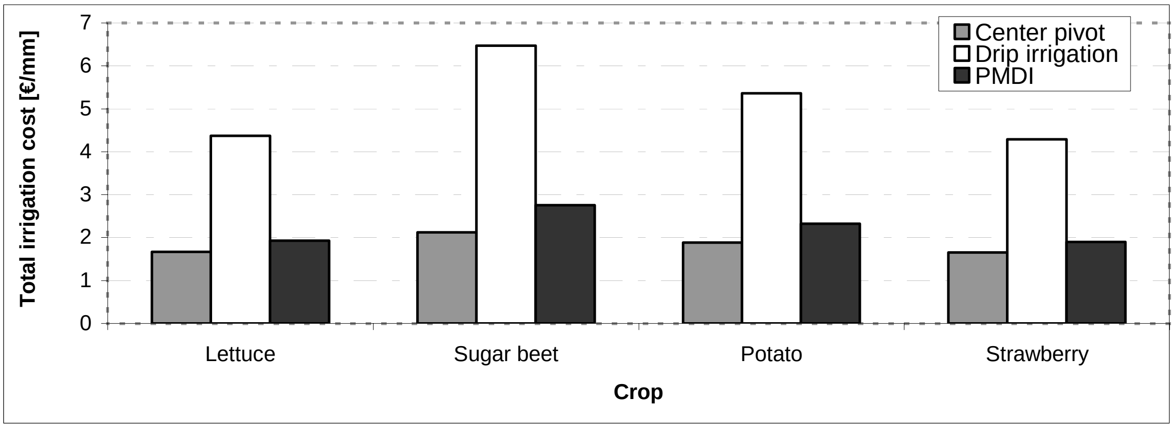


Figure 4.29: Cost of each millimetre irrigation depth for different crops and irrigated by different irrigation system

4.3.4 Farming benefit

PI has additional farming benefits related to more yield quantity and better yield quality. For the sake of simplification in economic analysis, and also in agreement with King et al. (2006) and Oliveira et al. (2003), the yield under PMDI is considered to be 5 % more than under drip irrigation, but continued research and development is needed in order to realize an increase in productivity. Moreover, in spite of better yield quality under PI than other irrigation systems (King et al., 2002 and 2006; Nijbroek et al., 2000 and 2003), the same yield price was considered for production under all four irrigation systems in the current study. Although total farming costs were not calculated in this study, but by assuming the same costs of tillage, sowing, fertilization, herbicide, harvesting and irrigation costs up to the hydrant on the ground surface for different irrigation systems, total farming cost and consequently farming benefits [€/(ha×year)] can be compared for the same crops irrigated by different irrigation systems using Equation (4.2). In Figure 4.30, total incomes [€/(ha×year)] are compared for different irrigation systems. With due attention to the possibility of double cropping per year in Iran, total income (Figure 4.30c) and farming benefit can be increased. It was considered that under double cropping conditions in Iran, total income and total cost can be increased by about 70 and 100 %, respectively. Figure 4.30 shows that PMDI and surface irrigation provide the maximum and minimum total income for all crops and both countries, respectively. Moreover, the effect of the crop type on total income shows that although lettuce and strawberry show a high total income, they have a higher farming cost in comparison to other crops (Figure 4.30).

By comparing the farming benefit of different irrigation systems (based on Equation 4.2), it could be concluded that PMDI has the highest benefit in all cases. The results show that even without any increase in yield under PMDI in comparison with drip irrigation, it is more economical than the drip irrigation system. Significant benefit differences of 1800, 534, 1211 and 1928 [€/(ha×year)] between PMDI and drip irrigation for different crops (lettuce, sugar beet, potato and strawberry) in Germany show the profitability of PMDI despite its high capital requirements. This advantage is also derived from Iran´s farming conditions where 228, 428, 315 and 506 [€/(ha×year)] more benefit of PMDI as compared with drip irrigation resulted for cotton, lettuce, potato and strawberry crops, respectively. More benefit of PI in this study is comparable to the field study of Oliveira et al. (2003) that found 1926 [€/ha] (€ 31285 in a 16.24 ha field) more average annual benefit of PI as compared with uniform and conventional irrigation.

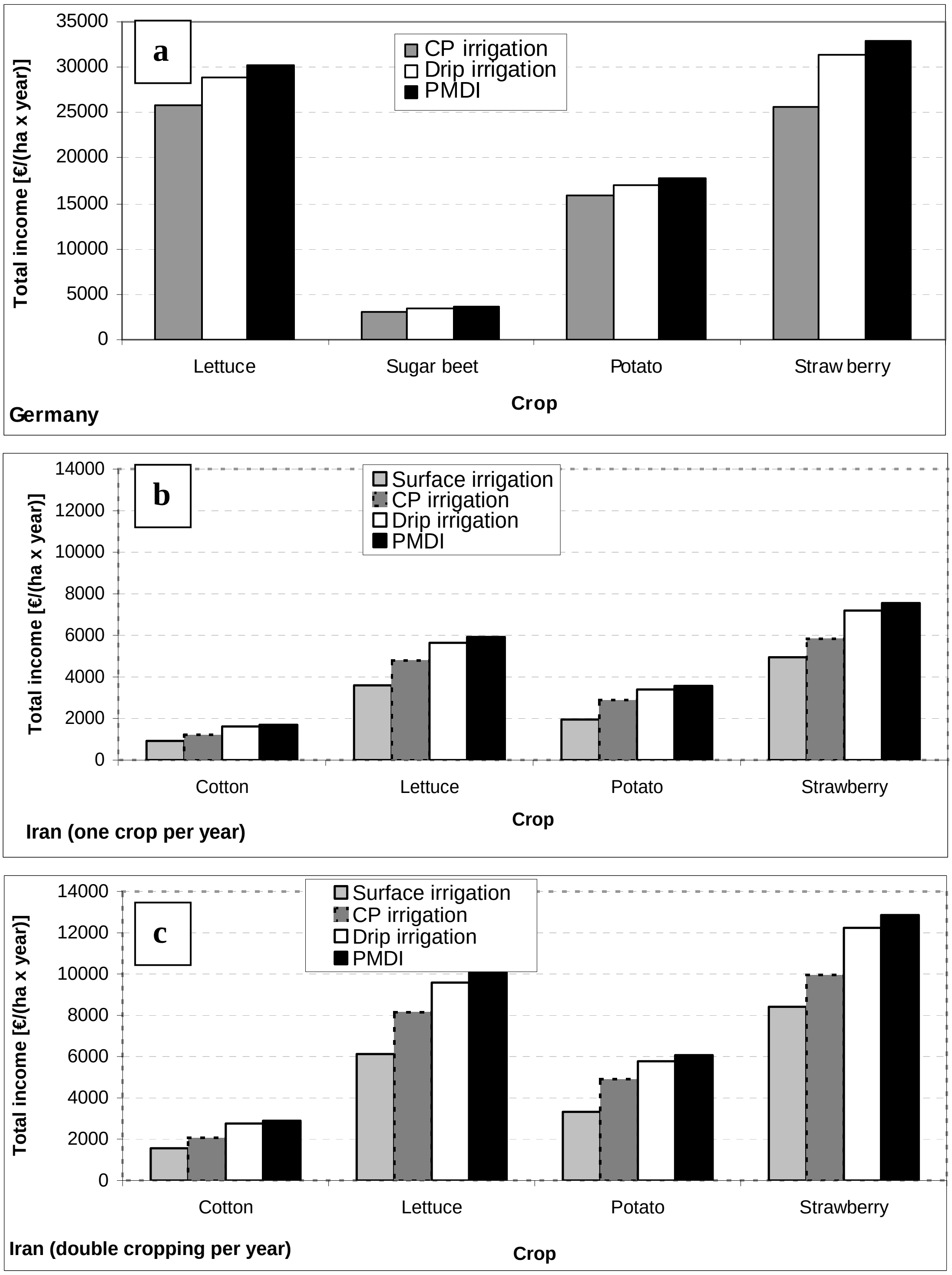


Figure 4.30: Comparison of total income under different irrigation systems and crops in Germany and Iran (a and b). Total income under double cropping conditions in Iran is also shown (c)

PI will not likely be an economically viable practice for all crops and all growing conditions. It seems that planting low income crops like wheat is not economical under PI and PMDI. PI can preferably be used for deluxe and high income crops like strawberry, melon, lettuce. PI will most likely be economical on crops where yield and quality are highly water sensitive and crop price structure is heavily dependent upon crop quality like in potato (King et al., 2002). With due attention to creating a better yield quality under PI (King et al., 2002 and 2006; Nijbroek et al., 2000 and 2003), and especially under PMDI, and since marketable yield is the primary factor in computing gross income, gross income closely follows marketable yield in each irrigation zone. King et al. (2002) found that the average gross income across the field derived from potato cultivation under site-specific irrigation management was € 118 per hectare higher as compared with conventional uniform irrigation management because of better quality and more yield.

The profitability of PMDI is more obvious when its benefit is compared to centre pivot and surface irrigation systems. With due attention to the expense and economic considerations of PMDI, at first glance the results suggest that to extend and develop PMDI, its advantages and especially its economic benefits must be presented to the farmers. However, a greater net return will depend upon the cost and useful life of the equipment required for site-specific management as well as the operational costs. In agreement with the tentative conclusion from Heermann et al. (2002), the potential economic benefit of site specific management is small where the farmer's management tolerance for risk is low. Meanwhile their costs are dependent on the accuracy desired and the rate of soil texture variation. Therefore the economic viability of PI practice also depends on the:

a) Number of irrigation zones that can affect the number of soil moisture monitoring devices including soil moisture sensors and the ISM modem and
b) Degree of variability within a field that can affect the number of solenoid valves and in large part on the value people place on the environment and the value of the crops grown. Therefore with due attention to the low degree of variability of the study field, more water is expected to be saved on highly variable fields.

4.4 Other advantages of precision irrigation

In order to recover the additional costs caused by the adoption of PI, farmers would need to achieve advantages and savings, which could be the following in addition to water and energy savings:

a) High water distribution and no water losses due to wind drift and evaporation by PMDI
b) Savings in inputs due to taking into consideration the off-target spray problems, which include watering non-cropped areas such as roads, rocks, etc (Sanders et al., 2000).
c) No value judgement concerning energy saving could be expressed as to the adoption of this new practice, but there could be some savings.
d) In addition to these benefits, other savings could be realized, due to the possibility of chemigation and reductions in the quantities of chemicals and fertilisers applied and/or loss rates in chemical and fertiliser application.
e) In agreement with the investigation of King et al. (2002) and Nijbroek et al. (2000; 2003), the expectations regarding the use of PI anticipate an improvement in yield quality, which should be assessed and added to the benefits. Based on investigations by King et al. (2002) and the increased tuber quality of tomatoes, the trend in gross receipts was approximately 84 [€/ha] greater under site-specific water management as compared to conventional uniform irrigation management for the field site. Also the strategy of irrigating the soybean field uniformly according to the optimal schedule for the largest MZ produced 2 % less than independent zone irrigation (Nijbroek et al, 2000 and 2003).
f) This management system would exhibit small, but positive effects on most of the current environmental concerns. Therefore, environmental protection, the decrease in ecosystem damage, low CO_2 emissions and the sustainability of the agricultural resources should be also evaluated and added to the benefits.

