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Potentials and development of precision irrigation technology

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POTENTIALS AND DEVELOPMENT OF PRECISION IRRIGATION TECHNOLOGY

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LIST OF ABBREVIATIONS

AWC (nFK)	Available Water Content (nutzable Feld Kapazitaet), mm
CU	Coefficient of Uniformity %
CU_{cp}	Coefficient of Uniformity for Centre Pivot %
d_n	Depth of irrigated water (mm)
EMI	Electromagnetic Induction
EC	Soil Electrical Conductivity (mS/m)
EC_a	Profile-weighted EC (mS/m)
EC_e	EC measured in the laboratory using paste extract (mS/m)
FC (FK)	Field Capacity (Feld Kapazitaet), mm
FAL	Federal Agriculture Research Centre
GIS	Geographic Information System
GPS	Global Positioning System (*D* Differential)
ha	Hectare
kWh	Kilo-Watt-Hour
MCM	Million Cubic Meter
m/h	meter/hour
mS/m	milli Siemens per meter
ρ_b	Soil Bulk Density (g/cm^3)
PF	Precision Farming
PI	Precision Irrigation
PLC	Programmable Logic Control
PWP	Permanent Wilting Point (mm)
R	Replicate
v_p	Travel-speed programmed (m/h)
v_m	Travel-speed measured (m/h)
WP	Welkpunkt, mm
yr.	Year

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1. INTRODUCTION

At the start of the new millennium, nations are still facing the crucial challenge of ensuring food supplies and sustainable utilization and development of agricultural resources. An ever-increasing population, resource shortages and degradation of the ecological environment have added even greater pressure on countries. In Jordan, for example, the population is 5.04 Million and growing at growth rate of 2.8% (Dept. of Statistics, 2000), so that land and water are unable to be sustained (Abu-Sharar et al., 1999). The need for increasing agricultural production also has an impact on fresh water resulting in water shortages and subsequent quality deterioration. Unfortunately, the Jordanian per capita allocation of water for household purposes falls below 80 l/day, compared to other countries such as Germany, which is estimated to be at more than 110 l/day (Statistisches Jahrbuch BMVEL, 2001). Such a low figure is even less than the minimum water requirement for per capita annual consumption of domestic water. The present shortage in water resources and the expected sharpening of demand should give rise to water policies involving more efficient conservation systems rather than only the traditional search for new resources. Now is the time to formulate new policies and shift toward more efficient management strategies, especially in the irrigation sector, which consumes a large percentage, about 70%, of water resources in Jordan, through developing and introducing the necessary technologies for watering systems.

Since the 1990's a new management concept for sustainable utilization and efficient use of agricultural inputs, known as "precision farming" or "site-specific management", has started to receive great interest as a new experimental tool. Using conventional practices, farm managers tend to treat the field as a single unit and manage it to optimize the average production as a whole. The objective behind precision farming is dividing the field into several homogenous sub-units and treating them independently. Thus, the production of each unit can be optimized, because of the spatial variability in soil properties which, in turn, affects the profitability of inputs to plants. Precision farming technology has attracted great interest and the technical support has been quickly commercialized and continuously improved in trial practice. It is regarded as a revolutionary approach for improved crop management and for sustainable agricultural development. Many related research institutions, academic communities, manufacturers, service industries, and dealers have become involved in the development of this potential market (Maohua, 2001). Therefore, it seems to be a promising technology for the present century.

A successful precision farming management system is one in which the key limitations to optimum profitability and environmental protection can be identified, characterized and managed at the appropriate locations and times (Mulla and Schepers, 1997). Management of variation across a field, known as spatial variability, is the keystone to effective use of precision farming technology. The better knowledge of spatial soil variability within a field would be valuable information, fundamental to the management areas development and basis for management decisions regarding cultivation activities, such as irrigation practices, since different soils have different water holding capacities (Han et al., 1996; Evans and Harting, 1999). Up to now, soil sampling followed by laboratory analysis remains the most used method, and to describe the smaller-scale spatial variability, relatively fine grid spacing is required, which makes sampling activities too expensive and time consuming. The enlargement of grid spacing and the interpolation between different sample points may lead only to a rough or even to a false pattern of the investigated fields. The principally required technologies for spatial variability mapping are partly available commercially and are rapidly improving. They include:

- Differential Global Positioning Systems, DGPS,
- Geographic Information System, GIS,
- Remote Sensing technologies, RS,
- Quasi-real time sensing technology,
- Spatial data processing and mapping tools,
- Decision support systems based on modeling,
- Incorporating simulation with expert systems,
- Intelligent farm machinery or appropriate technological tools for treatment, and/or
- System integration software and standardization.

Challenges facing engineers in promoting precision farming are to develop fundamental and applied research on GPS, GIS and RS for farming use and real-time sensors and control technology for spatial variables in the field such as crop yield and soil parameters (Maohua, 2001; Türker, 2001a; Ehlert et al., 2001; Vosshenrich et al., 2001; Sparovek and Schnug, 2001; Werner et al.,/*pre agro* 2002). Development of less costly methods is therefore of great interest, and one of the most promising new methods and techniques is dependent on measuring a surrogated property, which depends on and correlates with other soil properties, such as measuring of soil electrical conductivity (EC), and this could be fast, cheap and can deliver a large number of measurements per unit of area (Sudduth et al., 2000; Ehlert et al., 2001; Domsch, 2001a, b). Soil EC is primarily a function of texture (mainly clay content), soil water content and salinity (McNeill, 1980). If soil EC is well correlated to soil property, for example texture, it could be used to identify relatively homogeneous areas with regard to the given soil property within a field. Remote measuring of soil electrical properties has recently emerged as a potential tool to differentiate and map various soil parameters related to EC (King and Dampney, 2000; Domsch, 2001a, b). Electromagnetic Induction (EMI) is a rapid and low-cost method for scanning and collecting soil EC data and identifying spatial soil variability.

Up to now, the main efforts and applications have focussed on site-specific crop management, in order to improve sustainability and reduce environmental impacts, by allowing today's agricultural producers, advisors and researchers to integrate information technology with the field and office activities. Precision farming is being tested for weed, insect and disease control through variable-rate technology, to apply chemicals at different rates across a field or only an area of a field that needs control measures (Torre-Neto et al., 2001; Biller, 1998). Fertilizers were tested spread variably so each location within the field received the right amount of nutrients it needed (Camp et al., 2000). Irrigation systems have been developed (Sourell and Sommer, 2002), but still apply the same amount of water in the field, without taking soil spatial variability into consideration. The use of precision farming for irrigation water management/scheduling, known as "precision irrigation", in order to apply water in the right place at the right amount at the right time is just beginning to be explored and still in the development stages. More experimental work is required to determine its feasibility and applicability.

Agricultural cropping systems depend on the use of water resources for survival. Accordingly, irrigation systems have become a necessary part of most cropping systems, especially in arid and semi-arid regions such as Jordan and in countries that need to stabilize yields such as Germany, because of inadequate and/or uneven rainfall distribution. Irrigated agriculture is viewed as an industry that contributes to excessive ground and surface water degradation, due to inefficient water management (Sanders et al., 2000; King et al., 1999). Water needs vary spatially in many fields because of soil spatial variability (Morton et al., 1998). Different soil types have different textures, topography, water holding capacities and infiltration and drainage rates. Therefore, the need for irrigation may differ between different zones of a particular field. Since irrigation systems apply water at constant rates, some areas may receive more/less water than required within one field. Excessive water application could contribute to surface water runoff and/or leaching of nutrients and chemicals to groundwater. Inefficient water application causes reductions in yield quantity and quality, inefficient use of fertilizer and other inputs, and lower overall water use efficiency (Sanders et al., 2000).

Irrigation management must become a priority for agricultural producers in Germany and worldwide. Due to growing concerns of water quality and quantity, and the recent surge in energy costs, it is both an economically and environmentally sound decision to improve irrigation systems. The more that is known about "precision irrigation", the more accurate the irrigation management can be, due to the delivery of irrigation water in optimum amounts over an entire field (Sourell and Sommer, 2002). It is also an important element of precision farming, because fertilizers and chemicals are carried along with irrigation water. The accuracy and timing of irrigation will maximize fertilizer uptake and chemical efficiency, and reduce the chance of losses. "Precision irrigation" previously eluded farmers, who have had to treat agricultural fields as a singular unit, even though soil moisture, weed and pest populations, salinity or vegetation quality could differ from one area to another, as a result, water and chemicals have been overdosed. A solution to this problem may exist in a site-specific system to be developed by many industries.

In the past 50 years, world agriculture has experienced enormous changes, such as the developing of modernized irrigation systems with expected high productivity and advanced technology by industrialized countries (Sourell and Sommer, 2002; Maohua 2001; Faci et al., 2001). Self-propelled commercial travelling irrigation systems, such as center pivots and moving-laterals, are particularly amenable to site-specific approaches because of their current level of automation and large area coverage with a single pipe lateral. Such systems implemented with control systems allow variable application depths in the direction of travel by adjusting system speed. Currently, most of the travelling irrigation systems in-use, such as booms, big guns, centre pivots, etc., apply either constant rates of water or allow for pie-shaped areas of the field to have varying rates by adjusting the travel speed of the irrigation system in those areas. Similarly, some fields contain areas that are not cropped and could benefit from the ability to apply varying amounts of irrigation water. In addition, precision irrigation systems provide an outstanding platform on which to mount sensors for real time monitoring of plant and soil conditions which would interact with a control system for optimal environmental benefits.

It seems improving irrigation systems to apply water uniformly over the field has received great attention from both research and technology, but has reached a stage in which any further improvements will not significantly increase profitability. It is important now to shift toward and concentrate on optimization of the net profit from this water by applying it at the appropriate place and quantity. It is possible to take the advantages of some existing technologies to be adapted for precision irrigation, such as speed-control systems, which are still used for one speed along the whole field, although it can be used for different speeds. Solenoid valves are known on the irrigation market, but they need software to control their operation. So the next generation in irrigation scheduling should be re-defined to be when/how much/where to irrigate not just when/how much (Evans et al., 1996). A precision irrigation system would have the ability to apply the right amount of water directly where it is needed, therefore saving water through preventing excessive water runoff and leaching.

Precise management of water in agriculture in the 21st Century has become crucial due to the increasing demands from the industry and urban sectors. Precision irrigation merges the new technologies borne of the information age with a mature irrigation industry. The goal is not new, but the new technologies now available allow the concept of precision irrigation to be realized in practical production settings to save water and energy.

2. Literature Review

2.1. Background

During the past decade there has been a growing concern about the environmental degradation of the planet (Fraisse et al., 1995a). With severe limitations on the availability of water, as one of the basic natural resources, about 665 MCM in 2005 in Jordan for instance (Table 2.1, pp. 33), conservative and efficient use of water is a major consideration for balancing future demand and supply. Undoubtedly, this decade will be characterised by growing scarcity, competition and conflict among users, growing demands for water for other uses, in particular for drinking and industry, decline in the share of water available for agriculture and decline in investments in irrigation expansion. The decrease in the availability of water for agricultural purposes, coupled with the requirements for higher agriculture productivity in irrigated areas, due to population growth and the necessity to feed them, means that the world has no option but to improve the efficiency with which water is used for agriculture, in order to achieve “more with less”. Therefore, improved irrigation management should be a major conservation option in the future.

2.2. Precision Farming: Definition, Tools and Potentials

A promising technology in the present century regarded as revolutionary approach for improved resource management for sustainable agricultural development is the site-specific management or management according to local conditions and known as precision farming (Shueller, 1992; Mulla and Schepers, 1997; Heermann et al., 2000; Domsch, 2001a,b; Ehlert et al., 2001; Vosshenrich et al., 2001; Sparovek and Schnug, 2001; Werner et al.,/*pre agro*, 2002). It implies using information about *in-situ* variability and climatic characteristics to manage specific sites within the field with best practices. If fields were uniform, there would be no need for precision farming, but, since most fields contain a complex arrangement of soils and topography, extensive spatial variability in soil properties and crop productivity is the norm rather than the exception. Climatic variability is no less important, and may often be even more important than spatial variability. However, the differences in yield between poor and excellent climatic years can often be one order of magnitude, and the impact of spatial variability may be negligible in some years (Huggins and Alderfer, 1995). To date, precision farming management decisions have focussed largely on strategies for managing spatial variability in an average to good growing season climate, rather than managing for both spatial and temporal variability.

Potential improvements in environmental quality are often cited as a reason for using precision farming (Pierce and Nowak, 1999). Reduced agrochemical uses, raised inputs use efficiencies and increased protection of soils from erosion is frequently cited as potential benefits to the environment. The environmental impacts of precision farming are difficult and costly to quantify, particularly as the temporal component of variability increases. Some areas, in which potential environmental benefits of precision farming/irrigation exist include:

- Reduction in nutrient inputs,
- Reduction in pesticide inputs through variable rate applications,
- Reduction in irrigation water inputs in areas subject to leaching using variable rate irrigation,
- Minimizing or avoiding nutrient and pesticide additions where the potential for significant losses exist and
- Increased erosion control due to reduction in runoff achieved through site-specific tillage and residue management and management of field and landscape buffer zones not possible without precision management systems (Sparovek and Schnug, 2001).

The main ideas related to precision farming are to (Maohua, 2001):

- Understanding spatial variability of soil properties, crop status and yield within a field,
- Identifying the reasons for yield variability,
- Making farming prescription and crop production management decisions based on the variability and knowledge,
- Implementing site-specific field management operations and
- Evaluating the efficiency of treatment; and accumulating spatial resource information for further management decision making.

2.2.1. Spatial Variability Delineation

Three knowledge and skill levels (Figure 2.1) are necessary to develop site-specific cultural practices (Guerif et al., 2001):

- The first level is the description of the spatial variability of soil and crop characteristics which is the basis of all further developments. Sensors and associated interpretation models have been developed in geophysics, detection by vision, remote sensing and yield mapping.
- These characteristics should provide a basis for diagnosis and decision making at the second level, that concerning agronomy. It is reasonable to assume that all the current agronomic knowledge should be used and adapted to define methods and rules for site specific farming.
- The third level concerns the technology of variable application for different cultural practices and refers to skills in automatism and the control of machines.