In addition, future environmental regulations may greatly change the economic feasibility of the site-specific irrigation control system. For example, application restrictions on the aerial application of chemicals and recent changes in the endangered species listing of the various salmon and steelhead fish runs could have a large impact on the adoption of site-specific irrigation control programs in the Pacific Northwest (Evans and Harting, 2005).

5 CONCLUSION

Precision irrigation provides the opportunity to decrease input costs and the potential to increase net income by applying water at the right place in the right quantity and at the right time. Fields that show spatial variability in TAWC would benefit from a precision irrigation system which has the ability to vary the amount of water applied. Despite the inherent high frequency and fairly uniform applications of CP, considerable yield variations still exist, which are often attributed to spatial variability in TAWC and related nutrient availability.

5.1 Delineation of irrigation management zones

Sensor-based measurements of ECa using VERIS 3100 at field capacity and under the non-saline conditions of the study field could provide important information on within-field variation of the TAWC in an upper shallow soil profile. It is better to select an ECa sensing system to delineate TAWC be based on its nominal depth of investigation as an initial selection. The need for irrigation was different between various zones of the study field, because of spatial soil variation of TAWC. Differences were attributed to differences between the depth-weighted response functions for the four data types, the differences in sensing depth between the different sensors (VERIS 3100 and EM38) and data collection modes (deep vs. shallow or vertical vs. horizontal, respectively). This study showed that, while qualitatively similar, ECa data obtained with different commercial sensors were quantitatively different. With these differences, the selection of an ECa sensing system for a particular application should be based on both practical implementation issues and the intended use of the data. Fields with high variations of soil properties affect ECa and especially when these properties are heavily weighted in the upper layers, there is a big difference between EM38 and VERIS 3100 readings. VERIS 3100 readings can reflect the spatial variability better than EM38 because the VERIS 3100 is heavily weighted in the upper layers as compared with EM38.

In this study, a better coefficient of determination between VERIS 3100 readings and TAWC was found. Six zones were identified to be the optimum number of IMZs based on VERIS 3100-sh readings. It was concluded that under conventional uniform irrigation, IMZ_1 and IMZ_2 were over-irrigated whereas IMZ_4, IMZ_5 and IMZ_6 had deficit irrigation and thus were drier. With reduction of water consumption within IMZ_1 and IMZ_2 and the accretion of water used within IMZ_4, IMZ_5 and IMZ_6, water consumption is optimized and water use efficiency is increased, but by using PI and the subdivision of the field into some IMZs, total water and energy consumption can not necessarily be reduced because of some overlapping of deficit irrigation and over consumption of energy and water (the rate of energy use at any time is a function of flow rate and pressure). But by replacing the drop tube with low operation pressure instead of a sprinkler, energy consumption is certainly reduced. This result has an important policy implication because PI is not necessarily a water and energy saving technology, but it is a water and energy optimising technology. On the other hand, PMDI is certainly a water and energy saving and optimising technology. Considering the free capacity to absorb probable rainfall after irrigation is a logical decision and can save water and energy under German weather conditions.

5.2 Performance and evaluation of remote real-time and site-specific distributed irrigation control systems

The concept of pulse irrigation was a feasible and viable technique. The system was able to vary the amount of water in proportion to the pulsing level, as the system is capable of controlling fifteen banks of fifteen nozzles to discharge a variable amount of water using the pulsing method (for example between 0 mm and 33 mm per application in each plot under 20 % of CP speed). During the field tests, there were no apparent problems with the pulsing water delivery system. It could be concluded that water application under pulsed conditions was directly proportionate to the fraction of time the valve was opened and that the technique is viable for the control of applications on study plots. The pulsing technique used to deliver variable amounts of irrigation and CP speed had a few adverse effects on system uniformity and the nozzle flow rate. Uniformity coefficients were reduced by decreasing the pulsing level and increasing CP speed. As application rates get lower, irrigation adequacy declines due to time delays in the system. Although the observations and measurements of water application indicate that control system performance is acceptable, more detailed evaluations and improvements of fertiliser and chemical application will be required before definitive conclusions can be reached. A continuing part of the future development of the site-specific irrigation control system must be the application of fertilizers and fungicides using the precision irrigation control system. Further studies on this concept should be conducted to determine its potential and extend its use beyond the research phase to commercial irrigation machines for which spatially varied water application is desired. The main hardware issue holding this technology back is the lack of a good, inexpensive variable-rate sprinkler with a wide range of flow rates for a given design (ideally 0-100 % of full) and essentially constant relative spray distribution at all flow rates. If these sprinklers could be controlled using some addressable bus or wireless control system, it would reduce wiring costs and difficulties. DGPS may be the eventual solution to determining the location, except possibly for shorter pivots where the bow doesn't cause errors using the resolver. The control programs must also keep an automatic record of the amount of water applied during the growing season (flow rate monitoring) and take the decreased water application due to the variable irrigation control program into account.

Field observation showed that installing a metallic bar parallel to the CP wheel in a 0.5 m distance is necessary to avoid drop tube tangling in the mobile drip CP wheel (Appendix G). Selecting SV with good inertia, short closing periods and longer pulsing cycle duration in order to decrease water hammering due to valves being turned on and off can improve system operation. SV with good inertia and low energy requirements will make PI implementation easier. In the near future, solenoid valves and many other products will require alternate plating compounds. Also using sprinklers having a smaller wetted diameter will improve water distribution uniformity near IMZ borders.

The problem of water pressure variations and water hammering due to valves being turned on and off at various flow rates can be solved by:

a) Using variable-rate pumps, which are expensive
b) Using multiple staged pumps, for example, a series of three or four increasingly larger pumps, each drawing from a reservoir. The pumps may be linked in parallel and used in combination with a pressure bypass to the reservoir to provide constant pressure at all flow rates
c) A third alternative might be a constant-rate with a re-circulating bypass.

To address this problem, some research was done by Archer et al. (2000) and Zhu et al. (2002). However, if there is no big soil TAWC variation in the field, a normal pump (not an expensive variable-rate pump) can be used but if there is significant variation of TAWC in the field, a variable-rate pump will be necessary. Also with due attention to emitter clogging and for the future application of MDI with CP, a filtration system can easily be installed between the supply and the pivot point. A priori knowledge is required to manage the system at the current state of development. Additional research and development is needed to allow for automatic operation based on sensory input.

The control system was able to monitor wireless soil moisture sensors via radio telemetry. Soil moisture data were easily received by mobile phone and then transferred to an Excel table on a computer using “Kurznachricht Pro 2.2” software to calculate irrigation depth and graphically present its variation. Although “Kurznachricht Pro 2.2” software and the simple Excel program (to automatically calculate irrigation depth and draw its variation) were found to be easy and suitable for use and to improve application facility, the EnviroSCAN sensor was found to be delicate, and intricate to use and calibrate. It could be concluded that in this study not only the universal calibration equation used in the software of the EnviroSCAN system as it has been generated from varying soil types, but also soil-specific calibration equation were not able to produce accurate estimates of the soil water content even though the equipment and techniques developed by the manufacturers of EnviroSCAN were applied. Underestimates of soil water content due to the uncalibrated equation in the current study and other research, and its overestimation by Jabro et al. (2005), suggest that more calibration research and especially soil-specific research with the EnviroSCAN capacitance sensor are needed. In this study, using a GSM-mobile phone with RS232 installed on a computer instead of a mobile phone for connecting the computer to the PLC can be another aspect of future trends in wireless data transmission. Local wireless sensor networks can be overlaid with a wireless LAN to accomplish various farming operations in a systematic, precise and well-managed fashion. In the near future, wireless sensors and computer controlled robots are a good combination to use instead of large-power and heavy weight farm machines that cause permanent damage to fields by compaction. Also when radio frequency identification technology (RFID) is combined with wireless sensors, the RFID system can record environmental parameters and specific quality/safety attributes of the product along the chain. It can be predicted that the deployment of RFID and wireless sensors in traceability systems will experience a great boom in the near future. The main drawbacks of RFID technology are the relatively short communication range (1-2 m) and the fact that the devices are passive, which limits future extensions, such as the monitoring of temperature and motion.

The field tests also showed that soil moisture data can be transferred between two ISM modems without any problem over maximum distances of 400 m. A soil specific calibration of each sensor would have been necessary to obtain a high degree of absolute accuracy in soil water content measurements and improve the sensor´s accuracy and performance. The results indicates that EnviroSCAN sensors installed at a depth of more than 40 cm (where soil texture is more sandy), are not able to repeat soil moisture condition, but a better calibration coefficient is found for sensors installed in loamy sand layers (upper 40 cm). The results suggest that EnviroSCAN sensors are able to follow the general trends successfully as the soil water content measured by sampling changed during the growing season, but are not a reliable sensor to report moisture conditions on sandy soils (at greater depths than 40 cm). The AMBAV model is capable of determining and simulating SWC in the root zone of grass crops as a cheap, safe and reliable method. Monitoring plant response using the potential of remote sensing to determine environmental stresses offers an opportunity for early detection and remediation.

5.3 Laboratory experiments

The MDI in the field requires drop tubes which are easy to install and have the smallest distance between the emitters as well as high discharge in order to reduce both the length of the drip tubes and the number of emitters. In addition, MDI requires emitters which operate at low pressure to reduce the energy costs. Moreover, the MDI in the field requires in-line emitters which provide high emission uniformity and the lowest coefficient of variation to enhance water distribution on the soil surface. High uniformity of water distribution is required in trickle irrigation to minimize irrigation losses. After the system is installed, flow variation due to pressure differences, emitter clogging, temperature variation and aging have an adverse effect on uniformity. It is also very important to look at manufacturing variations when choosing an emitter. Design should be based on reliable test data, not on data provided by the manufacturers. Because of the need for high uniformity in a trickle system, every effort should be taken to test the emitters before and after they are installed. Manufacturers should provide specifications that describe their products. The effect of operating pressure on the discharge of Siplast emitters is highly significant and the emitter discharge is strongly influenced by the operating pressure. In spite of high emission uniformity and a low coefficient of variation of the Siplast drop tube, which consists of hard and inflexible material, it deviates to some extent from the design flow rate claimed by the manufacturer.