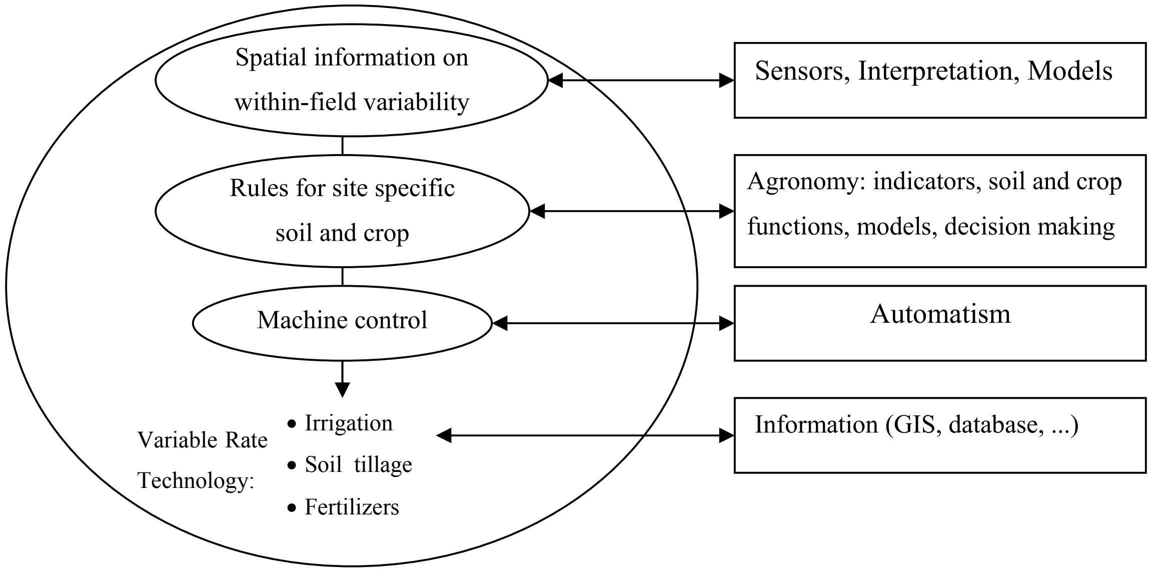

Figure 2.1: Different skills to gather for handling within-field variability into cultural practices (Guerif et al., 2001).

It is becoming increasingly recognized among agriculturists that crops and soils are not homogeneous within a given production field (Shueller, 1992). Precision farming is information-intense; a lot of positioning tagged and sensed data, i.e., mapped data, is required to generate treatment maps, therefore, one of the factors limiting its commercial application is the cost of sampling data at sufficient intensities to provide accurate mapped information (Weiss, 1996; Frogbrook, 1999; James et al., 2000). The variation of crop and soil properties has led to attempts to understand those variations and to manage accordingly, in order to enable agriculture to be more able to meet agricultural-environmental constraints.

One component of precision farming is relating management to site-specific conditions in the soil. The amount of research activity in this field is expanding rapidly. Numerous procedures have been examined for identifying management areas within fields:

- Traditional soil surveys give a general understanding of the effects soil mapping units have on crop productivity (Schmidt, 1997). Soil data, such as moisture and texture, can be obtained, but only by laborious and costly manual or semi-automated sampling and analysis, or by visual surveying. The complex interaction between soil and crop growth means that it is difficult to infer spatially variable treatment from mapped soil factors.
- Slope position and landform are topographic features that also have been used to explain water and crop productivity relationships (Mulla et al., 1992; Sudduth et al., 1997; Fridgen et al., 2000).
- More detailed soil productivity indices have also been developed using various soil properties to characterize variability between soil types at the field levels (Scrivner et al., 1985). However, few farmers have adopted productivity indices since measurement is expensive and time consuming.
- Many technological advances have been made in the last decade: Global Positioning Systems, GPS, and Differential Global Positioning System, DGPS, which is used to record the actual position in Easting and Northing (Blackmore, 1996; Weiss, 1996; Sparovek and Schnug, 2001; Lilienthal, 2001). Satellite remote sensed images are available but not processed into a form that is suitable for the crop manager to use as a quantified data source (Stafford, 2000).
- Various sensing systems, data exchange and computing variable application technologies were presented for spatial variability. These advances make it possible to take into account the spatial information in husbandry decisions, leading to the concept of precision farming (Robert, 1999; Guerif et al., 2001; Türker, 2001a).

- Yield maps are produced by fitting a yield monitor to a combine harvester to know the amount of grain harvested at any particular time (Sparovek and Schnug, 2001; Werner et al.,/*pre agro*, 2002).

Direct measurement of spatial crop productivity by yield monitoring and mapping is one way to determine soil variability. However, the yield map is confounded by many potential causes of yield variability (Pierce et al., 1997). Using yield maps alone to identify the influence of soil and landscape properties on soil water and crop production without also using spatial measurement of the numerous other potential and often transient yield-limiting factors (e.g., pest incidence, nutrients, and management variation) may be futile. Averaging multiple years of yield maps has been suggested as one way of establishing stable yield productivity patterns related to soil water (Stafford et al., 1996; Kitchen et al., 1995; Colvin et al., 1997). In some cases however, high producing areas of a field during dry years can be low producing areas of the same field in wet years (Colvin et al., 1997; Sudduth et al., 1997).

The ideal to be attained are real-time, robust, low-cost mapping systems for soil, crop and environment variables. Sensing and mapping of soil factors provides decision support information to the crop manager in identifying factors limiting to growth and yield in various parts of the field. However, the only commercial systems available to date are yield mapping and soil electrical conductivity (EC) mapping systems.

2.2.1.1. Soil EC as Surrogate Factor

The concept of surrogate sensing and mapping is one that is likely to be taken up more in the present decade, where factors are difficult or impossible to sense directly. Rapid methods for scanning large volumes of information, i.e., scanning soils EC (Fleming et al., 1999; Sudduth et al., 1999; Kitchen et al., 2000; Fridgen et al., 2000; Suduth et al., 2000; Domsch, 2001a,b; Ehlert et al., 2001) are to be used extensively in precision farming decision making. Spatial measurement of EC have been reported as a potential measurement for predicting crop production variation caused by soil water differences (Jaynes et al., 1995; Sudduth et al., 1995; Sudduth et al., 2000;

Heermann et al., 2000). Soil EC is a function of moisture content, salinity and clay content (Rhoades et al., 1976; McNeill, 1980; Hendrickx et al., 1992; James et al., 2000). Also it can provide information on soil texture, in addition to estimating soil water content (Hanson and Kaita, 1997; Sudduth et al., 1999). Since soil EC integrates texture and moisture availability, two characteristics that vary over the landscape, and also affect productivity, it shows promise in interpreting grain yield variations, at least in certain soils (Sudduth et al., 1995; Jaynes et al., 1995; Sudduth et al., 1999; Fridgen et al., 2000). Williams and Baker 1982 observed in areas of salt-affected soils 65-70% of the variation in measurements could be explained by the concentration of soluble salts, however, in non-saline soils, EC variations are primarily a function of texture, moisture content and CEC (Sudduth et al., 2001).

Four major methods are available for salinity surveys land (Hendrickx et al., 1992):

i. Visual crop observations that relate appearance to the salt content near or at the soil surface,
ii. Collection of soil samples in the field and measurement of the EC_e in the laboratory,
iii. Four-electrode sensors, and
iv. Electromagnetic induction sensors (EMI), which measure the profile-weighted soil electrical conductivity, EC_a, of the soil directly in the field.

Profile-weighted soil electrical conductivity (EC_a) is a sensor-based measurement that can provide an indirect indicator of important soil properties (Sudduth et al., 2000; Domsch, 2001a,b; Ehlert et al., 2001). The first method is quick and economical, but has the disadvantage that salinity development is detected after crop damage has occurred. The second method gives reliable quantitative data, but requires considerable resources for field sampling and laboratory analysis. Moreover, the small volume of the samples results in a larger variability than the four electrode sensors and electromagnetic induction sensors. The performance of the four-electrode sensor depends on a good contact between soil and electrodes and, therefore, produces less reliable measurements in dry soils. The effect of soil water content on electrical resistance measurements has been studied by many researchers, using a four-electrode salinity probe (Hanson and Kaita, 1997). These studies showed that for a given salinity treatment, the higher the soil-water content, the higher the EC_a. EC_a can be measured remotely using EM techniques

(Rhoades et al., 1989; Domsch, 2001a, b; Ehlert et al., 2001). The EMI sensor does not depend on sensor-soil contact and has become the first choice for salinity surveys in different parts of the world. Its advantages are:

- Measurements can be taken as fast as one can move from measurement location to another,
- The large volume of measured soil reduces the variability so that relatively few measurements yield a reliable estimate of the mean EC, and
- Measurements in relatively dry or stony soils are possible because contact between the soil and EMI sensor is not necessary.

2.2.1.2. Electromagnetic Induction (EMI)

EMI surveying provides a cost-effective method to complement traditional soil survey practices by providing rapid, non-invasive information on soil features, especially EC, which in turn, provides information including soil moisture and textural variation (Domsch, 2001a,b; Ehlert et al., 2001; Dalgaard et al., 2001; Domsch and Giebel, 2001; King and Dampney, 2000; Waine et al., 2000; Williams and Hoey, 1987). Research studies, e.g. Lund et al., 1999; Sudduth et al., 1995; Domsch, 2001a,b; Ehlert et al., 2001, have shown how mapping soil EC can be a good surrogate measurement for spatially variable factors that are not easy to sense and map, such as soil type and moisture content. Sensing by EMI may find ready applications in activities such as (King and Dampney, 2000):

- Soil surveying; to locate boundaries between soil types more easily and accurately
- Identification of distinct management zones within fields,
- Integrated with analysis of yield map sequences and
- Location and management of hydrologically different areas in fields, either that prone to drought or wet patches.

EMI technique is now available as a commercial service using: direct EC measurement via two soil cutting discs as *Veris* System[1] (Veris Technologies, Salina, KS, USA), or indirectly using non-contact EMI probe as *EM38*[1], latest model, (Geonics Ltd, Mississauga, Ont., Canada).

2.2.1.3. EM38-Applications for Variability Delineation

Hendrickx, et al., 1992, characterise the variability and statistical distribution of EMI measurements for salinity assessment on irrigated land to optimise future sampling schemes. It was found that EM38 was in good agreement with the visual agronomic surveys. The EM38 was superior because it had a better resolution, was more sensitive to salinity changes with depth and spatiality, and measurement could be conducted with or without a crop or at any growth stage.

EM38 provided information that would be useful for investigating soil variability and potentially for controlling variable management on clay-pan soils (Sudduth et al., 1999). Soil conductivity measurements have the potential for providing estimates of within-field variations. In areas with low soil salinity, spatial variation in soil moisture content is often a major factor determining variations in bulk soil EC. Sheets and Hendrickx, 1995, carried out further field scale tests in an arid region of southern New Mexico by measuring monthly soil water at 65 locations along a 1950 m transect with neutron probes to a depth of 1.5 m and with EM31. A linear relationship between soil EC and soil water was found. Five neutron probe access tube locations were calculated as the minimum required for accurate calibration of the EM31, and there was no improvement in calibration by adding more access tubes.

The EM38 measurements reflect an integration of both soil salinity and soil-water content over the depth of measurement (Hanson and Kiata, 1997). The effect of soil salinity and soil-water content on EC_a as measured with the EM38 has been investigated. Results showed substantial changes in the meter's readings as soil-water content changed. The higher the soil salinity, the

[1] Mention of trademark, proprietary product or vendor does not constitute a guarantee or warranty of the product by the FAL or author and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

more sensitive the meter's readings were to changes in soil-water content. A linear relationship existed between soil-water content and EC_a for each level of soil salinity over the range of measured soil-water contents. A potentially smaller evapotranspiration rate of the high and medium salinity treatments could account for this behaviour.

Salinity in Germany is low, so the EC readings measured by field capacity display the variability of clay content and textural boundaries (Domsch and Giebel, 2001). Therefore, an EC map can be used to target the locations of representative textures. The influence of clay content on the EC readings at field capacity can be accounted at 59% for Brandenburg soils. If the silt content is taken into account as well, the relation between EC and texture becomes even more obvious. In another study, it was found that the clay content is linearly correlated to EC readings measured by EM38. Thus about 79% of the variation in clay content could be explained by the measured EC (Dalgaard et al., 2001). Another study in Germany conducted by Durlesser in 1999 found that 51% of the variations of the EC, in a 24 ha area in the state of Bavaria, could be explained by variations in the clay content (Domsch and Giebel, 2001). Under Danish conditions, experiences from soil surveys revealed that, apart from areas covered with organic soils, the soil clay content is the most important factor controlling the spatial variation in soil EC (Nehmdahl and Greve, 2001).

Due to the annual rainfall distribution in Jordan, where rainfall in the northern part is about 500 mm and decreases toward the southern part to about < 50 mm and about 250 mm in western part to about < 30 mm at eastern sites, the soil salinity followed rainfall distribution. Therefore, the Jordanian soil salinity pattern is characterized by a big range, which could provide an opportunity to build a database and relate the EC_a measured with EM38 to the AWC.

Waine et al., 2000 (Domsch and Giebel, 2001) classified conductivity for the Gamlingay site (England), between 0-10 mS/m as sandy loam, 10-20 mS/m as clay loam and greater than 20 mS/m as clay.

Kachanoski et al., 1988, found that the spatial variation of soil water content in the top 0.5 m measured by time domain reflectrometry at 52 sites in a 1.8 ha field in Canada was highly correlated with EMI readings. In another Canadian field, Kachanoski et al., 1990, found that EC measured by EMI accounted for more than 80% of the variation in water stored in the top 1.7 m of soil measured at 10 m intervals along a 660 m transect.

As research results in the last few years concerning precision farming have shown, the topic is multidisciplinary and interdisciplinary teams are needed to develop solutions. However, in agreement with Sigrimis et al., 1999, some of the barriers to be overcome before precision irrigation/farming is widely implemented include (Stafford, 2000):

- Lack of rational procedures and strategies for determining application requirements on a localised basis and a parallel lack of scientifically validated evidence for its benefits. Both of these can be addressed by research and experimentation.
- Although data required on soil, crop and environmental factors can be obtained, most methods are labour-intensive and costly (such as soil sampling followed by laboratory analysis). The data required must be generated by automatic sensor systems sensing specific factors or suitable surrogates. Therefore, the development of rapid sensing systems that can provide data at fine spatial resolution, more precise application technologies and precise and reliable position computation has become necessary and must take place.
- This new management system is 'information-intense', meaning different soil, crop and environmental factors within a field produce large quantities of data for the manager to deal with. This 'data overload' has to be overcome by development of data integration tools, expert systems and decision support systems, and part of the development must include the standardisation of data formats and transfer protocols.