5.4 Potential economic implications

The economic returns of PI methods need to be improved before wide-range acceptance can be reached. It could be concluded that PMDI is more economic than the drip irrigation system even without any increase in yield because of lower expenses for labour, energy and water, in particular at locations where double cropping is possible. This study showed that using a safe and cheap irrigation model can decrease the cost of PI. Calculation shows that although annual fixed costs under PMDI are more than CP, it causes perceptibly less annual fixed expenses than drip irrigation in both Germany and Iran. Economic calculation showed that although capital requirement per hectare under PMDI is about € 338 and € 250 more than drip irrigation in Germany and Iran, respectively, it causes perceptibly less annual fixed expenses than drip irrigation (111 and 128 [€/(ha×year)] and is cheaper than drip irrigation in both countries. As an important policy implication, the results showed that site-specific or variable rate irrigation (PI) is not necessarily a water saving technology, but that it provides an optimization of water use (irrigation without any deficit or over watering) that leads to increasing yield. However, using a drop tube instead of a sprinkler in PMDI can increase water use efficiency by deleting wind draft and evaporation losses in comparison with CP.

Site-specific irrigation management will most likely be economical on crops where yield and quality are highly water sensitive and crop price structure is heavily dependent upon crop quality. With regard to the possibility of high level water management and other agricultural input applications under PMDI or PI, it is better that deluxe and high income crops like strawberry, melon, lettuce, etc. be planted. The number of irrigation zones and the degree of variability within a field has an effect on the economic viability of PI in practice. Besides lower wiring costs, a DIC system is simpler and more flexible than a hard-wired centralized control system. Continued research and development is needed to reduce the capital and operational costs of site-specific irrigation management and to realize an increase in net return.

5.5 Resume

With due attention to expensive and destructive soil sampling methods and also shallow depth measurement by means of aerial photography to delineate irrigation management zones, sensor-based ECa measurement at F.C. in non-saline soil can be used as an cheap, rapid and non-destructive alternative to delineate irrigation management zones when an acceptable coefficient of determination between soil EC data and TAWC of soil samples is found. More work will be needed in areas with a wide range of ECa differences, such as Iran, to verify these results and establish a standard relationship between ECa and TAWC. In any case, if the uncertainty in results appears to be too high, either sampling density has to be increased or an attempt has to be made to back-calculate soil properties from yield maps. Field studies using larger irrigation systems on fields having different soil types, topographic, or crop characteristics are recommended to validate the precision irrigation concept.

Although Siplast was found to be a unique in-line drop tube having a short length with higher emitter discharge at low operation pressure and less emitter distance, the difficulties of installing Siplast and working with it on the field and in the laboratory because of its hard and inflexible material causes scientists to seek a flexible drop tube.

Although pulsing with the aid of a solenoid valve and PLC was a feasible and viable variable rate irrigation technique, the extra costs of industrial accessories for this technique must be minimised in the coming years. Given the early stage of development of the PI technique and improvements in industrial technology, such a development can be expected. Considerable research and development is needed to realize and validate the potential benefits of site-specific irrigation and chemigation and insure a positive net economic return to the producer.

Sensors developed to economically conduct appropriate monitoring for different stresses and soil water levels on a near real time basis are urgently needed. More work on soil-based or machine-based sensing of crop conditions needs to be integrated into irrigation machine control.

6 SUMMARY

Site-specific irrigation: Improvement of application maps and dynamic steering of modified centre pivot irrigation system

Introduction: A management concept for sustainable utilization and the efficient use of agricultural inputs is known as “Precision Agriculture” (PA). The PA concept, when applied to irrigation management is known as Precision Irrigation (PI). In PI, the need for irrigation may differ between zones of a particular field due to the spatial variation of soil properties or the cropping of different plants on the same field. Spatial variation of total available water content (TAWC) as a primary factor causes spatial variation of irrigation depth and frequency within fields. While moving irrigation systems apply water at constant rates, some areas of the field may receive too much water and others not enough. In this regard, precision irrigation (PI) is capable of applying water in the right place in the right amount at the right time using the right irrigation system. Therefore the key objectives of the present study were a) Delineation of irrigation management zones (IMZs) using sensor-based soil electrical conductivity (ECa) measurement with the aid of EM38 and VERIS 3100, b) Developing and evaluating a precision mobile drip irrigation (PMDI) and c) Evaluating wireless EnviroSCAN sensors and AMBAV-models to measure the soil moisture content.

Materials and methods: EC_{25} data (ECa in 25° C) were collected using EM38 and VERIS 3100 at field capacity on a 16.6 ha non-saline field in the FAL, Braunschweig, Germany. ECa data were obtained in 1-s intervals corresponding to a 2 to 3 m data spacing on transects spaced approximately 4 to 6 m apart. An ArcView (ESRI) software program was used to create the EC_{25} and TAWC maps after the readings were interpolated using a spherical kriging model. 29 calibration points taken at a depth of 0 - 60 cm depth were located using DGPS based on the ECa spatial variability pattern and with the objective of covering the whole range of ECa values present to determine the best sensor-based method to monitor TAWC.

The second span of the centre pivot irrigation machine (CP) was modified to PMDI and controlled for variable-rate water application with a pulsing technique by installing solenoid valves (SV), programmable logic control (PLC) and using a Siplast drop tube instead of sprinklers. One quarter of the study field was controlled by the EnviroSCAN soil moisture sensor and another quarter was controlled by the AMBAV-model to determine irrigation depth. In addition, the hydraulic performance of the Siplast drop tube was evaluated in the laboratory by collecting discharge rates at different pressure of 50, 100, 150 and 200 kPa.

Results and discussion: This study showed that, while qualitatively similar, EC_{25} data obtained with different commercial sensors were quantitatively different because of different depth-weighted response functions. The highest coefficients of determination (R^2) were generally found between EM38_h and EM38_v ($R^2 = 0.55$). In this study, a better value of R^2 between TAWC and the VERIS 3100 readings was found. The R^2 value from VERIS 3100-sh data for TAWC estimation was maximally (0.77) and matched the TAWC data quite well, whereas R^2 values to EM38-h and EM38-v data were low and apparently could not adequately reflect the spatial variability of the TAWC due to the higher influence of the EM38 on deeper layers. Six IMZs (IMZ_1: 99 to 105, IMZ_2: 105 to 116, IMZ_3: 116 to 127, IMZ_4: 127 to 138, IMZ_5: 138 to 149 and IMZ_6: 149 to 152 mm/60 cm) were identified based on fuzzy-k-means unsupervised classification as an optimum number of IMZs within the study field. It was concluded that under conventional uniform irrigation, IMZ_1 and IMZ_2 were over-irrigated, whereas IMZ_4, IMZ_5 and IMZ_6 were under-irrigated.

The developed concept of pulse irrigation was a feasible and a viable technique. Water application was directly proportional to the fraction of time the valve was opened as the system was capable of controlling fifteen banks of fifteen nozzles. There were no apparent problems with the pulsing water delivery system where the field tests were conducted. CP speed and the pulsing technique used to deliver variable amounts of irrigation had little adverse effect on system uniformity and the nozzle flow rate. Uniformity coefficients were reduced by decreasing the pulsing level and increasing CP speed.

The control unit was able to monitor wireless soil moisture sensors via radio telemetry and communication from the EnviroSCAN sensors to the central ISM modem, which worked as expected. Although the EnviroSCAN soil moisture sensor was found to be delicate and intricate to use and calibrate, soil moisture data were easily sent from the control unit and received by the mobile phone and then transferred to an Excel table on a computer using easy and suitable "Kurznachricht Pro 2.2" software to calculate irrigation depth. The results suggest that EnviroSCAN sensors are able to follow the general trends successfully as soil water content measured by sampling changed during the growing season, but are not a reliable sensor to repeat moisture conditions on sandy soils (at greater depths than 40 cm) despite its soil-specific calibration. Meanwhile, an AMBAV model as a cheap and reliable alternative instead of the expensive EnviroSCAN sensor was capable of determining and simulating soil moisture in the root zone of grass crops.

Drip irrigation design should be based on reliable data sets, but not on data supplied by the manufacturer. The laboratory experiments showed that the effect of operating pressure on the discharge of Siplast emitters was highly significant and the emitter discharge was strongly influenced by the operating pressure, while some deviation from the design flow rate claimed by the manufacturer occurred. CV values were classified as good, on the basis of the ISO standard. Based on the laboratory experiments, it was found that the in-line Siplast emitter has high emission uniformity and a low coefficient of variation. In spite of high emission uniformity and a low coefficient of variation of the Siplast drop tube, it must consist of hard and inflexible material. To have a shorter drip tube installed on CP, using an in-line drop tube lateral with higher emitter discharge at low operation pressure and less emitter distance is proposed.

The economic analysis of this study showed that although capital requirement per hectare under PMDI is about € 338 and € 250 more than for drip irrigation in Germany and Iran, respectively, it causes perceptibly less annual fixed cost than drip irrigation (111 and 128 [€/(ha×year)] cheaper than drip irrigation in Germany and Iran, respectively). Although PMDI causes more annual fixed expenses than CP irrigation, it has less total irrigation cost per hectare and year than CP and drip irrigation and has the potential benefit to increase yield quantity, quality and farming benefit. The results showed as an important policy implication that PMDI is not necessarily a water saving technology and it does not necessarily involve a reduction in total water use, but that it can optimize water consumption. Given a reduction of energy and water consumption of 70 % and 25 %, respectively, achieved by the PMDI as compared with the CP, results showed that about 575, 378, 462 and 588 kWh energy per hectare can be saved by PMDI in comparison with the conventional CP irrigation of lettuce, sugar beet, potato and strawberry.

Conclusion: Sensor-based ECa measurement at F.C. in non-saline soil can be used as a cheap, rapid and non-destructive alternative to delineate IMZ instead of using soil sampling and aerial photography methods. Field studies using larger irrigation systems and fields with different soil types, topographic or crop characteristics are recommended to validate the precision irrigation concept and to realize and ensure a positive net economic return to the producer. With due attention to the success of PI in the early stages and developments in industrial technology in the coming years, the extra costs of industrial accessories could be minimised.

7 ZUSAMMENFASSUNG

Teilflächenspezifische Beregnung: Entwicklung von Beregnungsapplikationskarten und einer dynamischen Steuerung für Kreisberegnungsmaschinen

Einleitung: Ein Management Konzept für nachhaltige und effiziente Nutzung landwirtschaftlicher Maßnahmen ist bekannt als teilflächenspezifische Landwirtschaft (PA – Precision Agriculture). Wird das teilflächenspezifische Konzept im Bewässerungsmanagement eingesetzt, wird es teilflächenspezifische Bewässerung genannt (PI – Precision Irrigation). Bei der teilflächenspezifische Bewässerung kann die Bewässerung zwischen den Bereichen eines Feldes auf Grund der Variabilität der Bodeneigenschaften oder dem Anbau von verschiedenen Pflanzen auf dem selben Feld variieren. Die räumliche Veränderung der nutzbaren Feldkapazität als Primärfaktor bedingt die räumliche Veränderung der Bewässerungshöhe und der Bewässerungsfrequenz. Die Bewässerungssysteme verteilen das Wasser bis heute gleichmäßig, so dass die Flächen teilweise überbewässert oder unterbewässert sind. Bezogen auf dieses Problem ist die teilflächenspezifische Beregnung geeignet, das Wasser an der richtigen Stelle zum richtigen Zeitpunkt unter Benutzung des richtigen Bewässerungssystems auszubringen. Folglich sind die Schlüsselziele dieser Arbeit: a) die Abgrenzung von Beregnungsmanagementzonen (IMZs – Irrigation Management Zones) unter Nutzung von sensorbasierten Messungen der elektrischen Leitfähigkeit (ECa – depth-weighted apparent soil electrical conductivity) des Bodens mit EM38 und VERIS 3100, b) die Entwicklung und Evaluierung einer teilflächenspezifischen mobilen Tropfbewässerung und c) Auswertung von drahtlosen Bodenfeuchtesensoren (EnviroSCAN) und der klimatischen Wasserbilanz (AMBAV-Modell) zur Bestimmung der Bodenfeuchte bzw. der Bewässerungshöhe.

Material und Methoden: EC_{25}-Daten (ECa bei 25° C) wurden unter Verwendung von EM38 und VERIS 3100 Geräten bei Feldkapazität auf einem 16,6 ha großen Feldstück der FAL, Braunschweig, Deutschland, gemessen. Die ECa Daten wurden im Sekundenintervall mit zwei bis drei Metern Messabstand und in Reihenabständen von etwa vier bis sechs Metern gemessen. Zur Erstellung der EC_{25}- und Bodenfeuchte Karten wurde die Software ArcView genutzt, nachdem die Messdaten mit Hilfe des sphärischen Kriging-Verfahren interpoliert wurden. 29 Kalibrierungspunkten wurden mit Hilfe von DGPS lokalisiert, um die beste sensorbasierte Methode zur Abgrenzung der Beregnungsmanagementzonen zu bestimmen. Bodenproben wurden in 0 - 60 cm Tiefe entnommen.

Der zweite Bogen der Kreisberegnungsmaschinen wurde für die teilflächenspezifische mobile Tropfbewässerung umgerüstet. Eine kontrollierte Wassermenge konnte, durch Installierung einer Pulstechnik mit Magnetventilen (SV – Solenoid Valve), einem Computer gesteuerten Programm (PLC – Programable Logic Control) und Auswechseln der Düsen durch Siplast Tropfrohre ausgebracht werden. Ein Teil des Feldversuches wurde durch EnviroSCAN Bodenfeuchtesensoren gesteuert und der andere Teil wurde durch das AMBAV-Modell gesteuert, um die Beregnungshöhe zu bestimmen. Die hydraulische Genauigkeit der Siplast Tropfrohre wurde im Labor bei unterschiedlichen Wasserdrücken von 50, 100, 150 und 200 kPa untersucht.

Ergebnisse und Diskussion: Die Untersuchung zeigt, dass EC_{25}-Daten von verschiedenen gewerblichen Sensoren auf Grund der unterschiedlichen Gewichtung der Tiefe quantitativ unterschiedlich sind. Das höchste Bestimmtheitsmaß wurde zwischen EM38_h und EM38_v (R^2 = 0,55) gefunden. In dieser Arbeit wurde ein gutes Bestimmtheitsmaß zwischen nFK und den VERIS 3100 Werten gefunden. Eine Kalibrierungsgleichung zur Abschätzung der nFK von VERIS 3100-sh zeigte eine hohe Ähnlichkeit zu den nFK Daten auf und hatte das höchste Bestimmtheitsmaß (R^2 = 0,77). Die Bestimmtheitsmaße zu EM38-v- und EM38-h-Daten waren niedrig und anscheinend nicht ausreichend, um die räumliche Variabilität der nFK reflektieren zu können. Ein Grund kann die größere Messtiefe von EM38 sein. Sechs Beregnungsmanagementzonen (IMZ_1: 99 bis 105, IMZ_2: 105 bis 116, IMZ_3: 116 bis 127, IMZ_4: 127 bis 138, IMZ_5: 138 bis 149 und IMZ_6: 149 bis 152 mm/60 cm) wurden als optimale Anzahl an Beregnungsmanagementzonen auf dem Versuchsfeld, basierend auf den fuzzy-k-Mittelwerten (Boydell and McBratney, 1999) der zufälligen Einteilung, erkannt. Es wurde gefolgert, dass unter konventioneller Beregnung IMZ_1 und IMZ_2 überbewässert und IMZ_4, IMZ_5 und IMZ_6 unterbewässert wurden.

Das entwickelte Konzept der Pulsbewässerung hat sich als eine zuverlässige Technik bewährt. Die Wasserapplikationsmenge war direkt proportional zur Öffnungsdauer des Ventils, und das System war in der Lage, die Wassermenge entsprechend des Bewässerungspulses zu variieren. Weiterhin war es in der Lage, 15 Reihen mit jeweils 15 Düsen zu steuern. Es gab keine offenkundigen Probleme mit dem gepulsten Wasserabgabesystem in den durchgeführten Feldversuchen. Die Kreisberegnungsmaschinengeschwindigkeit und Pulstechnik zur Bereitstellung verschiedener Wassermengen hatten einen geringen nachteiligen Einfluss auf die Gleichmäßigkeit der Beregnungshöhe. Die Gleichmäßigkeitskoeffizienten wurden durch sinkende Pulszeiten und steigende Kreisberegnungsmaschinengeschwindigkeiten gesenkt. Die Kontrolleinheit war wie erwartet in der Lage die Bodenfeuchtedaten mittels Fernmesstechnik von dem EnviroSCAN Sensor zum zentralen Modem zu senden. Obwohl der EnviroSCAN-Bodenfeuchtigkeitssensor empfindlich und kompliziert zu benutzen und zu kalibrieren ist, wurden die Bodenfeuchtigkeitsdaten fast störungsfrei von der Kontrolleinheit empfangen, gespeichert und zum Mobiltelefon gesendet. Für die Übertragung auf den PC wurde die Software „Kurznachricht Pro 2.2“ genutzt. Anschließend wurde die differenzierte Bewässerungshöhe kalkuliert. Die Ergebnisse zeigen, dass die EnviroSCAN-Sensoren in der Lage sind, den Verlauf der Bodenfeuchte während der Wachstumsperiode erfolgreich zu verfolgen. Weniger gut arbeitet der Sensor, um die Feuchtigkeitsverhältnisse auf sandigen Böden (unter 40 cm Tiefe), trotz bodenspezifischer Kalibrierung zu bestimmen. Während dessen hat sich das AMBAV-Modell als eine Alternative zum kostenintensiven EnviroSCAN erwiesen, das in der Lage ist, die Bodenfeuchtigkeit in der Wurzelzone der Graspflanzen als eine preiswerte und verlässliche Methode zu simulieren.

Das Tropfbewässerungssystem sollte auf verlässlichen Testergebnissen und nicht auf Herstellerangaben beruhen. Die Laborexperimente zeigten, dass der Einfluß des Betriebsdrucks auf den Durchfluss am Siplast Tropfer hoch signifikant war und der Tropferdurchfluß stark vom Betriebsdruck abhing. Die CV-Werte wurden auf dem ISO-Standard basierend als gut eingestuft. Aus den Laborexperimenten wurde herausgefunden, dass der in-line Siplast Tropfer eine hohe Ausbringungsgleichmäßigkeit und einen geringen Variationskoeffizienten aufweist. Das Rohrmaterial des Siplast Tropfer ist hart und unflexibel. Es sollte nach weiteren Produkten gesucht werden, die flexibler sind und somit die Kulturen schonen.

Die ökonomische Analyse dieser Arbeit zeigt, dass der Kapitalbedarf pro Hektar unter teilflächenspezifische mobile Tropfbewässerung um etwa 338 € und 250 € höher liegt als bei entsprechender Tropfbewässerung in Deutschland und im Iran. Die jährlichen Fixkosten sind geringer, als bei der Tropfbewässerung (111 und 128 [€/(ha × Jahr)] in Deutschland oder im Iran). Obwohl die teilflächenspezifische mobile Tropfbewässerung teurer ist als die Beregnung mit Kreisberegnungsmaschinen, verursacht sie weniger Wasser- und Energiekosten als die Kreisberegnungsmaschinen und hat das Potenzial den Ertrag qualitativ und quantitativ, sowie den landwirtschaftlichen Gewinn zu steigern. Die Ergebnisse zeigen, als wichtige Folge des Verfahrens, dass die teilflächenspezifische mobile Tropfbewässerung nicht notwendiger Weise eine wassersparende Technologie ist, aber es kann den Wasserbedarf optimieren. Der Energiebedarf kann um 70 % und der Wasserbedarf kann um 25 % durch die teilflächenspezifische mobile Tropfbewässerung gegenüber der Kreisberegnungsmaschine gesenkt werden. Die Modellbetrachtungen zeigten, dass durch die teilflächenspezifische mobile Tropfbewässerung im Vergleich mit der konventionellen Kreisberegnungsmaschine bei Salat, Zuckerrübe, Kartoffel und Erdbeere etwa 575, 378, 462 und 588 kWh Energie pro Hektar gespart werden können.

Schlussfolgerung: Die sensorbasierte Messung der elektrischen Leitfähigkeit bei Feldkapazität von nicht salzigen Böden ist eine preiswerte, schnelle und das Bodengefüge nicht zerstörende Alternative, um die Beregnungsmanagementzone räumlich abzugrenzen und ist den Methoden der Bodenprobenahme und Luftbildauswertung vorzuziehen. Feldstudien mit größeren Bewässerungssystemen und Felder mit verschiedenen Bodentypen, Topographie oder Pflanzenbeständen sind weiterhin zu untersuchen, um die Genauigkeit des Bewässerungskonzeptes zu validieren. Vor dem Hintergrund, dass teilflächenspezifische Bewässerung in den Anfängen steckt und eine weitere Verbreitung dieser Technologie zu erwarten ist, könnten die zusätzlichen Kosten für industrielle Ausrüstungsteile gesenkt werden. Beträchtliche Forschung und Entwicklung ist noch nötig, um die möglichen Vorteile der teilflächenspezifischen Beregnung und der Flüssigdüngung besser zu realisieren, um ein positives ökonomisches Ergebnis für den Erzeuger zu sichern.