2.2.2. Precision Farming in Practice

Probably, the first real application of precision farming was the 'on-the-go' fertiliser blending and distribution system developed by Soil Teq in the USA (Fairchild, 1988; Stafford, 2000). Information from aerial photography and grid soil samples was used to generate a fertiliser application map. Positioning of the field vehicle, however, was by dead-reckoning as GPS was not sufficiently developed for civilian use. Further applications and greater research effort were made in the early 1990s, as GPS became more reliable (Stafford and Ambler, 1994; Stafford, 2000). Amongst such developments were spatially variable herbicide applications (Miller and Stafford, 1993), dynamic sensing of soil organic matter using spectral reflectance sensors (Price and Hummel, 1994) and yield mapping (Searcy et al., 1989; Stafford et al., 1991).

Spatially-variable crop production has been widely studied and developed to improve agricultural use efficiencies and to reduce environmental impacts. But most of the early research and commercial developments in spatially-variable crop production have been concentrated on variable-rate fertiliser and chemical application (Torre-Neto et al., 2001; Biller, 1998). Experiences with yield maps have convinced many researchers and agriculturists of the importance of water availability in determining spatial yield patterns. Many think that water availability is the major determinant of yield variation.

Implementation of precision farming to date has utilised existing field machinery and added controllers and GPS to enable spatially variable application (Vosshenrich et al., 2001). Thus, conventional spray booms have been used for patch spraying (Miller and Paice, 1998) and spinning disc applicators for variable fertiliser application (e.g. Amazone ZA-M spreader). The potential of precision farming will lead, however, to demands for the development of novel, precise application techniques. These should achieve the precision and reliability in material placement that follow from the precision and accuracy achievable by positioning and sensing systems.

Precision farming should be implemented in all field activities in order to achieve high profits. Of these activities, irrigation and irrigation systems are now a complementary part in field machinery, therefore, precision irrigation should be tested to prove its applicability.

2.3. Irrigation and Precision Irrigation

2.3.1. Background

Water is one of the important management inputs directly affecting crop yield and amenable to site-specific management. It is still being applied uniformly by the different types of irrigation systems. Variability of soil properties, topography, plant density, growth stage, and precipitation patterns result in a lack of uniformity of water infiltration, storage and subsequent plant water use across a field (Schmitz and Sourell, 2000; Sanders et al., 2000; Türker, 2001a; Duke et al., 1997). A new aspect of precision farming that is just beginning to receive interest for efficient irrigation water management/scheduling is precision irrigation, in order to apply water in the right place at the right amount at the right time (Sanders et al., 2000; Grashoff et al., 2001). It is still in the development stages and requires a lot of experimental work to determine its feasibility and applicability. With increasing competition, not only among neighbouring irrigators but also among agricultural and non-agricultural users of water, the notion of water conservation was born (Burt et al., 1997). At the present time, with irrigation needs often constituting the largest portion of a region's water consumption and the competing users often in a political majority, the need for sagacious use of irrigation water has become paramount.

To establish a common ground, the traditional meaning of precision irrigation should be redefined to refer to site-specific irrigation. Site-specific irrigation is still very much a research issue (Sourell and Sommer, 2002). Literature on this topic is limited and mostly from 1992 and later. Fully integrated packages have not yet been created, much less been made commercially available. However, assuming the farm economy will recover enough for capital investment, the situation may change quickly. It was predicted that the ability to avoid watering roads and other non-cropped areas would be a requirement for water conservation at the present time.

Success of precision irrigation management has been achieved with regard to application control (Pierce and Nowak, 1999). The key to its success depends to a large extent on how well the water needs of the soil plant system can be measured or predicted, and the accuracy of the water application (and agri-chemical) prescription. The value of precision irrigation management depends on whether increased profits and the reduction in pollutants more than offset the cost of increased resolution needed in irrigation systems to apply an irrigation site specifically.

Agricultural production requires space and varies over it (Feinmann and Voet, 2000). Inputs such as irrigation water, fertilizers or pesticides are intended to eliminate moisture and nutrient deficiencies or pests that reduce crop yield. However, non-uniform input application and variability in soil texture can cause significant variations in the efficiency of water (or fertilizer) usage, by influencing the rate at which water infiltrates the root zone and affects plant growth and commercial yield. As a result, the yield of a given crop, grown during a specific season in a certain field and under a certain management and cultivation condition is also spatially variable, and is directly dependent on the spatially variable input effectiveness (e.g. Warrick and Yates, 1987; Bresler and Laufer, 1988; Fiez et al., 1994; Niven, 1994).

The lack of commercially available variable rate sprinklers represents the single biggest obstacle to commercial development of a centre pivot irrigation system capable of site-specific crop management (King et al., 1995). The second obstacle to commercial development is the lack of a service infrastructure to generate and deliver the maps needed to control and manage the irrigation system throughout the season.

The concept of available water content (AWC) 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). This amount represents the difference between amount of water at field capacity (amount of water held by the root zone against gravity) and at wilting point (amount of water that is bound so strongly to the soil matrix that it cannot be consumed by plants). Available water content is more useful for management decisions than volumetric moisture content (Waine et al., 2000), since volumetric moisture content is defined as the proportion of water in a given volume of soil, whereas AWC expresses the plants ability to remove water from the soil. An AWC map can be interpreted without the need to consider the effects of different soil types as it is already a function of moisture content, texture and structure. Spatial variability in AWC often develops during the irrigation season under a properly designed and managed conventional irrigation due to spatial variability in evapotranspiration and water application efficiency. Evapotranspiration is largely dependent upon micrometeorological conditions and crop growth, both of which vary spatially and temporally. Water application efficiency is influenced by many factors that vary spatially and temporally, but the soil infiltration rate is likely the most important. Differences in the available water content across an agricultural field can produce variable amounts of deep percolation as well (Sanders et al., 2000; Jordan et al., 1999). The amount of deep percolation for specific areas of the fields studied appears to be dominated by water application in some instances and by available water holding capacity in others. Both spatial variability of water application and AWC can therefore potentially lead to spatial variability in yield, due to problems in irrigation scheduling for optimum crop yield and quality, and both should be considered in precision farming (Türker, 2001a). Therefore, areas of the field with low yield productivity appear to have the greatest potential to benefit from variable rate water.

Variable rate application (VRA) refers to the application of agricultural inputs in specific and changing rates throughout the field (Sanders et al., 2000; Watkins et al., 1999). The goal of VRA is to apply a precise amount of water, fertilisers or other inputs to specific areas in the field when and where they are needed for crop growth. VRA has the potential to increase both agricultural productivity and environmental stewardship, but it must be first being proven profitable, however, before farm operators will adopt it. With an increase in crop yield monitoring equipment, it is now more feasible to measure spatial crop response to variable water and nutrients applications (Camp et al., 2000). During the past decade, there has been increasing interest in applying water and chemicals to crops based on their needs or yield potential rather than applying uniformly to the entire field.

Watkins, et al., 1999, evaluated the profitability and environmental outcomes associated with spatial variation of N-fertiliser and irrigation water in seed potato production. The results indicate greater economic and environmental benefits may be achieved from varying water application than by varying N application across the field. Variable rate N application did not reduce the level of N loss from the field when compared with conventional water application. However, variable rate water application cut N losses by half when compared with uniform water application.

Yule, et al., 1996, (Feinermann and Voet, 2000) focused on variable-rate irrigation water, which is performed via subdivision of the spatially variable field area into a controlled number of individually irrigated management units (MUs), each composed of a few neighbouring basic soil units (BSUs). The impact on profits and input decision of the MU's size, the degree of irrigation uniformity (technology-dependent), and the soil properties (cultivation-dependent) was investigated. The analysis suggests that utilisation of site-specific farming and adoption of improved irrigation and/or cultivation technologies do not guarantee a water-saving, because it depends on the type of the production function, and farm economy may not recover enough for capital investment.

2.3.2. Irrigation Systems: Definition, Types and Technology for Automation Water and Energy Saving

2.3.2.1. Background

Irrigation is defined as the application of water to soil through different types of systems, for the purpose of supplying the moisture essential for plant growth. Accordingly, it plays a vital role in increasing crop yields and stabilizing production. Irrigation systems fall into three categories; surface, localized and sprinkler (figure 2.2). Water management research frequently necessitates varying irrigation water application (Fraisse et al., 1995). The amount of water that can be conserved by improved irrigation systems and practices depends on the ability of a particular type of irrigation system to implement improved management. A critical link in improved management is the implementation of scientific irrigation scheduling techniques which will be required for any irrigation scheme. In the design and management of irrigation systems, efficient use of water is now often a major goal, as well as crop production. Of course, crop production is paramount to a grower who intends to stay in business, but also water costs and farm sustainability as well as the potential for pollution of resources by over-irrigating must be taken into consideration (Burt et al., 1997). Unfortunately, irrigation systems that spatially vary either water or nutrient application are still not perfected and 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). Center pivot 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. Thereby, they have expanded row crop and grain production into areas with rolling topography, soils with hard to manage hydrologic properties, and fields with variable fertility (Schepers, 1996). Managing water and nutrients in such spatially variable fields can be a nightmare due to difficulties encountered in scheduling under such irrigation systems, which make them prime candidates for variable rate water and fertiliser application. These systems are often advantageous compared to other irrigation systems.

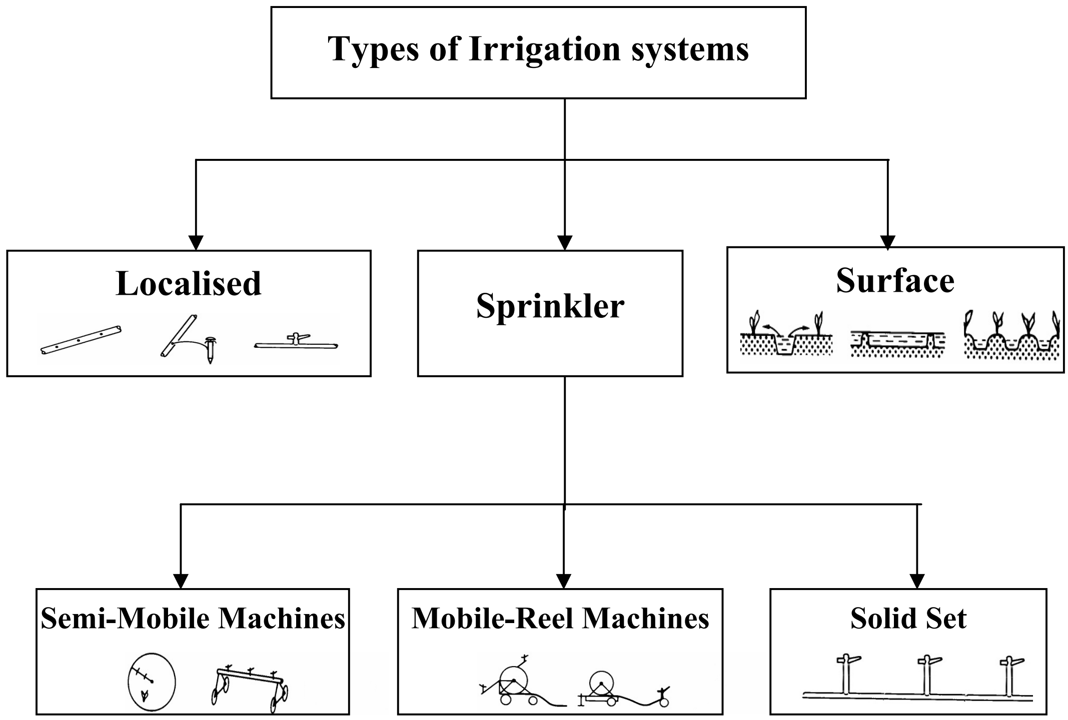

Figure 2.2: Irrigation water system (Sourell, 1998)

As recognised by the American Society of Agricultural Engineering, ASAE, the most important features of a properly designed sprinkler irrigation system are that (Bittinger and Longenbaugh, 1962):

- The rate of water application should be less than the soil infiltration capacity so that no run-off or ponding occurs,
- The water distribution should be reasonably uniform and
- The amount of water applied during irrigation event should be consistent with the moisture storage capacity within the crop root zone.

This is valid not only for the plot as a whole, but also for the varying parts of the field.

2.3.2.2. Semi-Mobile and Mobile-Reel Machines

Although centre pivot and moving lateral machines are classified as continuously-moving systems, in reality they move in a series of starts and stops controlled by a cyclical timer. The movement of a guide tower determines the machine’s speed; the other towers follow with a start/stop sequence to maintain alignment. Consequently, the lateral does not move in a straight line, nor does it move with uniform speed. The first continuously moving sprinkling irrigation system was invented in 1948 and patented in 1952 by Frank Zybach in eastern Colorado. The early systems were the foundation of the development of modern centre pivot and moving-lateral irrigation systems. These very adaptable water application methods have experienced tremendous growth around the world in recent years due to their (Pair, 1968):

- Potential for highly efficient uniform water applications,
- High degree of automation requiring less labour than most other irrigation methods,
- Large coverage area and
- Ability to economically apply water and water soluble nutrients over a wide range of soil, crop and topographic conditions.

Historically, efforts to improve linear-moving and centre pivot irrigation system designs have primarily concentrated on reducing energy use by reducing operating pressure and increasing water application uniformity (King et al., 1999). Technological advances on both fronts are now to the point that the upper practical limits are being approached with very little return from incremental improvements.

Despite the inherent high frequency and fairly uniform applications of these systems, considerable yield variations still exist which are often attributed to spatial variability in soil water holding capacities and related nutrient availability. Variations in water availability across a field pressure the farmer to manage:

- To ensure that areas with the lowest water holding capacity maintain adequate water levels,
- The whole field based on average soil water depletions, and/or
- To avoid over-irrigation in the wettest areas.