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9 LIST OF APPENDIXES

Appendix A: Position of irrigation blocks and solenoid valves installed on modified centre pivot irrigation system

Angle°	Number of solenoid valve														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Distance between solenoid valve and pivot point [m]														
	40.50	43.00	45.65	48.15	50.70	53.20	55.70	58.35	60.85	63.45	65.80	68.35	70.80	73.35	76.10
	Position of irrigated area by solenoid valves [m]														
	39.05-41.75	41.75-44.33	44.33-46.9	46.9-49.43	49.43-51.95	51.95-54.45	54.45-57.03	57.03-59.6	59.6-62.15	62.15-64.63	64.63-67.08	67.08-69.58	69.58-72.08	72.08-74.73	74.73-77.00
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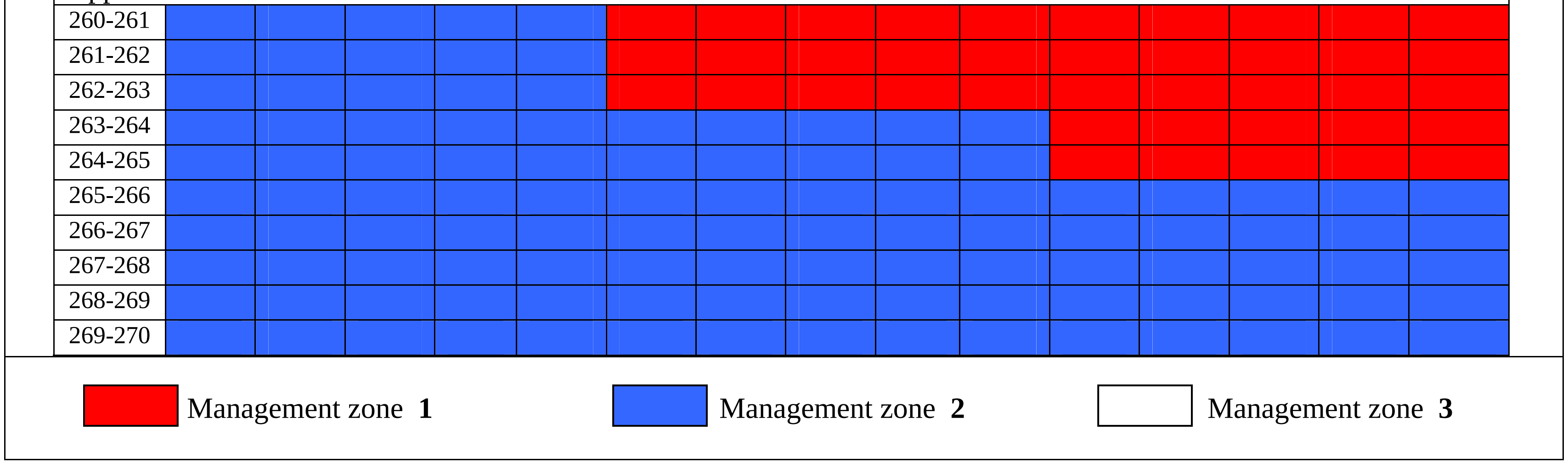
Appendix A: Cont´d



Appendix B: Discharged water from laterals which are including Ne = 19, LT = 3.8m and Ne=35, LT = 7.0m during 30 minute and maximum and minimum pressure at pivot point and at the beginning of drop lateral

Pulsing level [%]	Discharged water from lateral which is including Ne = 19 and LT = 3.8m during 30 minute [litre]	Discharged water from lateral which is including Ne = 35 and LT = 7.0m during 30 minute [litre]	Pressure [bar]			
			Pivot		Lateral	
			Min	Max	Min	Max
10	18	26	1.5	7	0	1.2
20	32	57	1.5	6.5	0	1.2
30	46	69	1.6	6.5	0	1.2
40	56	100	1.6	6.3	0	1.2
50	64	121	1.5	6.2	0	1.2
60	72	148	1.6	5.2	0	1.2
70	89	164	1.6	5	0	1.3
80	115	218	1.5	5	0	1.4
90	140	252	1.5	5	0	1.4
100	145	269	1.5	5	0	1.4

Appendix C: Details of IMZs and also variation of irrigation depth with volumetric soil moisture for all three IMZs

Irrigation Management Zone 1 (IMZ_1):

EC_{25} = 4 .65-7.80 [mS/m]

P.W.P. = 4.0 – 4.3 [vol %]
F.C. = 20.6 – 24.1 [vol %]
TAWC = 165 - 193 mm/m = 99 - 116 mm/60cm
Rz = Depth of root zone = 60 cm
SML = soil moisture level [%]
SML $_{min}$ = minimum SML before every irrigation = 60 % TAWC
SML $_{max}$ = maximum SML after every irrigation = 80 % TAWC
θ x [vol %]=Volumetric soil moisture before irrigation [vol %]= P.W.P.+ (SML/100) × (F.C. – P.W.P.)
θ **i** [vol %]=(P.W.P.+0.80× (F.C. – P.W.P.)) - θx
In [mm] = net irrigation depth = θ_i × 600/100

SML [%]	θ x [vol %]	θi [vol %]	In [%]
60	15.040	3.6300	21.7
61	15.222	3.4485	20.7
62	15.403	3.2670	19.6
63	15.585	3.0855	18.5
64	15.766	2.9040	17.4
65	15.948	2.7225	16.3
66	16.129	2.5410	15.2
67	16.311	2.3595	14.2
68	16.492	2.1780	13.1
69	16.674	1.9965	12.0
70	16.855	1.8150	10.9
71	17.037	1.6335	9.8
72	17.218	1.4520	8.7
73	17.400	1.2705	7.6
74	17.581	1.0890	6.5
75	17.763	0.9075	5.4
76	17.944	0.7260	4.4
77	18.126	0.5445	3.3
78	18.307	0.3630	2.2
79	18.489	0.1815	1.1
80	18.670	0	0.0

Appendix C : Cont`d

Irrigation Management Zone 2 (IMZ$_2$):

EC_{25} = 7 .81 – 10.62 [mS/m]

P.W.P. = 4.3 – 4.9 [vol %]
F.C. = 24.1 – 27.2 [vol %]
Rz = Depth of root zone = 60 cm
TAWC = 193 – 216 mm/m = 116 – 130 mm/60cm
SML = soil moisture level [%]
SML $_{min}$ = minimum SML before every irrigation = 60 % TAWC
SML $_{max}$ = maximum SML after every irrigation = 80 % TAWC
θ x [vol %] = Volumetric soil moisture before irrigation [vol %] = P.W.P.+ (SML/100) × (F.C. – P.W.P.)
θ **i** [vol %] = (P.W.P.+0.80× (F.C. – P.W.P.)) - θ x
In [mm] = net irrigation depth = θ **i** × 600/100

SML [%]	θ x [vol %]	θ **i** (vol %)	In [mm]
60	17.260	4.220	25.3
61	17.471	4.009	24.1
62	17.682	3.798	22.8
63	17.893	3.587	21.5
64	18.104	3.376	20.3
65	18.315	3.165	19.0
66	18.526	2.954	17.7
67	18.737	2.743	16.5
68	18.948	2.532	15.2
69	19.159	2.321	13.9
70	19.370	2.110	12.7
71	19.581	1.899	11.4
72	19.792	1.688	10.1
73	20.003	1.477	8.9
74	20.214	1.266	7.6
75	20.425	1.055	6.3
76	20.636	0.844	5.1
77	20.847	0.633	3.8
78	21.058	0.422	2.5
79	21.269	0.211	1.3
80	21.480	0	0.0

Appendix C : Cont`d

Irrigation Management Zone 3 (IMZ_3):

EC_{25}=*10.63-16.43* [mS/m]

P.W.P. = 4.9 – 6.7 [vol %]
F.C. = 27.2 – 33.7 [vol %]
Rz = Depth of root zone = 6 0cm
TAWC = 216 - 253 mm/m = 130 – 152 mm/60cm
SML = soil moisture level [%]
SML min = minimum SML before every irrigation = 60 % TAWC
SML max = maximum SML after every irrigation = 80 % TAWC
θ x [vol %] = Volumetric soil moisture before irrigation [vol %] = P.W.P.+ (SML/100) × (F.C. – P.W.P.)
θ **i** [vol %] = (P.W.P.+0.80× (F.C. – P.W.P.)) - θx
In [mm] = net irrigation depth = θ_i × 600/100

SML[%]	θ x [vol %]	θ **i** [vol %]	In [mm]
60	27.58	7.260	43.6
61	27.943	6.897	41.4
62	28.306	6.534	39.2
63	28.669	6.171	37.0
64	29.032	5.808	34.8
65	29.395	5.445	32.7
66	29.758	5.082	30.5
67	30.121	4.719	28.3
68	30.484	4.356	26.1
69	30.847	3.993	24.0
70	31.210	3.630	21.8
71	31.573	3.267	19.6
72	31.936	2.904	17.4
73	32.299	2.541	15.2
74	32.662	2.178	13.1
75	33.025	1.815	10.9
76	33.388	1.452	8.7
77	33.751	1.089	6.5
78	34.114	0.726	4.4
79	34.477	0.363	2.2
80	34.840	0	0.0

Appendix D: Simulated values of SWC during measuring period by AMBAV model

Plant phenology data					
Phase		Beginning of vegetation		Beginning of sleeping phase	
Date		02.03.		30.11.	
Irrigation from (% of TAWC)		65		65	
Soil data					
max. Root depth [mm]	F.C. [vol %]	P.W.P. [vol %]	SWC at the beginning phase [% F.C.]		
			obere 30cm	unter 30cm	
60	24	4	83	83	
Water balance from 02.03.2007 to 05.08.2007					
Saved water in the soil [mm]	Deep percolation [mm]	Evaporation [mm]	Irrigation [mm]	precipitation [mm]	Water balance [mm]
47.1	9.8	418.0	38	342.6	0.0

Irrigation data for Grass and sprinkler irrigation

Date	Recommended irrigation [mm]	Available water			Deep percolation [mm]	Evaporation [mm]	Irrigation [mm]	Precipitation [mm]
		Upper 30cm in % F.C.	Under 30cm in % F.C.	Root zone [mm]				
02.03.	0	85.7	82.7	101.1	0.0	0.7	0	2.2
03.03.	0	95.2	82.7	106.7	0.0	0.1	0	5.8