All of these cases will cause over- or under-irrigation of other areas due to the current inability to differentially irrigate based on soil and plant factors within a single irrigated field. Research (Evans and Han, 1994; Han et al., 1995; Mulla et al., 1996; Mallawatantri and Mulla, 1996) has shown that, in grossly simplified terms, about 75% of the leaching occurs in about 25% of the areas in many centre pivot irrigated fields in the central Pacific Northwest. Thus, it is evident that the ability to more precisely manage small areas of the field will be necessary to reduce groundwater degradation and energy. Thus, the next advances in centre pivot and lateral moving irrigation will likely come from site-specific application of water, being able to vary water applied based on the spatial variability inherent in irrigated agricultural landscapes. The different water applications are normally applied by changing the frequency and/or the depth of irrigation (Heermann et al., 1974). High distribution uniformity, precise water applications, and operational flexibility in time and space are required in these 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, helps in further development of mobile-reel irrigation; irrigating more area with less energy, water and labour requirements (Sourell, 1999).

2.3.2.3. Controllers

Advances in electronics, communications and software over the past several decades have removed those earlier impediments. Inexpensive sensors and microprocessors -coupled with integrating software, mobile power sources and satellite communications- now enable farmers and natural resources managers to collect vast amounts of geo-referenced data, which lead to mapping (Schmoldt, 2001). Hardware, software and communication systems for precision applications of self-propelling irrigation worked well; the major limitation was the inability to rationally develop coherent prescriptions for prescription maps (Evans et al. 1996).

In order to exploit the potential of precision irrigation for accurately and selectively applying water to the grids, a system made up of a series of control boxes is required (Zazueta et al., 1994; Türker, 2001a). A controller is an integrated part on an irrigation system, to function as a tool to apply water in the right quantity at the right time. After data regarding a field's specific water needs are collected and interpreted, an application map is made and stored on a computer in the control box which also contains the control program. The controller is installed onto mechanised irrigation equipment like any travelling sprinkler, boom type sprinkler, any low pressure system or centre pivot irrigation system. Information from the control system gets fed to the nozzle control boxes which are installed near the boom to control the flow of water to the particular parts of the field. This information and an application record can be accumulated and transferred to a PC.

Irrigation controllers have been available for many years in the form of mechanical and electro-mechanical irrigation timers (Zazueta et al 1994). These devices have evolved into complex computer-based systems that allow accurate control of water, energy and chemicals while responding to environmental changes and development stages of the crop. Two general types of controllers are used to control irrigation systems (Figure 2.3): Open control loop systems and closed control loop systems. The difference is that closed control loops have feedback from sensors, make decisions and apply decisions to the irrigation system. On the other hand, open control loop systems apply a pre-set action, as is done with irrigation timers. A computer-based control system consists of a combination of hardware and software that acts as a supervisor with the purpose of managing irrigation and other related practices. This is done by a closed control loop, which consists of: monitoring the state variables, comparing them with their desired or target state, deciding what actions are necessary to change the state of the system and carrying out the necessary actions.

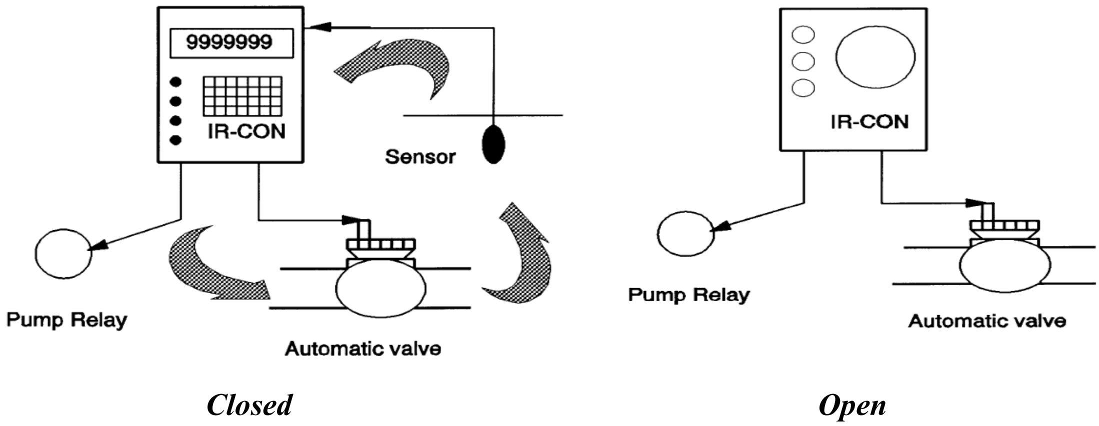

Figure 2.3: Basic elements of closed and open loop control systems (Zazueta et al., 1994).

Sensors are an extremely important component of the control loop because they provide the basic data that drives an automatic control system, because they are placed in the system and produce an electrical signal directly related to the parameter that is to be measured. In general, there are two types of sensors:

a) Continuous: produces a continuous electrical signal, such as a voltage, current, conductivity, or any other measurable electrical property. One example is thermocouples, which produce a voltage difference that increases as the temperature increases. Continuous sensors are used where values taken by a state variable are required and an on/off state is not sufficient, for example, to measure pressure drops across sand filter.
b) Discrete: are basically switches, mechanical or electric, that indicate whether an on or off condition exists. Discrete sensors are useful for indicating thresholds, such as the opening and closure of devices (vents, doors, alarms, valves, etc.). Some examples of discrete sensors are a float switch to detect whether the level in a storage tank is below a minimum desirable level

or a thermostat to indicate if a certain temperature has been reached. When combined with a timer, pulses from switches can be used to measure rates.

Understanding the operating principle of a sensor is very important. Sensors many times do not react directly to the variable being measured. The ideal sensor responds only to the "sensed" variable, without responding to any other change in the environment. It is important to understand that sensors always have a degree of inaccuracy associated with them and they may be affected by other parameters besides the "sensed" variable. Another important factor related to the sensor is its time response. A sensor must deliver a signal that reflects the state of the system within the frame of time required by the application.

2.3.2.4. Precision Irrigation

One of the goals of new developments in irrigation technology and irrigation management is site-specific precision irrigation (Sourell and Sommer, 2002). The potential to optimise water and chemical application by combining site-specific crop management techniques with continuously-moving irrigation systems exists (King et al., 1995). All of the techniques that can be used to define crop/irrigation management zones for variable rate applications by conventional ground based equipment can be used with continuously-moving irrigation systems. The designers aimed to have the most uniform water application pattern possible along the entire length of the centre pivot or moving lateral. However, this criteria is not necessarily the best in terms of crop quality and the environment.

Semi-mobile and mobile-reel irrigation systems are well known for their capability of uniformly applying controlled amounts of water and chemicals, enabling efficient management of irrigated agriculture, and saving water resources (Sanders et al., 2000; Fraisse et al., 1995). The possibility of carefully controlling the water depth applied allows the uniform application of a wider range of chemicals, reducing the water quality degradation. Prescription agriculture, as the new trend in managing agricultural inputs is called, requires the capability of applying water and chemicals variably due to the soil spatial differences. It has the potential to conserve both water and agricultural chemicals.

Camp et al. (2000) concluded that, while ground-driven variable-rate chemical application equipment is now being used, most irrigation systems continue to apply at a nominally uniform water depth. In the absence of a commercially available variable rate sprinkler, the immediate solution has been to replace each sprinkler along the lateral with multiple sprinklers (two or more) and each with a solenoid valve, then sizing the sprinkler nozzles to provide part of the original single sprinkler flow rate effectively, which provides a step-wise variable application rate through on-off control of each solenoid valve (King et al., 1995). This approach is acceptable for research purposes but is likely too costly for commercial development. A prototype control system enabling site-specific crop management using continuously-moving irrigation systems has been developed to facilitate needed research, evaluation and demonstration of the technology. The prototype control system primarily consists of a microprocessor based controller, a location sensor, and solenoid valves under the control of individually addressable relays which switch solenoid current on and off. The controller monitors the location of the system and maintains the appropriate flow rate at each sprinkler location by turning on/off the correct combination of sprinklers. A second generation control system allows bi-directional communication between a master controller and individually addressable slave controllers placed anywhere on the system. The slave controllers provide digital input and output capability for actuation of relays and input from any type of transducer through analogue to digital conversion. The main reason for developing bi-directional communication is to have a closed loop control system so that equipment failures (controllers, wiring, valves, solenoid, etc) can be detected by software and an operator warning issued. The developed prototype control system enabling site-specific application of water and chemicals using continuously-moving irrigation system has been evaluated. Preliminary results show that water and chemical application uniformity equal to that of conventional uniform application system can be achieved. Commercial development of such a system is impeded by the lack of a variable rate sprinkler and an existing service infrastructure to produce the maps needed to operate the system throughout the growing season. Research is needed to determine the information required to manage and operate the system throughout the season and evaluate potential benefits and system performance.

Some of the semi-mobile and mobile-reel irrigation systems have the capability to vary application depths by changing travel speed but only for large areas constrained to swaths along the system structure (Roth and Gardner, 1989; Camp et al., 2000). For site-specific crop management to be acceptable to growers, variable application depths must be available in smaller, arbitrary areas, which requires that each sprinkler or nozzle be capable of variable flow rates. The flow rate of a sprinkler or nozzle can be regulated by the pressure drop of the fluid across the orifice and the orifice size.

Current commercially available semi-mobile and mobile-reel irrigation systems are capable of applying relatively uniform controlled amounts of water and injected chemicals for efficient crop production (King et al., 1999). The systems are normally managed to apply uniform levels of water along the system lateral. Water application depth is determined by the system sprinkler parameters (i.e. pressure, nozzle size and spacing) and system travel speed. Commercial systems providing programmable control of travel speed allow one dimensional control of water application.

However, commercially available, semi-mobile and mobile-reel sprinkler irrigation systems are not yet capable of selective application of water and chemicals along the pipeline. Normally the system is set to apply a unique depth of water over the entire length of the lateral sprinkler line (Fraisse et al., 1995). One possible alternative, to allow variable application rates, is to provide the system with more than one sprinkler line or lateral, each with different design (Roth and Gardner, 1989; Duke et al., 1992; McCann et al., 1993). Another possible alternative is to use the concept of pulsed irrigation (Fraisse et al., 1992), where solenoid valves are used to control the flow through sprinkler heads. Different water application depths are obtained by pulsing the flow and varying the pulse cycle.

Pulse irrigation, as discussed by Karmeli and Peri 1974 (Fraisse et al., 1995), defined a series of irrigation time cycles, where each cycle includes two phases: the operating phase of the irrigation system (time on) and the phase during which the system is at rest (time off). The main purpose is to achieve a lower application rate from the sprinkler head by pulsing the system. Irrigation during the operation phase is achieved at the normal sprinkler application rate, but when the resting phase is taken into account, the average precipitation rate is lower. This concept was initially intended for solid set or periodically moved irrigation systems. The duration of a single cycle could be in the range of hours or minutes, which would not be feasible for continuous-move systems. Nevertheless, the relationships between the main variables of pulse irrigation are the same in both cases.

It may be desired to vary depth of irrigation under semi-mobile and mobile-reel systems to account for uniformity, and/or to avoid application to unproductive zones such as rock outcrops or waterways (Duke et al., 1997). The ability to vary irrigation depth across a field may substantially reduce the potential for leaching chemicals into the water bodies. The pulsed irrigation system has been implemented using commercially available components. Field tests indicate that it will provide a very flexible means of applying variable water treatments while delivering acceptable uniformity of water application (CU> 90%). The variable water application system has operated successfully for four irrigation seasons.

Pulsing irrigation sprinklers were explored as a technique for applying a variable water depth with linear-move irrigation system (Duke et al., 1992; Fraisse et al., 1995). An existing simulation model for the evaluation of centre pivot systems was modified by Fraisse et al., 1995, to allow simulation of linear-moving systems. Donut-shaped water distribution patterns were adapted to represent distribution patterns for low pressure sprinkler heads. A subroutine to simulate the water depth applied under pulsed conditions was also included in the model. It was concluded that pulsed irrigation is technically feasible and is an efficient way to apply variable water depths along the lateral of self-propelled linear irrigation systems. Application uniformity values generally increase with increased pulsing duty cycle and decreased timer setting. Measured CU values increased an average of 3.7% when the cycle increased from 25 to 75%. Pulsing frequencies of 1 cycle/min are recommended. When operating the system at timer settings greater than 45% and pulsing duty cycle less than 50%, pulsing frequencies greater than 1 cycle/min should be considered (Fraisse et al., 1995b).

Another aspect related to precision irrigation is to control the head and the water supply with relation to windy conditions, in order to minimise the water distortion by wind and the amount of the wasted water. Wind distorts the water distribution pattern from sprinklers causing poor uniformity in the field (Sourell and Sommer, 2002; Türker, 2001b; Ozaki, 1999; Sourell 1998). Dispersion increases from the zero wind application patterns with increasing wind speed. If the required depth is not applied, some parts of the field will receive less water than other parts, resulting in reduced crop yields. A robotic sprinkler head was developed to control the sector and trajectory angle of the jet, to deliver water more accurately to a given location after compensating for real time wind conditions (Türker, 2001b; Ozaki, 1999). A standard sprinkler head was modified with stepper motors to allow for two degrees of freedom. The rotation speed, sector and trajectory angles were controlled by a computer to allow the water jet to be positioned optimally for the local wind conditions in real time. The prototype head was tested in the field, and it was found that changing sector and trajectory angle in real time improved the accuracy of the application pattern. Also, from the design point of view, the system should receive more attention, in order to maximise the effectiveness. This mechatronic approach to an age-old problem should herald the start of a new generation of highly efficient mobile-reel sprinklers.

To deal with the beneficial aspects of precision farming and irrigation is beyond the objectives of this work. But although, the benefits of precision irrigation may vary by location, when combined with proper agronomic practices, it can become a powerful tool to (Türker, 2001a):

- Reduce input costs,
- Improve crop quality and quantity,
- Minimise non-point source pollution and
- Uses existing nozzles.

In agreement with Cassman and Plant, 1992 (Plant, 2001), who conducted a theoretical comparison of site-specific and whole-field-fertiliser application, the economic benefits depend in a complex way on the costs of inputs relative to crop price, the level of variability in field and plant response to the input. Regardless of the economical and practical limitations that appear at the beginning of this new management system, it is believed that it will help in the sustainability and development of the agricultural resources in the present century and will help in environment protection.

Precision irrigation could be re-installed as part of a new system to save water and no surface runoff. Regarding precision farming benefits, a recent study at Cranfield University using standard UK statistics estimated that a precision farming approach to cereal production could yield a net benefit of $ 25/(ha.yr) (Blackmore et al., 1994). This analysis did not evaluate the environmental benefits that occur. In light of extensive on-going research activities, development and implementation of precision farming around the globe is rather discouraging (Auernhammer, 2001). Approximately 10% of the available agricultural land in the U.S. Midwest benefits from yield mapping. In Europe, application of precision farming includes well-developed sites in the UK, Eastern Germany and Denmark. Adoption of precision farming in the Middle East region is not known to date, and hopefully would be expanded in the coming time. For instance, Jordan suffers from scarcity of water due to the dominance of arid and semi arid climate over about 90% of its area, where low rainfall (less than 200 mm/year) and coupled with high evaporation (reaching 2000 mm/year) have been found by (Abu-Sharar et al., 1999). Table 2.1 shows the Jordanian Water Budget for 1995, 2000 and the expected budget for 2005. The agricultural sector uses about 70% of the available water resources, and the rest is divided between the other sectors (industrial and urban). Due to the increases in industrial and urban activities, large amounts of irrigation water are being shifted towards the non-agricultural activities. Accordingly, new management systems for water must be introduced in order to save on the amount of water being used to meet the requirements for increasing the agricultural production. In South Jordan, the area irrigated with centre pivot systems was estimated to be 3600-4000 ha, and as an option, precision irrigation has an opportunity to be implemented in those areas to save water, energy and minimise the pollution in the groundwater.

Table 2.1: Jordanian Water Budget (MCM) for the years 1995, 2000 and 2005[1]

Resources	Amount (MCM)		
	1995	**2000**	**2005**
Available	**818.5**	**973.5**	**973.5**
Surface	400.0	555.0	555.0
Renewable groundwater	275.5	275.5	275.5
Non-renewable groundwater	143.0	143.0	143.0
Needed	**1449.5**	**1548.0**	**1638.0**
Agriculture	1088.0	1088.0	1088.0
Industry	61.5	101.0	124.0
Urban	300.0	359.0	426.0
Deficit	**631.0**	**574.5**	**664.5**

[1] Abdulla Ahmad. Water use and conservation in Jordan. USAID, Regional Symposium on water use and conservation. Nov. 28 – Dec. 2, 1996.

3. OBJECTIVES AND HYPOTHESIS

It is important to build a rich database in order to form a complete decision support system for precision farming. This system should include all field activities such as irrigation, fertilisation, tillage, plant protection, etc. Therefore, as a partner, this work will concentrate on one part, precision irrigation. To establish a common ground, the traditional meaning of precision irrigation should be redefined to refer to site-specific irrigation.

3.1. Objectives

A study was conducted during 2001/2002 in Federal Agriculture Research Center (FAL)/ Institute of Production Engineering and Building Research/ Braunschweig in cooperation with the Department of Agricultural Engineering/ University of Kassel/ Witzenhausen/ Germany. The main objectives of this work were to review and to add new experiences to the state of precision irrigation at the turn of the millennium and to offer some speculations as to its future. To achieve such objectives, the following activities, each with a specific objective, were conducted:

- Define site-specific management strategies for precision irrigation
- Characterise the soil spatial variability by creating maps showing spatial variability in available water content (AWC) using scanned information from EM38 about soil EC
- Describe the development of a variable rate water application system to independently apply variable water application depths to small discrete areas under semi-mobile and mobile-reel irrigation machines.
- Evaluate the performance of a centre pivot irrigation system equipped with solenoid valves operated in a pulsed mode to apply variable rates of water along the length of the machine, and evaluate the application uniformity obtained under various pulse conditions.
- Test a computer control system for variable rates of water with a centre pivot irrigation machine developed in the FAL.

An irrigation system with the ability to automatically and efficiently apply different water treatments by means of pulse irrigation is expected. The concept of pulse irrigation can eventually be incorporated into commercial systems, helping farmers to better control their irrigation activities. It will increase the flexibility of moving systems, offering an additional tool to apply the right amount of water required by the crops. It can also increase the uniformity of application by helping farmers to cope with problems such as runoff, by reducing the application rate of low pressure systems in places with heavy soils or accentuated slopes.

3.2. Structure to Establish a Strategy for Precision Irrigation

The structure for establishing the strategy for precision irrigation is summarized in Figure 3.1 and includes:

1. ***Soil-Yard Maps***: The first information needed to delineate *in-field* spatial variability is originated from these maps, which are to be found in many agricultural planning offices. This information is not sufficient to be used for precision irrigation, because these maps provide information about *in-region* (Large scale) spatial variability.
2. ***Variability Delineation***: The next step is to obtain *in-field* information (small scale), which comes from taking advantage of the fast, non-destructive real-time sensors, such as EM38, and the concept of surrogated properties, such as EC.
3. ***Soil Sampling*** must be followed based on the maps produced from this sensor, and correlate the surrogate property with the property in question (EC vs. AWC).
4. ***Application Map***: Maps for the management zones within the field for the field activity, here irrigation, showing the different quantities (depths) and their location within the field are established.
5. ***Variable-Rate Technologies:*** A decision must be made concerning the technologies that must be integrated with the present field machinery or need to be introduced. Two methods will be used and evaluated: travel speed adjustment and discharge rate regulation.

According to this strategy, the hypothesis of this work suggested that EC measurements using EM38 could be used as a help-estimate to determine spatial variability in AWC. Also, some available electro-techniques to vary the irrigation depth to meet the spatial variability are used.

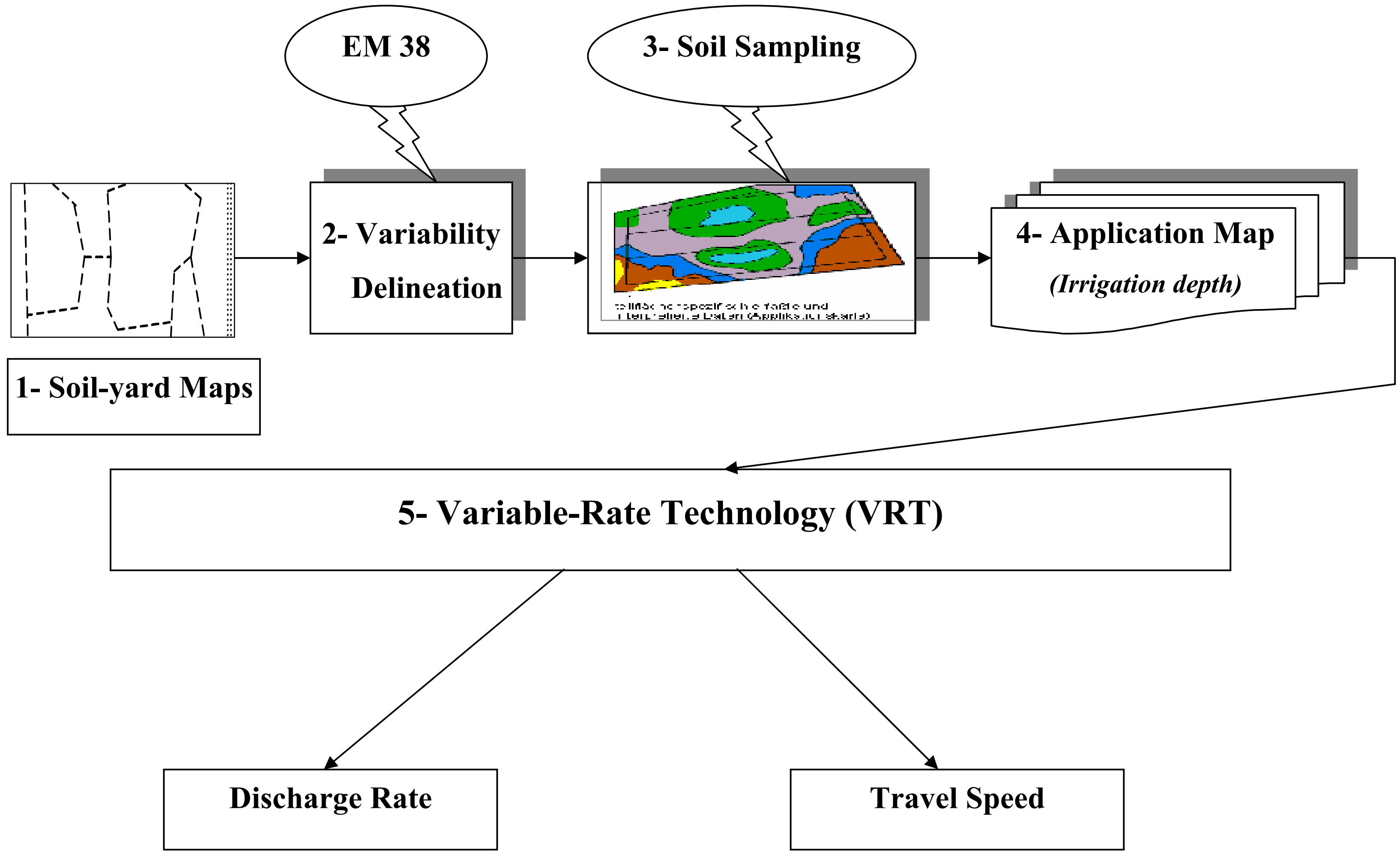

Figure 3.1: Hypothesis and structure behind establishing a strategy for precision irrigation.

4. MATERIALS AND METHODS

4.1. Soil Variability Delineation

Soil electrical conductivity (EC) could be determined without physical contact between the sensors and the soil by use of commercially available dual coil Electromagnetic Induction (EMI) systems (Rhoades, et al., 1990; Hendrickx et al., 1992; Sudduth et al., 1999; Dalgaard et al., 2001; Sudduth et al., 2001; Ehlert et al., 2001; Domsch, 2001a, b). An EMI meter, EM38, developed by *Geonics Limited, Mississauga, Ontario, Canada*, Figure (4.1), provides fast, non-destructive measurements of apparent soil EC. An electrical current is induced in the soil electromagnetically, using principles similar to those in operation in electrical transformers (McNeill, 1980). Depending on the mode of operation, horizontal or vertical, the average measurement depth of the sensor is 75-150 cm as weighed by the instrument response functions and averaged over a lateral area approximately equal to the measurement depth. It contains a transmitter coil and a receiver coil, placed 1 m apart. The transmitter coil is suspended near the soil surface which is energised with an alternating current at an audio frequency and induces a small primary magnetic field (H_t) that induces a weak electrical current in the soil. This resulting current in the soil generates a secondary magnetic field a set distance from the transmitted coil (H_r). The receiving coil generates an alternating current in response to and proportional with that the in transmitting coil, but altered by the soil EC. This can be used to obtain a reading of the apparent ground conductivity (EC_a) which is linearly proportional to the ratio of the two magnetic fields (H_r/H_t). Tests showed that drift of the EM38 could be a significant fraction of within-field EC variation, therefore the use of calibration transect to document and adjust for this drift was recommended (Sudduth et al., 2001).

For soil reconnaissance to quantify EC (mS/m), a EM38 sensor was, after calibration and in the vertical operation mode, mounted on a PVC-sledge together with a DGPS unit and carried by a 4x4 motorbike. It was pulled across the field along the tramlines 5 m apart (Figure 4.1). The DGPS data were integrated with EM38 data to provide the coordinates of each measurement point. Values for EC and position with sub-meter accuracy for each individual measurement was merged and stored at a rate of 1 s^{-1} , approximately every 4-6 m of travel, (sensitivity of EC to variations in sensor operating speed and height was relatively minor Sudduth et al., 2001). The readings were logged to a data logger and interpolated using a spherical kriging model in Surfer (Golden Software, 1994) using Arcview to produce EMI-soil conductivity map. This procedure was carried out in September 2001 at 3-experimental sites/FAL with areas 6.4, 6.2 and 6.2 ha respectively. At this time of the year it was reasonable to anticipate the soil moisture content to be close to field capacity.

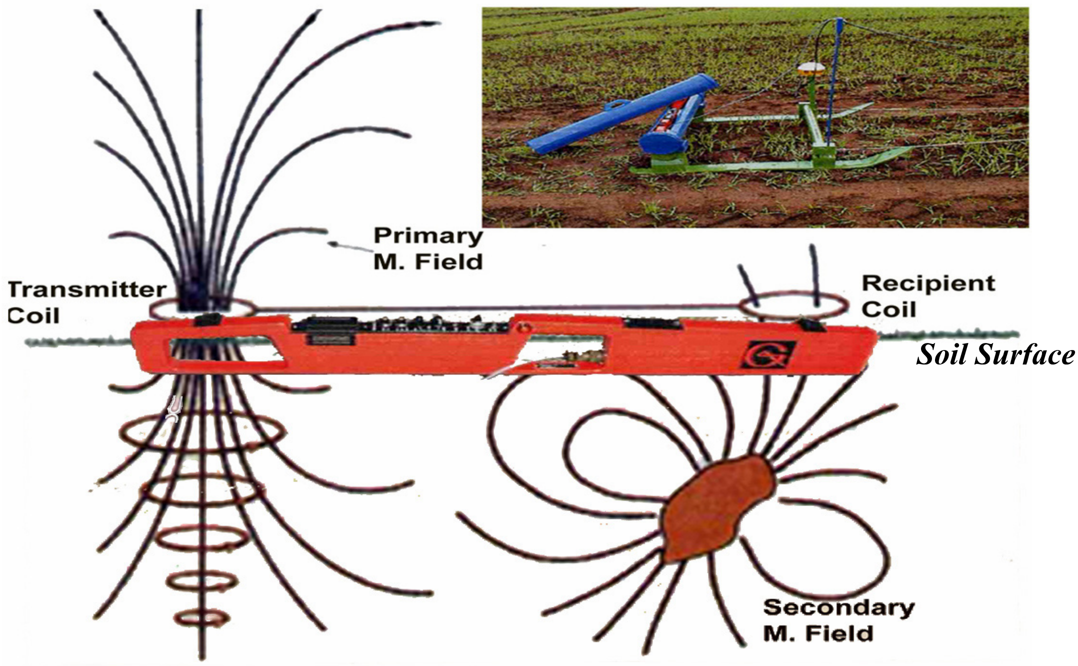

Figure 4.1: EM38 measurement principle and field measurements of EC.

The produced maps are expected to show zones with different soil EC-ranges, and in each zone sample positions were selected depending on the co-ordinates using DGPS. The soil auger-samples were collected from those zones to a depth of 90 cm to determine the water holding capacity in the laboratory. The same sampling points were subjected to in-situ description for texture using a feeling method.