Appendix D: Cont´d

04.03.	0	93.7	82.3	105.6	0.0	1.1	0	0.0
05.03.	0	96.5	82.0	107.1	0.0	0.9	0	2.4
06.03.	0	94.7	81.6	105.8	0.0	1.3	0	0.0
07.03.	0	96.1	81.3	106.5	0.0	0.8	0	1.5
08.03.	0	96.1	81.2	106.4	0.0	0.4	0	0.3
09.03.	0	99.6	81.8	108.8	0.0	0.9	0	3.4
10.03.	0	97.9	81.4	107.6	0.0	1.3	0	0.0
11.03.	0	95.2	80.8	105.6	0.0	2.0	0	0.0
12.03.	0	92.5	80.1	103.6	0.0	2.0	0	0.0
13.03.	0	90.4	79.6	102.0	0.0	1.6	0	0.0
14.03.	0	88.4	79.1	100.5	0.0	1.5	0	0.0
15.03.	0	86.0	78.5	98.7	0.0	1.8	0	0.0
16.03.	0	85.2	78.1	98.0	0.0	0.9	0	0.2
17.03.	0	87.1	77.9	99.0	0.0	0.7	0	1.7
18.03.	0	94.9	77.6	103.5	0.0	0.9	0	5.4
19.03.	0	93.1	77.2	102.2	0.0	1.4	0	0.0
20.03.	0	91.5	76.8	101.0	0.0	1.3	0	0.1
21.03.	0	103.7	80.9	110.8	0.0	0.4	0	10.2

Appendix D: Cont´d

22.03.	0	120.1	100.6	132.4	0.4	0.1	0	22.1
23.03.	0	110.3	105.8	129.7	3.8	1.5	0	2.6
24.03.	0	102.5	104.6	124.3	3.3	2.1	0	0.0
25.03.	0	97.8	101.7	119.7	1.8	2.8	0	0.0
26.03.	0	94.4	99.7	116.4	0.5	2.8	0	0.0
27.03.	0	91.1	98.4	113.7	0.0	2.7	0	0.0
28.03.	0	88.1	97.3	111.2	0.0	2.5	0	0.0
29.03.	0	84.9	96.0	108.5	0.0	2.7	0	0.0
30.03.	0	82.4	94.9	106.4	0.0	2.1	0	0.0
31.03.	0	79.6	93.7	103.9	0.0	2.4	0	0.0
01.04.	0	76.0	92.0	100.8	0.0	3.1	0	0.0
02.04.	0	73.3	90.7	98.4	0.0	2.4	0	0.0
03.04.	0	77.1	90.4	100.5	0.0	0.6	0	2.7
04.04.	0	74.4	89.1	98.1	0.0	2.4	0	0.0
05.04.	0	72.9	88.4	96.8	0.0	1.3	0	0.0
06.04.	0	71.7	87.8	95.7	0.0	1.1	0	0.0
07.04.	0	69.3	86.6	93.6	0.0	2.2	0	0.0
08.04.	0	67.5	85.7	91.9	0.0	1.7	0	0.0

Appendix D: Cont´d

09.04.	0	65.2	84.5	89.8	0.0	2.1	0	0.0
10.04.	10	63.6	83.5	88.2	0.0	1.7	0	0.1
11.04.	15	61.8	82.5	86.6	0.0	1.7	0	0.0
12.04.	15	58.5	80.5	83.4	0.0	3.2	0	0.0
13.04.	20	54.6	78.0	79.6	0.0	3.8	0	0.0
14.04.	20	50.4	75.1	75.3	0.0	4.3	0	0.0
15.04.	25	46.0	71.9	70.7	0.0	4.6	0	0.0
16.04.	25	41.9	68.6	66.3	0.0	4.4	0	0.0
17.04.	25	40.2	67.0	64.3	0.0	2.0	0	0.0
18.04.	30	38.2	65.2	62.0	0.0	2.3	0	0.0
19.04.	30 + 20	35.5	62.6	58.9	0.0	3.1	0	0.0
20.04.	30 + 25	34.1	61.1	57.2	0.0	1.7	0	0.0
21.04.	30 + 25	32.0	58.8	54.5	0.0	2.7	0	0.0
22.04.	30 + 30	29.3	55.8	51.1	0.0	3.4	0	0.0
23.04.	30 + 30	31.7	53.3	50.9	0.0	3.3	0	3.2
24.04.	30 + 30	31.0	51.9	49.7	0.0	1.7	0	0.5
25.04.	30 + 30	28.3	49.4	46.6	0.0	3.1	0	0.0
26.04.	30 + 30	25.7	46.8	43.5	0.0	3.1	0	0.0

Appendix D: Cont´d

27.04.	30 + 30	23.5	44.3	40.7	0.0	2.8	0	0.0
28.04.	30 + 30	21.5	41.9	38.0	0.0	2.6	0	0.0
29.04.	30 + 30	19.7	39.6	35.6	0.0	2.4	0	0.0
30.04.	30 + 30	18.1	37.5	33.4	0.0	2.2	0	0.0
01.05.	30 + 30	16.7	35.5	31.3	0.0	2.1	0	0.0
02.05.	30 + 30	15.4	33.5	29.3	0.0	1.9	0	0.0
03.05.	30 + 30	14.2	31.7	27.5	0.0	1.8	0	0.0
04.05.	30 + 30	13.0	29.7	25.7	0.0	1.9	0	0.0
05.05.	30 + 30	12.0	27.9	23.9	0.0	1.7	0	0.0
06.05.	30 + 30	12.7	26.3	23.4	0.0	1.6	0	1.1
07.05.	30 + 30	56.4	26.3	49.6	0.0	0.6	0	26.8
08.05.	30 + 30	53.1	26.0	47.5	0.0	2.3	0	0.1
09.05.	30 + 30	57.7	25.8	50.1	0.0	2.8	0	5.4
10.05.	30 + 20	69.3	25.7	57.0	0.0	1.5	0	8.4
11.05.	30 + 15	80.3	25.6	63.5	0.0	1.0	0	7.5
12.05.	30 + 10	83.4	25.5	65.4	0.0	2.0	0	3.8
13.05.	30 + 10	86.6	25.4	67.2	0.0	3.1	0	5.0
14.05.	30 + 10	89.3	25.3	68.7	0.0	3.4	0	4.9

Appendix D: Cont´d

15.05.	30 + 10	86.8	25.2	67.2	0.0	2.3	0	0.8
16.05.	30 + 10	89.1	25.1	68.5	0.0	1.7	0	3.0
17.05.	30 + 10	84.3	25.0	65.6	0.0	3.0	0	0.0
18.05.	30 + 15	77.6	24.8	61.4	0.0	4.1	0	0.0
19.05.	30 + 20	74.4	24.7	59.4	0.0	2.0	0	0.0
20.05.	30 + 20	68.5	24.4	55.8	0.0	3.7	0	0.0
21.05.	30 + 30	62.1	24.2	51.7	0.0	4.0	0	0.0
22.05.	30 + 30	57.3	23.9	48.7	0.0	3.2	0	0.2
23.05.	30 + 10	87.9	23.8	67.0	0.0	2.7	21	0.0
24.05.	30 + 5	93.3	23.8	70.3	0.0	4.2	0	7.4
25.05.	30 + 10	89.5	23.7	67.9	0.0	4.1	0	1.7
26.05.	0	100.8	29.4	78.2	0.0	3.1	0	13.4
27.05.	0	105.2	39.5	86.8	0.0	3.1	0	11.8
28.05.	0	104.6	45.7	90.2	0.0	1.1	0	4.5
29.05.	0	115.6	61.7	106.4	0.0	0.3	0	16.5
30.05.	0	102.0	68.7	102.4	0.0	4.0	0	0.0
31.05.	0	94.7	68.7	98.0	0.0	4.4	0	0.0
01.06.	0	89.2	67.7	94.2	0.0	3.9	0	0.0

Appendix D: Cont´d								
02.06.	0	87.9	67.4	93.2	0.0	1.2	0	0.2
03.06.	0	86.2	67.1	91.9	0.0	1.3	0	0.0
04.06.	0	83.6	66.6	90.1	0.0	1.8	0	0.0
05.06.	0	81.7	65.8	88.5	0.0	2.6	0	1.0
06.06.	0	76.8	64.8	84.9	0.0	3.6	0	0.0
07.06.	0	69.9	63.1	79.8	0.0	5.1	0	0.0
08.06.	30 + 5	62.2	61.0	73.9	0.0	5.9	0	0.0
09.06.	30 + 5	65.2	59.5	74.8	0.0	4.8	0	5.7
10.06.	30 + 10	58.0	57.5	69.3	0.0	5.6	0	0.0
11.06.	30 + 15	51.6	55.4	64.2	0.0	5.1	0	0.0
12.06.	30 + 20	46.4	53.4	59.9	0.0	4.3	0	0.0
13.06.	0	69.1	52.4	72.9	0.0	4.0	17	0.0
14.06.	30	77.6	51.6	77.6	0.0	4.0	0	8.7
15.06.	0	94.4	51.2	87.3	0.0	3.7	0	13.5
16.06.	25	89.2	50.7	84.0	0.0	3.4	0	0.0
17.06.	25	91.0	50.2	84.7	0.0	3.9	0	4.7
18.06.	20	93.2	49.9	85.9	0.0	2.1	0	3.2
19.06.	0	84.8	49.1	80.3	0.0	5.5	0	0.0

Appendix D: Cont´d

20.06.	0	76.7	48.2	74.9	0.0	5.4	0	0.0
21.06.	0	100.5	49.7	90.1	0.0	0.7	0	15.9
22.06.	0	96.8	51.9	89.2	0.0	3.8	0	2.9
23.06.	0	97.2	53.3	90.3	0.0	3.1	0	4.2
24.06.	0	91.2	52.7	86.3	0.0	4.1	0	0.1
25.06.	20	89.7	52.3	85.2	0.0	2.3	0	1.2
26.06.	25	88.1	51.9	84.0	0.0	3.0	0	1.7
27.06.	25	85.5	51.4	82.1	0.0	2.8	0	1.0
28.06.	25	82.7	50.9	80.1	0.0	2.8	0	0.8
29.06.	25	86.8	50.6	82.5	0.0	1.6	0	3.9
30.06.	0	86.2	50.3	81.9	0.0	2.4	0	1.8
01.07.	0	83.1	49.8	79.8	0.0	2.9	0	0.8
02.07.	0	99.2	51.8	90.6	0.0	2.0	0	12.8
03.07.	0	99.4	55.1	92.7	0.0	2.8	0	4.9
04.07.	0	96.6	55.5	91.2	0.0	2.8	0	1.4
05.07.	0	93.7	55.1	89.3	0.0	2.5	0	0.6
06.07.	0	91.0	54.7	87.4	0.0	2.4	0	0.5
07.07.	0	87.0	54.1	84.7	0.0	2.9	0	0.2