4.2. Irrigation Solenoid (Control) Valves

Irrigation valves are the heart of a sprinkler system; they control the flow of water to each of the individual zones in the system. Valves, which use electric actuators, convert it into hydraulic commands to cause open or close, are called electric control valves or *solenoid valves*. 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. In some cases the actuator piston can be a flow control element at the same time. The solenoid valve, 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 the valve. Electric control valves can also be manually closed or opened.

4.3. Description of the Mobile-Reel Machines

Research to reduce the tediousness and the man-power required for sprinkler irrigation has caused equipment manufacturers to design various systems which can be operated in a less tiring and laborious way (Roland, 1982, Sourell, 1999). One of these machines is the mobile-reel irrigation system (Figure 4.2), in which the machine pulls the watering unit (big-gun, boom, etc.) by means of a semi-rigid polyethylene pipe (PE). The general principle of their design includes:

- Irrigating contiguous strips,
- Feeding the water unit with a polyethylene pipe,
- Winding the pipe on a drum while moving and running the drum with a turbine obtaining its energy from the flow of water under pressure, and
- Equipping these machines with turbines receiving only a part of the water reaching the watering unit and the rest flows through a by-pass to the watering unit.

The flow entered into the turbine depends on the water going through the by-pass. Therefore, it is possible to adjust the turbine rotation speed, and consequently the speed of the watering unit-supporting trolley by adjusting the quantity of water entering into the by-pass, using some control units (Figure 4.2).

4.3.1. Sprinkler Travel-Speed Adjustment

Through precision irrigation, and due to spatial variability in soil, different application amounts of irrigation water should be added to maximise the benefits. Some commercial travelling irrigation systems with programmable management systems allow variable application depths in the direction of travel by adjusting system travel speed (figure 4.2). Two types of computerised speed-control electronic instruments from two different companies were tested, for application to mobile-real irrigation equipment.

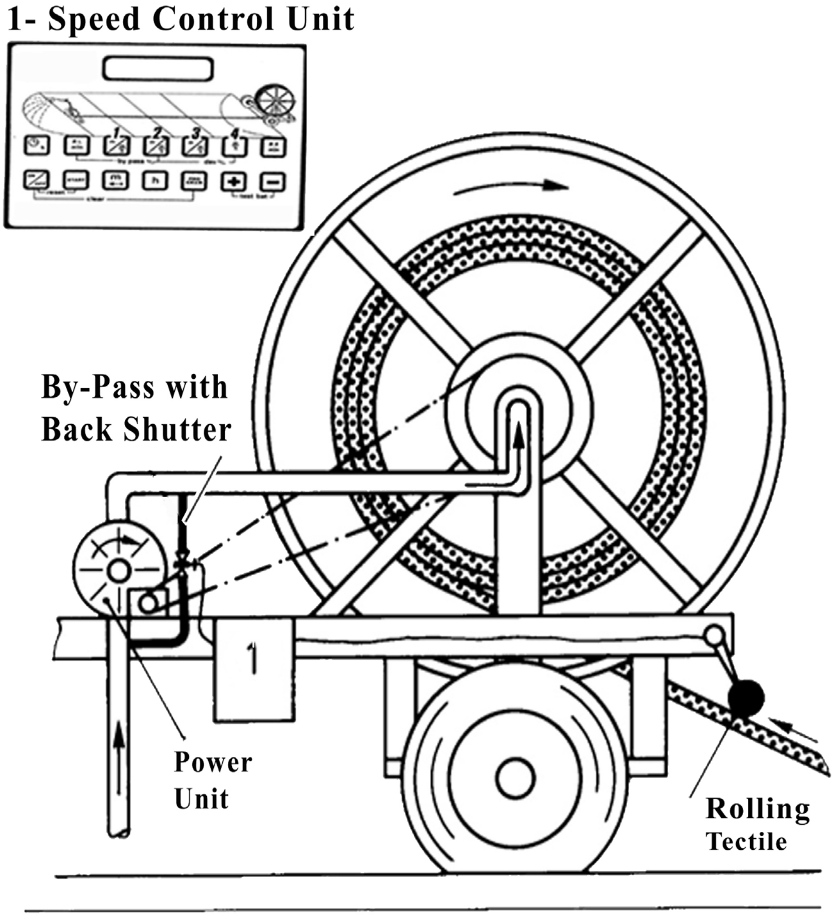

Figure 4.2: Main features of the rolling unit (water-powered drum) used by mobile-reel machine.

First computerised electronic system IRRIGAMATIC 350 produced by *Matermacc s.r.l./Italy*. IRRIGAMATIC 350 consists of: an electronic computerised console, roller and speed sensors, by-pass valve and electric gear-motor, end rewinding sensor, deviation valve and, optionally, a hose end sensor and pressure switch. The IRRIGAMATIC 350 electronic console is made up of a plastic container with 14 keys and a display located at the front side which lights up when the console is switched on. The function symbol is on the left of the display and its value on the right. Among the programmable functions that could be carried out by this instrument automatically are: start/end of irrigation and starting of rewinding with programmable irrigation at 4 different speeds 5 to 200 m/h. The monitore will continuously provide information about the function it is carrying out, the length (m) of hose to be rewound and the irrigation time necessary to complete the programmed irrigation. This control system is available in FAL; therefore, the experiment was carried out inside the FAL campus.

Second control system PROGRAM RAIN 9 is produced by *Nortoft Electronic/ Denmark*. Among the main features of this control systems are: speed regulation, pre- and post-irrigation and starting of rewinding with programmable irrigation at 5 different speeds. This control system was not available in FAL; therefore, the experiment was carried out on a farmer’s field outside of the FAL campus, in the country of Peine.

The travel speed, which many farmers in the region practised and which was recommended by the designer, was 40 m/h for the travelling big gun and nozzle boom systems. Four speeds 40, 32, 24 and 16 m/h, representing 100%, 80%, 60% and 40% from 40 m/h, respectively, were selected to be programmed (v_p). These were used to evaluate the change in irrigation depth by changing the speed of the irrigation system using the available control systems. The performance of the controlled systems was evaluated by calculating the mean and standard deviation of the measured speeds (v_m) and compared with the different selected programmed speeds at travelling distances of 30, 25, 20 and 20 m for 40, 32, 24 and 16 m/h, respectively (figure 4.3). After the required information was stored in both controlling systems, the (v_m) was measured by measuring the time required to travel a pre-set’s of 1 m on the moving main lateral using a stopwatch. Each experiment was replicated two times.

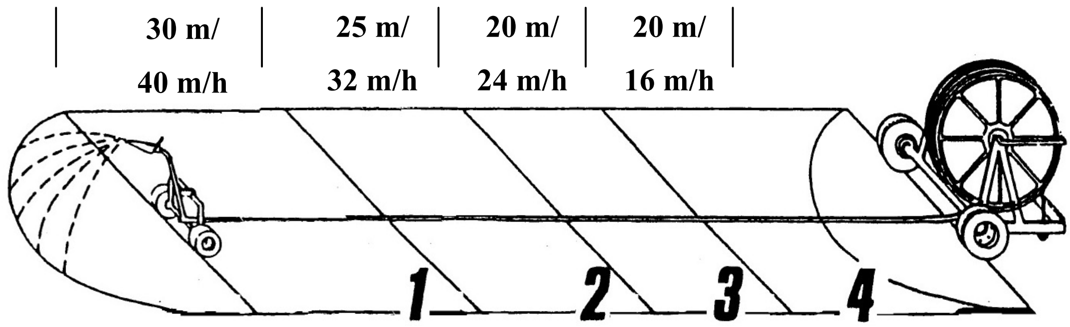

Figure 4.3: Measurement of sprinkler travel speed adjustment.

4.3.2. Change in Irrigation Water Depth

Measurements of irrigated water depth change with adjustment of the system travel speed were conducted on the FAL field using the IRRIGAMATIC 350. A 1x1 m grid of catch cans was established along the travel path under a boom irrigation system driven by a reel machine. Three speed switching, 32 to 16, 16 to 24 and 24 to 40 m/h was conducted independently on the same transect of cans, the speed was checked using the procedure described above. The system was allowed to move 10 m at the first speed to reach nearly constant speed and determine the depth of water for that speed, and then moved 20 m after switching from one speed to another to determine the water depth for the second speed.

4.4. Description of the Centre Pivot Irrigation System and Control Unit

4.4.1. System Description

A three-span commercial centre pivot system (Figure 4.4), located at FAL research field, and with a 117 m total length was used to irrigate an area of 4.3 ha. The irrigation system could be operated in forward or reverse, with and without applying water, which is pumped from an underlying network, and the pressure at the pivot was regulated to 200 kPa. A conventional overhead water application device (sprinklers) package from Nelson, R3000 Pivot Rotator™ that had a wide range of flow rate and size, was selected to be installed in the 2nd and 3rd spans for evaluation of water distribution (Figure 4.4). These sprinklers work at a pressure range of 100-340 kPa and a relative throw distance of 50-70' (15.2-21.3 m). The sprinklers were placed 3 m apart along the irrigation system at a height of 2 m above the ground to ensure good spray overlap and to reduce the effect of wind (Roth and Gardner, 1989; Sourell, 1999). A small weather station was installed at the experimental site to record wind speed and direction. Five field tests were conducted to evaluate the basic radial water distribution with this package, while the machine was travelling at constant speed of 9.3 and 17.9 m/h for the 1st and 2nd towers, respectively (the system moved 20 s and stopped 60 s to obtain this speed setting). The water depth (mm) was collected in 40 catch cans spaced 1 m apart along the system radius. The water depth measurements in these and the following experiments were conducted according to DIN/EN/ ISO 11545. The first step taken was adjustment of this present commercial system to a site-specific irrigation system by making some modifications, to evaluate the variable-rate application technology developed in FAL for precision irrigation with a centre pivot.

4.4.2. System Modifications

The irrigation system had to be modified so that the desired water level could be applied to the management zones (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 is being moved, to the management zones with different AWC, 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. The appropriate application depths were selected based on differences in AWC for different soils. Therefore four discrete depths were selected as a first approximation of true variable-rate application. Spatial location of each depth was to be determined by 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.

4.4.3. Solenoid Valves and Position Encoder

In order to control the depth of water applied along the system radius, 16 solenoid valves (*Baureihe 40*, Company GSR) were installed at each sprinkler position starting from the 2nd span and forward (Figure 4.4). These servo-assisted valves are normally closed (NC) and during the rest position (de-energised), the plunger is closed by spring power over the servo drilling causing pressure to drain through the bleed hole and forcing the seal down against the main orifice. When the solenoid system is energised, the control pressure is released by the exhaust drilling. The seal is supported by the media which places higher pressure under the seal than on the top. Each solenoid valve was wired individually and connected to a switch at the main control system that opened and closed, based on data- base values and the location in the field, to control the irrigation depth of each zone. The location in the field was determined using position encoders by counting the number of teeth, which gives a definite edge in reading the pivot's exact location relative to a 360° circle (Figure 4.4). The application rate was determined by the duty cycle of the solenoid valves that supplied water to each sprinkler. The valves were pulsed by switching the solenoids on/off for varying portions of a duty cycle of 10 min. The base radial water distribution after the installation of the solenoid valves was also measured (averaged over five replicates) using 120 collection cups divided into three lines 1° between lines (65-87 cm) and 1 m between the cans in one line. This data will be used to compare the original, calculated and obtained radial water distributions.

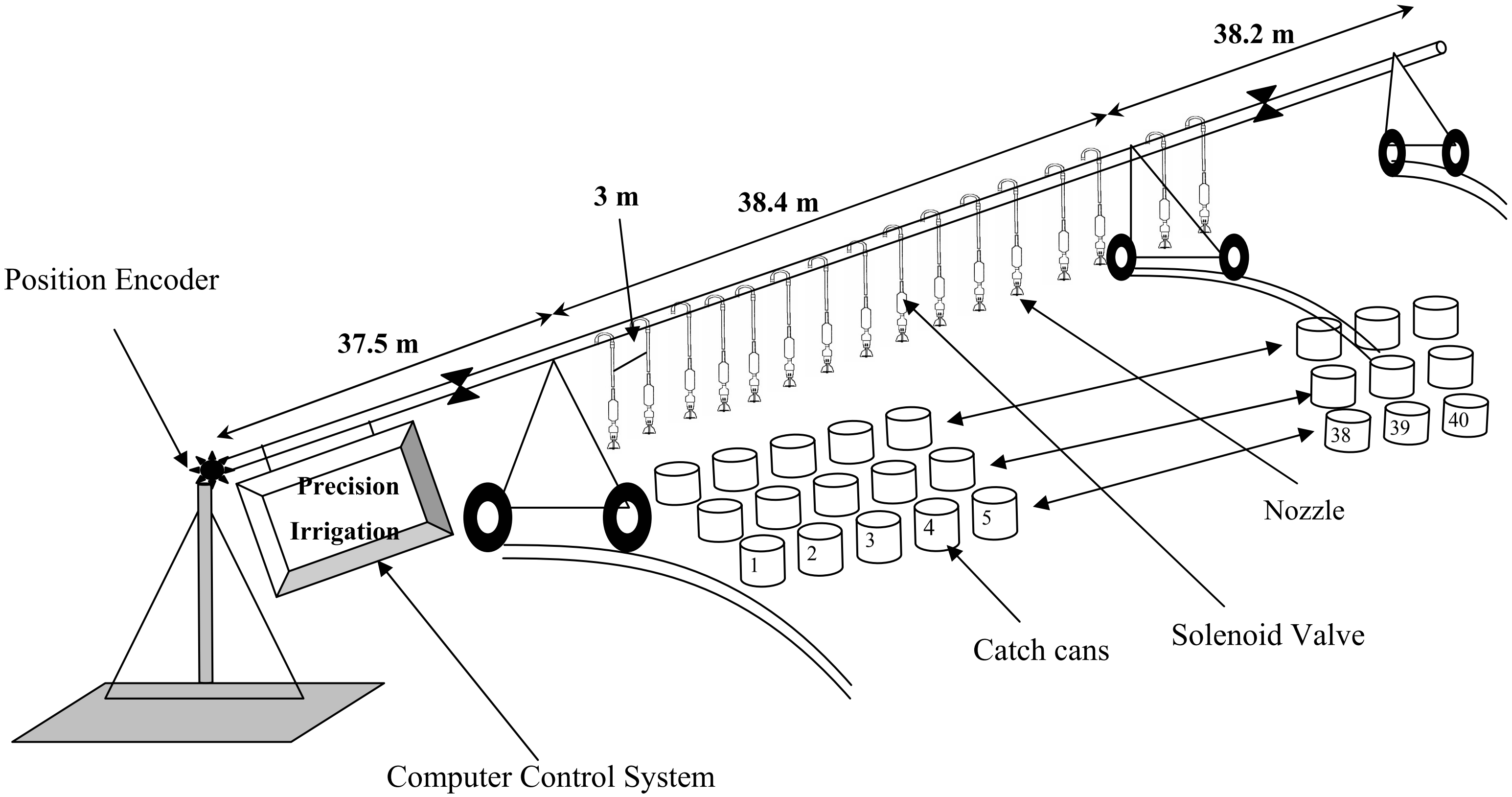

Figure 4.4: Schematic diagram illustrates the techniques for implementing and evaluating the variable rate control system on irregular shaped areas using the available control units on the modified centre pivot in FAL

4.4.4. Programmable Logic Control (PLC)

All electrical output devices (solenoid valves, position encoder, etc.) were controlled using PLC developed in the FAL and mounted on the mobile unit; about 3 m from pivot point (Figure 4.4). The integrative PLC had an on-board PC with software written as *plm* files, which can read a saved data file and allows changes in the system information and which can convert the map of control to on/off setting in the directly-addressable solenoid control registers of the PLC. The position, in polar co-ordinates, was found using the angle and the segment position on the truss, which, in turn, interrogated the on-board PC. The main features and flowchart and the circuit diagram of this PLC are shown in Figure 4.5 and 4.6, respectively. 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.

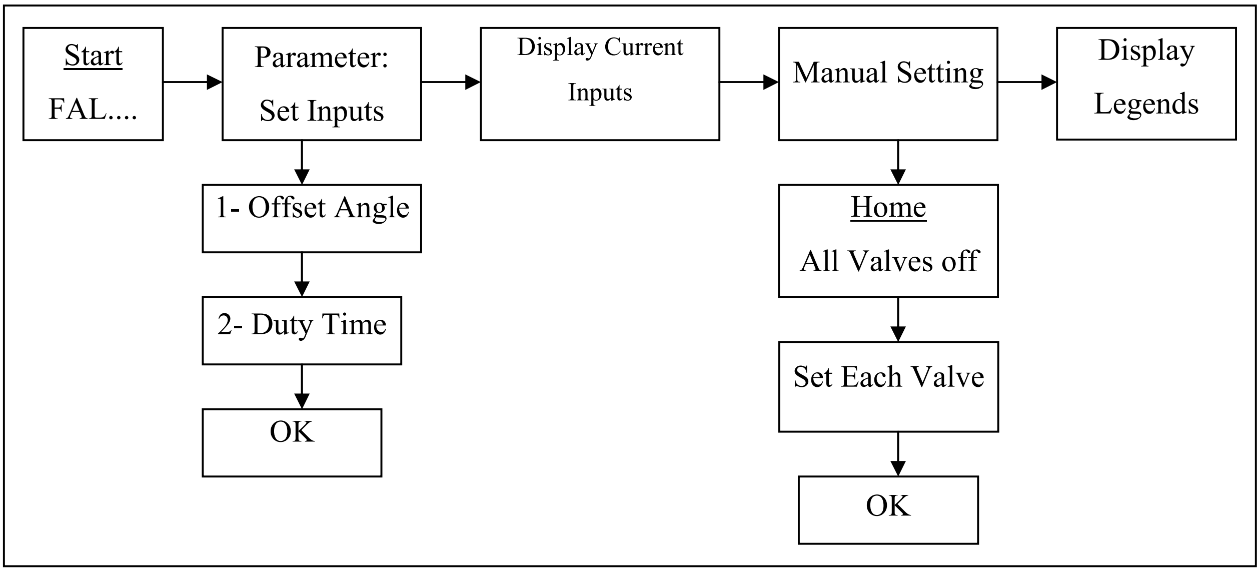

Figure 4.5: Flow-chart of the PLC

4.5. Field Tests to Evaluate the PLC Performance

The amounts of water to be applied ranged from 57% to 100% of the system design capacity when operated in the normal condition of speed at which the system can travel without potential runoff occurring, and divided into 4 levels: 100, 86, 71 and 57%. The irrigation depth normally used in FAL is equivalent to 24 mm, therefore, the amounts to be applied throughout the field are, 24, 20.6, 17 and 13.7 mm respectively. The distribution of these amounts in the field is shown in Figure 4.7. These levels represent the water quantities needed to be applied to return the soil moisture to the field capacity. The differences in the amount of water to be applied could be justified by the differences in AWC for the different soil types found in the FAL fields (personal communications and annual reports).

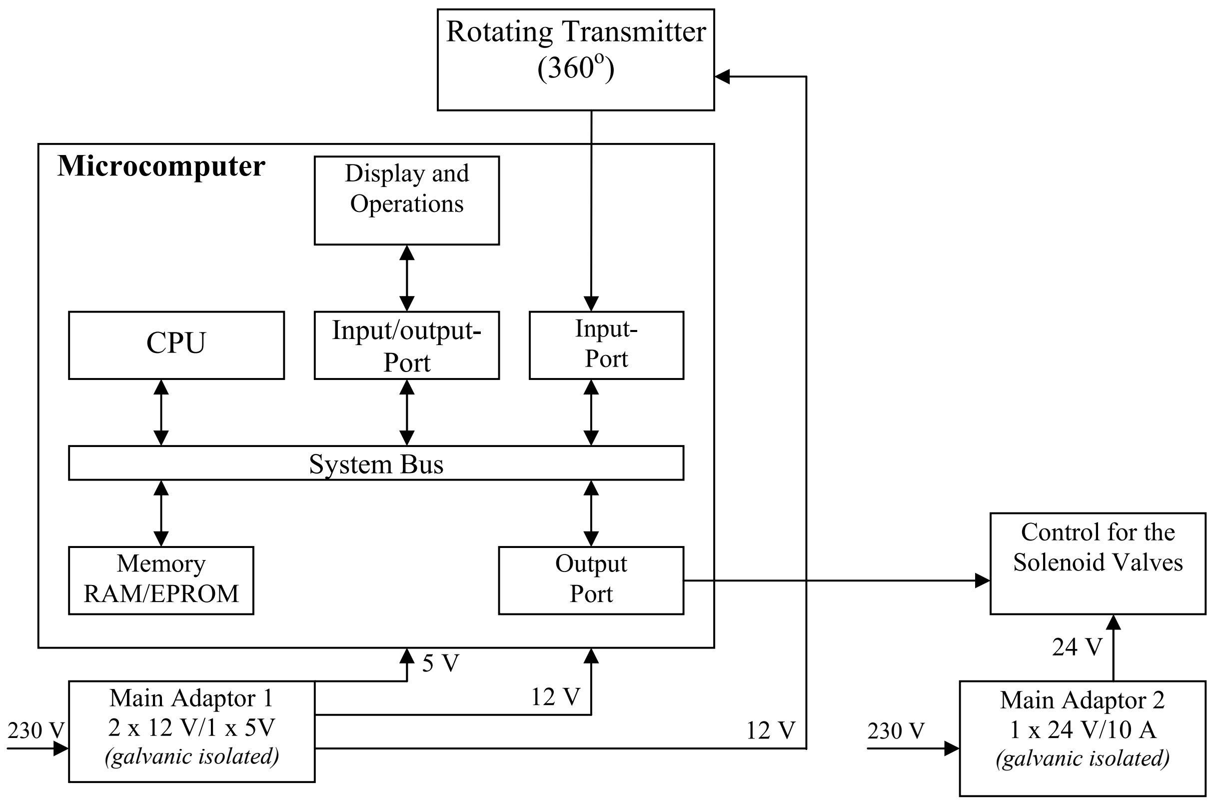

Figure 4.6: Circuit diagram of the PLC.

To examine and evaluate the validation the PLC and system modifications, tests, with five replicates for each, were conducted for some cases, in which different amounts of water should be added along the system radius. The water distributions were measured while the machine was operating under normal field conditions, except that the test periods were chosen so that the wind was relatively light and was moving across the line of collection cups. The tests were conducted during early morning hours, and the wind speed during test time was in the range 0.5-1.5 m/s and was assumed to have an insignificant effect on distribution. Water was collected in a three rows of collection cups placed 30 cm from the ground and extended radially from the pivot point. Depending upon the radius that was required to obtain a representative distribution, 40 cups/row spaced 1.0 m between cups and 1° between rows (65-87 cm) were used to obtain the radial water distribution.

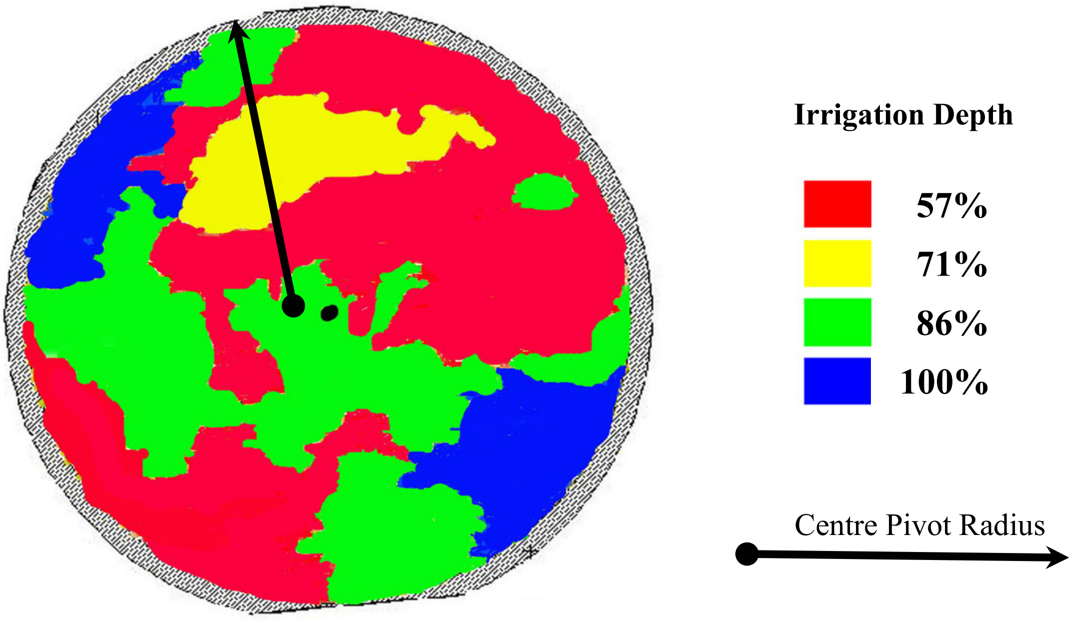

Figure 4.7: The application map used to evaluate the PLC developed in the FAL.

5. RESULTS AND DISCUSSIONS

The presented results will be arranged and discussed depending on the proposed approach to build a strategy for precision irrigation. The suggested method for variability delineation was dependent on the use of electromagnetic induction (EM38) to measure soil EC and relates it to AWC, through soil samples taken dependent on the produced maps from EM38. After determining the application map, the technologies for variable rate application will be compared to the earlier works. For instance, Omary and Sumner, 2001 summarised some of the experiments conducted to change the amount of water applied using different control techniques: a single sprinkler with linear-move system (Roth and Gardner, 1989; Fraisse et al., 1995a,b), a single irrigation system span with centre pivot (McCann and Stark, 1993), or small segments along each span (Omary et al., 1997; Camp et al., 1998). To date, these earlier works to modify irrigation systems, so that controlled quantities of water could be applied to field plots with regular borders, were used for studies and data collection to determine the water responses and range from irrigation scheduling to those which vary the depth of water applied (Roth and Gardner, 1989). But, increasing the number of segments or the length will increase the weight on the pump and increase the energy costs (Omary et al., 1997). In order to avoid this, some modifications must be made on existing systems, which could be achieved by controlling each sprinkler independently and using medium to large nozzles to reduce wind effects.

There are many different factors that must be taken into account when formulating a strategic approach, including balancing the economic returns with the environmental impacts and amount of risk envisaged (Blackmore, 1996). This point will be discussed at the end of this section, but not in detail, because the question goes in a special direction and requires appropriately specialised personnel. The costs of precision irrigation and farming are currently high, but will fall as the practices are increasingly adopted (Leiva et al., 1997). There are also opportunities for reducing average costs per hectare through economies of scale, which suggests that, under present circumstances, big farms are likely to derive financial benefits from PI and PF, while for smaller farms is likely to use contractors or consultants.

5.1. Soil-EC Variability Maps

On the basis of the EM38-sensor measurements Figure 5.1 shows EC measuring points and EC-delineation of the three fields displaying different EC-range zones. According to the results, there are no significant EC differences between the zones, due to the high amounts of rainfall, agreed with Domsch and Giebel, 2000; Dalgaard et al., 2001 and Durlesser, 1999. But, on the other hand, this could reflect the variability in texture, and this later affects the available water content (AWC) of the different zones. It is expected that, under arid and semi-arid conditions such as Jordan, the variability in EC will be a higher. Jordanian soils, due to the low amounts of annual rainfall and irregularity coupled with high potential to evaporation, are characterised by the high variability in soil EC even at small scales (Abu-Sharar et al., 1999). Therefore, application of EM38 for EC delineation under Jordanian conditions, which up until now was not familiar, will have a significant effect on mapping and sampling strategies, which will help in minimising the costs. Application of such techniques in Jordan should take into consideration the time of measurements, because it was found that the best time for measurements is when the soil moisture is near the FC. Also, using EM38 under these high variability conditions in EC will help in formulating standards between EC and AWC to help in facilitating precision irrigation in Jordan and world-wide.

Auger soil samples were taken from the sample points as shown in the EC-maps, to a depth of 90 cm in 30 cm increments. The number of samples (replicates) in each zone was different because of the size of the management zone. Texture, determined by feel, for Fields 1 and 2 was dominated by loamy sand at the first 50-60 cm, and more sandy in the lower depths especially for Field 1, while for Field 3, it was more sandy for the 90 cm depth. Organic matter contents for the upper 30 cm ranged between 2-4% and decreased with depth. In order to determine the available water content (AWC), which is the difference in the amounts of water at field capacity (FC) and permanent wilting point (PWP) for the upper 60 cm, the depth to which usually is irrigated, in the sample sites, the PWP was determined in the laboratory, using a ceramic plate method at 15 bar.