Appendix D: Cont´d

08.07.	0	84.3	53.4	82.6	0.0	4.4	0	2.3
09.07.	0	89.3	53.2	85.5	0.0	0.9	0	3.8
10.07.	0	90.9	52.8	86.3	0.0	2.5	0	3.2
11.07.	0	96.8	52.6	89.6	0.0	1.8	0	5.2
12.07.	0	95.6	52.3	88.7	0.0	1.8	0	0.9
13.07.	0	95.3	52.0	88.3	0.0	3.2	0	2.8
14.07.	25	86.6	51.1	82.6	0.0	5.7	0	0.0
15.07.	30	78.4	50.2	77.1	0.0	5.5	0	0.0
16.07.	30 + 5	68.8	48.8	70.6	0.0	6.7	0	0.1
17.07.	30 + 15	61.8	47.7	65.7	0.0	4.9	0	0.0
18.07.	30 + 20	55.9	46.5	61.4	0.0	4.2	0	0.0
19.07.	30 + 20	52.1	45.5	58.6	0.0	3.1	0	0.3
20.07.	30 + 25	47.3	44.3	55.0	0.0	3.7	0	0.1
21.07.	30 + 20	56.6	43.3	59.9	0.0	4.0	0	9.0
22.07.	30 + 20	57.9	42.6	60.3	0.0	2.9	0	3.3
23.07.	30 + 20	56.3	41.9	58.9	0.0	3.1	0	1.7
24.07.	30 + 15	66.1	41.6	64.6	0.0	1.8	0	7.5
25.07.	30 + 20	60.2	40.8	60.6	0.0	4.0	0	0.0

Appendix D: Cont´d								
26.07.	30 + 20	56.8	40.0	58.1	0.0	3.9	0	1.4
27.07.	30 + 25	52.8	39.1	55.1	0.0	3.7	0	0.8
28.07.	30 + 25	57.6	38.8	57.8	0.0	1.6	0	4.3
29.07.	30 + 15	66.5	38.7	63.1	0.0	0.8	0	6.0
30.07.	30 + 20	64.8	38.3	61.9	0.0	2.5	0	1.3
31.07.	30 + 20	60.7	37.8	59.1	0.0	2.9	0	0.1
01.08.	30 + 25	55.0	37.0	55.2	0.0	3.9	0	0.0
02.08.	30 + 15	69.8	36.9	64.0	0.0	1.3	0	10.1
03.08.	30 + 20	64.2	36.3	60.3	0.0	3.7	0	0.0
04.08.	30 + 25	58.5	35.7	56.5	0.0	3.8	0	0.0
05.08.	30 + 30	52.5	35.0	52.5	0.0	4.0	0	0.0

volumetric simulated SWC in root zone of grass can be calculated by followed:

SWC [vol %] = ([available water in root zone [mm] + (P.W.P. =24mm)]/ 600) × 100

Appendix E: Calculation related to number of emitters installed on drop tube and length of drop tubes

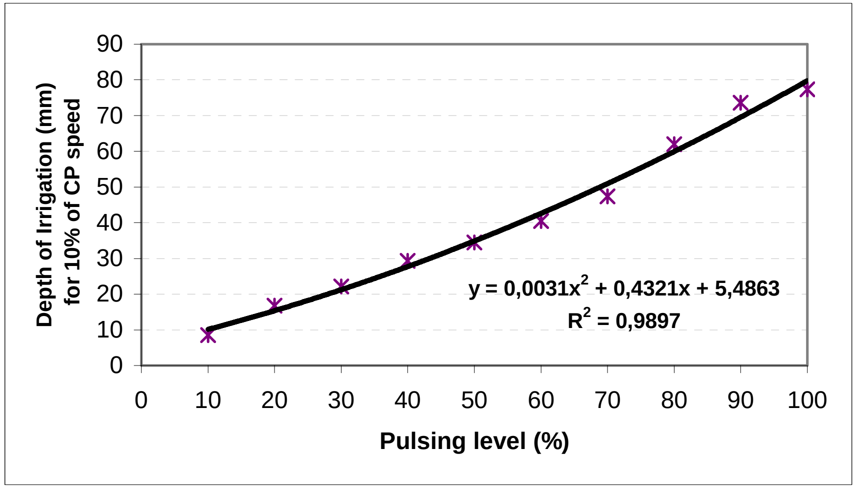
n	TRP [m]	D [cm]	dr [cm]	A [m^2]	V [litre]	Q [litre/h]	Ne-120	LT-120 [m]	Ne-170	LT-170 [m]
1	38.84	83	83	202.6	4597.9	102.2	7.0	1.4	6.0	1.2
2	39.67	83	83	206.9	4696.2	104.4	7.0	1.4	6.0	1.2
3	40.5	84	83.5	212.5	4823.3	107.2	7.0	1.4	6.0	1.2
4	41.34	83	83.5	216.9	4923.4	109.4	7.0	1.4	6.0	1.2
5	42.17	83	83	219.9	4992.2	110.9	7.0	1.4	6.0	1.2
6	43	89	86	232.4	5274.4	117.2	7.0	1.4	7.0	1.4
7	43.89	88	88.5	244.1	5540.1	123.1	8.0	1.6	7.0	1.4
8	44.77	88	88	247.5	5619.2	124.9	8.0	1.6	7.0	1.4
9	45.65	84	86	246.7	5599.5	124.4	8.0	1.6	7.0	1.4
10	46.49	83	83.5	243.9	5536.7	123.0	8.0	1.6	7.0	1.4
11	47.32	83	83	246.8	5601.8	124.5	8.0	1.6	7.0	1.4
12	48.15	85	84	254.1	5768.8	128.2	8.0	1.6	8.0	1.6
13	49	85	85	261.7	5940.5	132.0	8.0	1.6	8.0	1.6
14	49.85	85	85	266.2	6043.5	134.3	9.0	1.8	8.0	1.6
15	50.7	83	84	267.6	6074.3	135.0	9.0	1.8	8.0	1.6
16	51.53	83	83	268.7	6100.2	135.6	9.0	1.8	8.0	1.6
17	52.36	83	83	273.1	6198.5	137.7	9.0	1.8	8.0	1.6
18	53.19	85	84	280.7	6372.6	141.6	9.0	1.8	8.0	1.6
19	54.04	85	85	288.6	6551.5	145.6	9.0	1.8	9.0	1.8
20	54.89	85	85	293.2	6654.6	147.9	9.0	1.8	9.0	1.8
21	55.74	87	86	301.2	6837.1	151.9	10.0	2.0	9.0	1.8
22	56.61	88	87.5	311.2	7064.9	157.0	10.0	2.0	9.0	1.8
23	57.49	88	88	317.9	7215.8	160.4	10.0	2.0	9.0	1.8
24	58.37	84	86	315.4	7159.7	159.1	10.0	2.0	9.0	1.8
25	59.21	83	83.5	310.6	7051.6	156.7	10.0	2.0	9.0	1.8
26	60.04	83	83	313.1	7107.6	157.9	10.0	2.0	9.0	1.8
27	60.87	87	85	325.1	7379.5	164.0	10.0	2.0	10.0	2.0
28	61.74	88	87.5	339.4	7705.2	171.2	11.0	2.2	10.0	2.0
29	62.62	88	88	346.2	7859.6	174.7	11.0	2.2	10.0	2.0
30	63.5	78	83	331.2	7517.2	167.0	11.0	2.2	10.0	2.0
31	64.28	78	78	315.0	7151.2	158.9	10.0	2.0	9.0	1.8
32	65.06	78	78	318.9	7237.9	160.8	10.0	2.0	9.0	1.8
33	65.84	86	82	339.2	7700.3	171.1	11.0	2.2	10.0	2.0
34	66.7	85	85.5	358.3	8133.9	180.8	11.0	2.2	11.0	2.2
35	67.55	85	85	360.8	8189.4	182.0	12.0	2.4	11.0	2.2
36	68.4	82	83.5	358.9	8146.1	181.0	12.0	2.4	11.0	2.2
37	69.22	82.5	82.25	357.7	8120.3	180.5	11.0	2.2	11.0	2.2
38	70.045	83	82.75	364.2	8267.1	183.7	12.0	2.4	11.0	2.2
39	70.875	83.5	83.25	370.7	8415.6	187.0	12.0	2.4	11.0	2.2
40	71.71	84	83.75	377.4	8565.9	190.4	12.0	2.4	12.0	2.4
41	72.55	84	84	382.9	8692.1	193.2	12.0	2.4	11.0	2.2
42	73.39	96	90	415.0	9420.8	209.4	13.0	2.6	12.0	2.4
43	74.35	96.5	96.25	449.6	10206.8	226.8	14.0	2.8	13.0	2.6
44	75.315	96.5	96.5	456.7	10366.1	230.4	15.0	3.0	13.0	2.6
45	76.28	96.5	96.5	462.5	10498.9	233.3	15.0	3.0	14.0	2.8
46	100	100	100	628.3	14262.9	317.0	20.0	4.0	18.0	3.6
47	150	100	100	942.5	21394.3	475.4	30.0	6.0	28.0	5.6
48	200	100	100	1256.6	28525.7	633.9	40.0	8.0	37.0	7.4

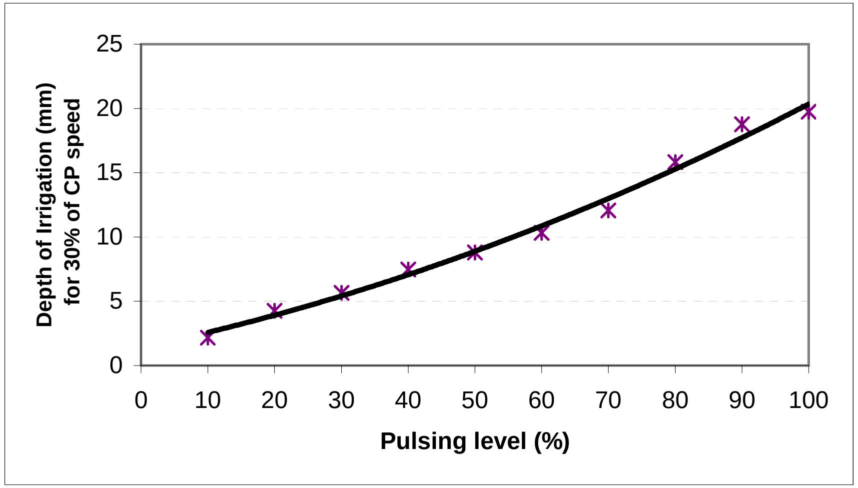
Appendix E: Cont´d

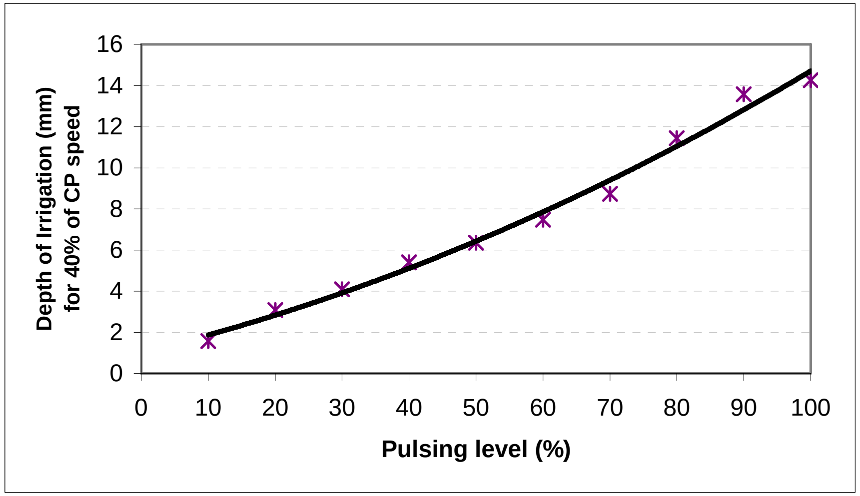
49	250	100	100	1570.8	35657.2	792.4	50.0	10.0	46.0	9.2
50	300	100	100	1885.0	42788.6	950.9	60.0	12.0	55.0	11.0
51	350	100	100	2199.1	49920.0	1109.3	70.0	14.0	65.0	13.0
52	400	100	100	2513.3	57051.5	1267.8	80.0	16.0	74.0	14.8
53	30	83	83	156.5	3551.5	78.9	5.0	1.0	5.0	1.0
54	20	83	83	104.3	2367.6	52.6	3.0	0.6	3.0	0.6
55	10	83	83	52.2	1183.8	26.3	2.0	0.4	2.0	0.4
56	5	83	83	26.1	591.9	13.2	1.0	0.2	1.0	0.2

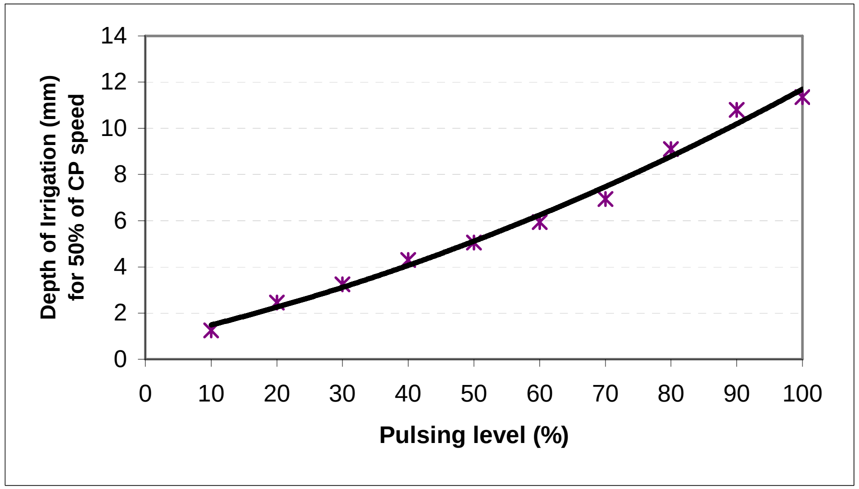
n = Number of drop tube installed on drop tubes
DTP = Distance between drop tube and pivot point [m]
D = Distance between drop tubes [cm]
dr = Narrow spacing covered by drip tube [cm]
A = Irrigated area covered by drip tube [m^2]
V= Volume of water which has to be discharged by drop tube for I_{max}=22.7 mm [litre]
Q= Discharge of water by drop tube for I_{max}=22.7 mm during a 48 h cycle [litre/h]
Ne-120= Number of emitters installed on drop tube for I_{max}=22.7 mm. P=120kPa and q=15.8 [litre/h] during a 48 h cycle
LT-120= Length of drop tube for I_{max}=22.7 mm. P=120 kPa and q=15.8 (liter/hr) during a 48 h cycle
Ne-170= Number of emitters installed on drop tube for I_{max}=22.7 mm. P=170kPa and q=17.2 [litre/h] during a 48 h cycle
LT-170= Length of drop tube for I_{max}=22.7 mm. P=170 kPa and q=17.2 [litre/h] during a 48 hr cycle

Appendix F: Field test variation of MDI depth against pulsing level for different programmed CP speed

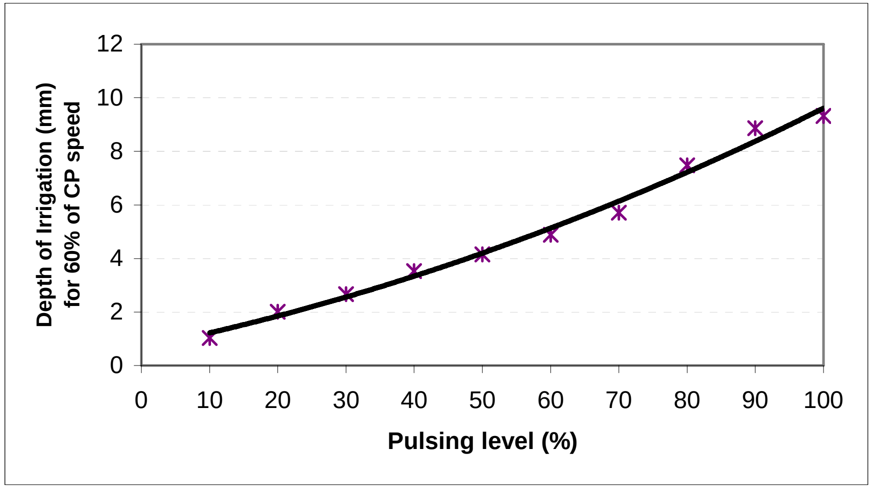


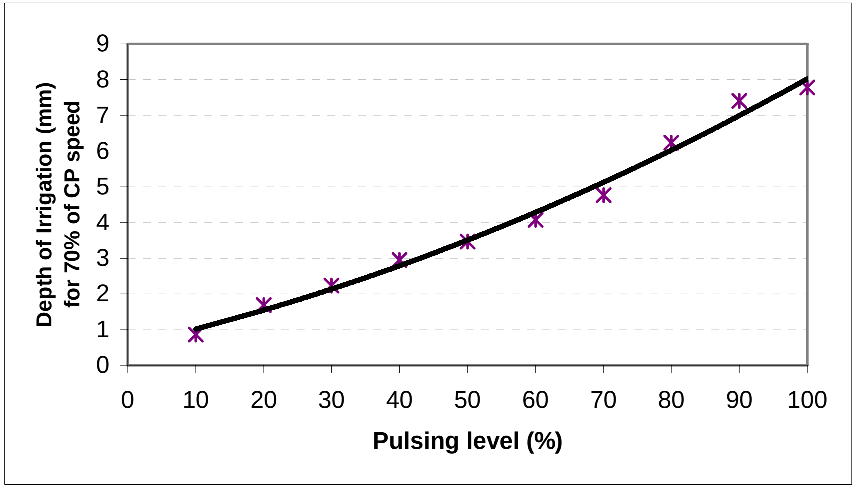


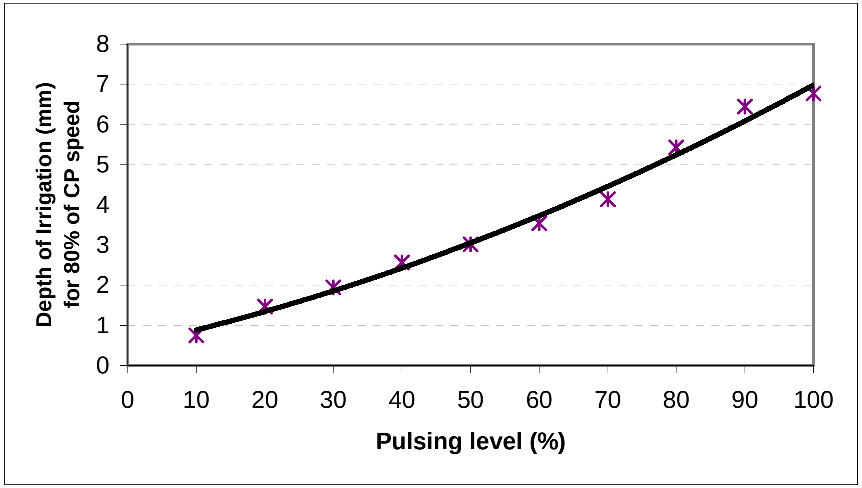


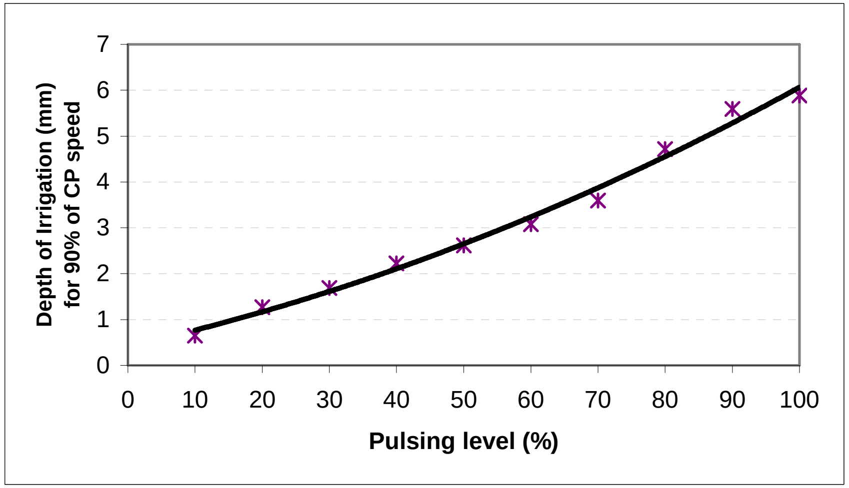


Appendix F: Cont`d









Appendix G: Installing a metallic bar parallel to CP wheel to avoid drop tube tangling in to mobile drip CP wheel

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"At the first of all my thanks to my GOD for all his grace"

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DEDICATION

I would like to dedicate this thesis to

the loving memory of

my father and my mother,

Never forgotten and always loved

Every success is a direct consequence of their influence in my life and their love.

A. Hezarjaribi

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