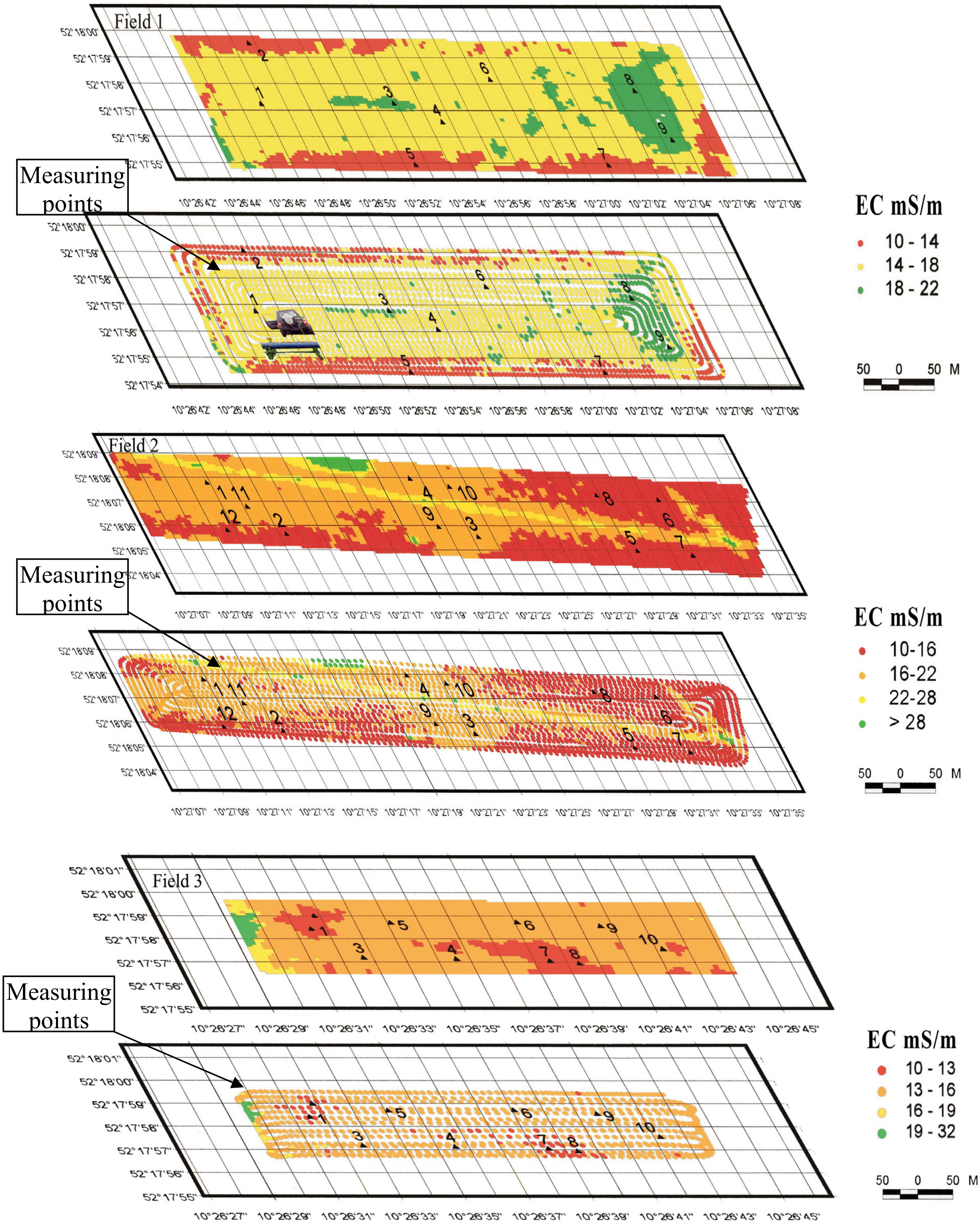

Figure 5.1: EC, mS/m, variability maps, EC measuring points and sampling sites for AWC at the 3 FAL fields.

The FC was determined by measuring the soil moisture after 2 days from 22 mm rainfall and the available data in FAL for the bulk density (ρ_b) were used. The results for the average PWP, FC, ρ_b. and AWC for the different EC zones in the 3 fields are shown in Table (5.1).

Table 5.1: Average PWP, FC, AWC and ρ_b for first 60 cm in three fields at different EC-zones

EC-zones (mS/m)	PWP	FC	AWC	ρ_b
	mm			g/cm^3
Field 1				
10-14	31.5	135.1	103.6	1.60
14-18	30.3	136.4	106.1	
18-23	29.6	137.3	107.6	
Field 2				
10-16	32.9	149.3	116.4	1.53
16-22	35.8	156.3	120.5	
Field 3				
10-13	23.4	97.6	74.2	1.50
13-16	25.2	104.3	79.1	

As shown in the Table 5.1, there are small differences in AWC between the different EC-zones in one field, and the differences increased between fields. The differences between zones in one field reflect the little variations in texture and this was proved by feeling the texture at the sampling points. The increased differences in AWC between the fields are mainly due to the change in texture, especially sand percentage, as indicated above. This could explain the lowest AWC in Field 3, compared with the other fields, because the texture is dominated by sand for the whole 90 cm. The heavier the texture, as in Fields 2 and 1, the higher the AWC, and the differences between fields due to more sand in Field 1 after 40-50 cm compared to Field 2.

As a general trend, previous studies indicate that any increase in moisture will increase the conductivity, because conductivity largely depends on the electrolytic solution within the soil rather than on the conductivity of the soil itself. Thus, the extent of soil's electrical conductivity is primarily attributable to the amount of any free moisture in the soil, therefore, as a soil dries, its conductivity decreases because the quantity of salts present must be ionised to provide the available conductive paths (Freeland, 1989). For these conditions, any increase in AWC due to texture, will result an increase in EC reading. As a conclusion, although the differences in EC in this work are small, but EC mapping using EMI shows promise and would give a good indication about the variability in AWC throughout the field, which could be considered as the basis for precision irrigation. To intensify the use of EMI for variability evaluation for precision irrigation, further research studies in this direction are required to be concluded with a standard relating EC measured with EMI sensors with AWC in order to reduce the intensity of sampling for delineation of the management zones.

The small scale variability influences the degree to which point sampling can reflect information and better relationships are to be expected if the range includes higher salinity values (Schmidhalter et al., 2001). The increase in research activities in this direction will help in establishing a standard relating different zones of EC vs. texture with the AWC, which will help later in the new notion of irrigation scheduling (When, how much and where to irrigate). On balance the results of investigation indicate, EM38 could be used as fast method to differentiate between zones of different AWC to build the application map for precision irrigation.

5.2. Variable-Rate Technology

As proposed in the suggested hypothesis to establish a precision irrigation strategy, after the spatial variability has been determined and mapped, the next stage is application of the variable rate technology to the irrigation system. Types of irrigation systems, as presented in Figure 2.2, could be further classified depending on their nature, to determine their applicability and suitability to precision irrigation as follows (Figure 5.2):

- **Surface irrigation including its different types**: Not suitable to precision irrigation due to the low degree of control on changing the application depth, and relatively small coverage area.
- **Localised Irrigation and its types**: could be used for precision irrigation through design layout and the distribution of the different types of water applicators (dripper, bubbler, etc.) in the field and relatively small coverage area.
- **Sprinkler irrigation**:
- **Solid set**: could be used for precision irrigation through design layout and the distribution of the risers in the field.
- **Semi-Mobile and Mobile-Reel machines**: have good chances due to the degree of automation and the large area that could be irrigated with one system (i.e. 50 ha for centre pivot). The change in water depth could be achieved through some of the available technologies like controlling travel speed and/or discharge rate.

It turns out that the semi-mobile and mobile-reel machines are the suitable irrigation systems for individual water distribution. Both of them can change the irrigation depth through adjustment of the travel speed (with constant sprinkler discharge rate) along the travel direction. The radial direction, the semi-mobile systems, such as centre pivot and linear move, the change in water depth applied achieved through controlling the discharge rate of each (or group) of sprinkler(s) using PLC, are discussed in section 5.3. Concerning mobile reel machines, experiments with some available speed control units will be carried out (Section 5.2.1.). The big gun is not suitable for precision irrigation due to the high effect of wind on water distribution. The bi-directional water control through speed and discharge rate adjustment is possible, similar to semi-mobile systems. But for the radial direction, the following should be taken into consideration: batteries should be installed to supply energy, position definitions

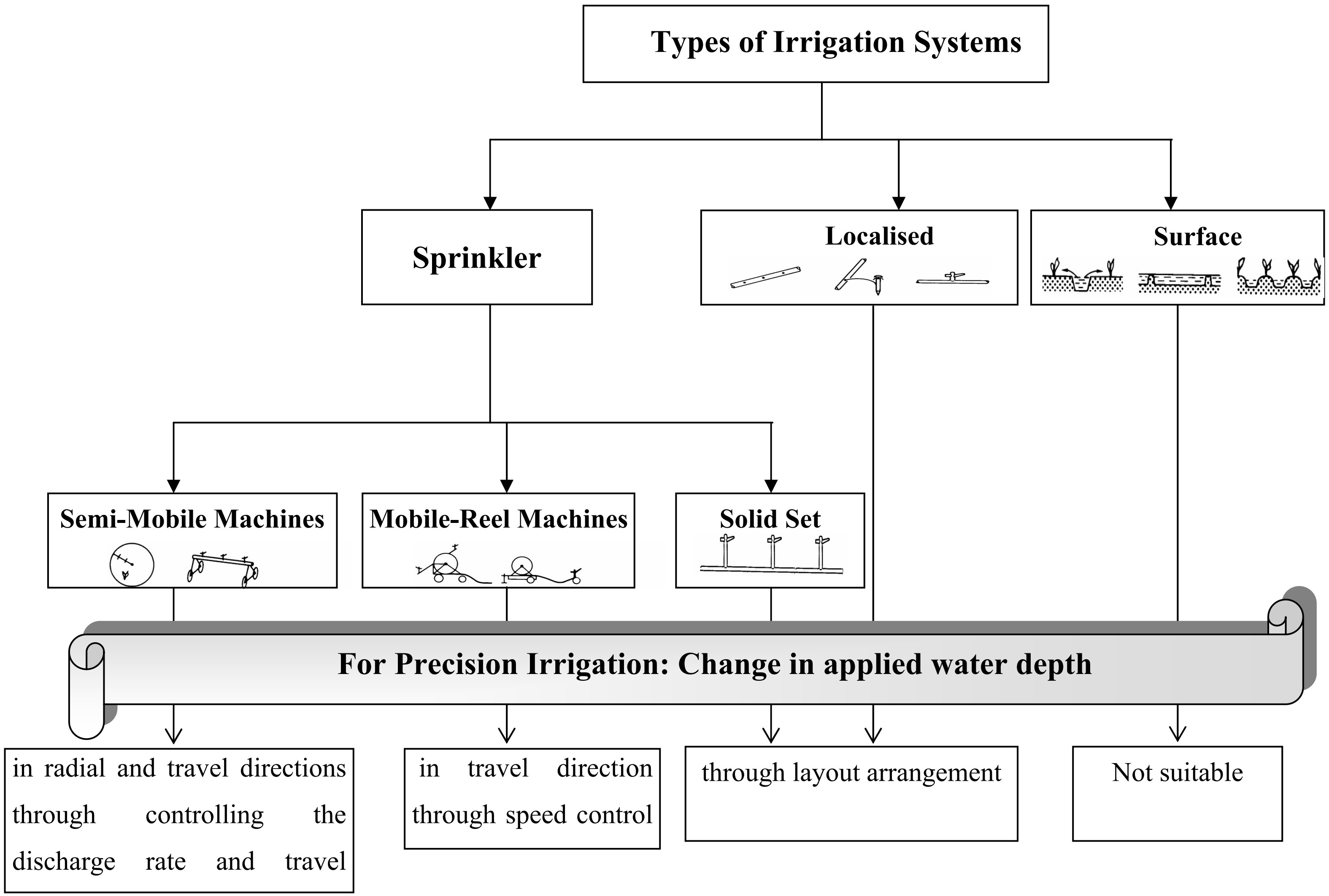

Figure 5.2: Types of irrigation systems and their applicability to precision irrigation.

5.2.1. Travel-Speed Regulation

Figures 5.3 through 5.5 show the results of the ability of the IRRIGAMATIC 350 and PROGRAM RAIN 9 control systems in regulating the speed of the mobile reel irrigation systems (big-gun and boom-sprinkler). The acceptable congruence in the two replicates (R1 and R2) between the programmed travel speed (v_p) and the measured travel speed (v_m) for the two control systems indicated the ability of these control systems in adjusting the system speed. Measure of the acceptance could be also shown in Table (5.2) where the standard deviation, SD, (m/h) and the coefficient of variation CV% are relatively low and ranged between 1.24 to 2.51 m/h and 4.16 to 10.12 %, respectively for Program Rain 9 and ranged between 0.33 to 0.89 m/h and 1.75 to 3.30 % respectively for IRRIGAMATIC 350. This means that though these speed control systems are now used with one speed through the field, they could be facilitated to regulate the speed of the irrigation system for precision irrigation. The jump from one programmed speed to other needs a distance of about 1 m to become constant, and this is also a good indicator for the ability in regulating the speed and also must be later taken into consideration when evaluating the change in irrigation water depth with speed, as suggested in the strategy for precision irrigation.

Table 5.2: Performance parameters described the ability of the control systems, in speed adjustment.

Parameters	**Unit**	**PROGRAM RAIN 9**[1]				**IRRIGAMATIC 350**[1]				**IRRIGAMATIC 350**[2]			
v_p	m/hr	16.0	24.0	32.0	40.0	16.0	24.0	32.0	40.0	16.0	24.0	32.0	40.0
v_m[3]	m/hr	15.5	24.8	29.9	38.5	15.8	23.6	31.4	39.3	15.8	23.8	31.7	39.6
SD	m/hr	1.44	2.51	1.24	2.05	0.52	0.55	0.66	0.78	0.33	0.57	0.89	0.69
CV	%	9.30	10.12	4.16	5.32	3.30	2.34	2.10	1.99	2.11	2.38	2.80	1.75

[1] with Big Gun [2] with boom-sprinkler [3] Averages along 20 m

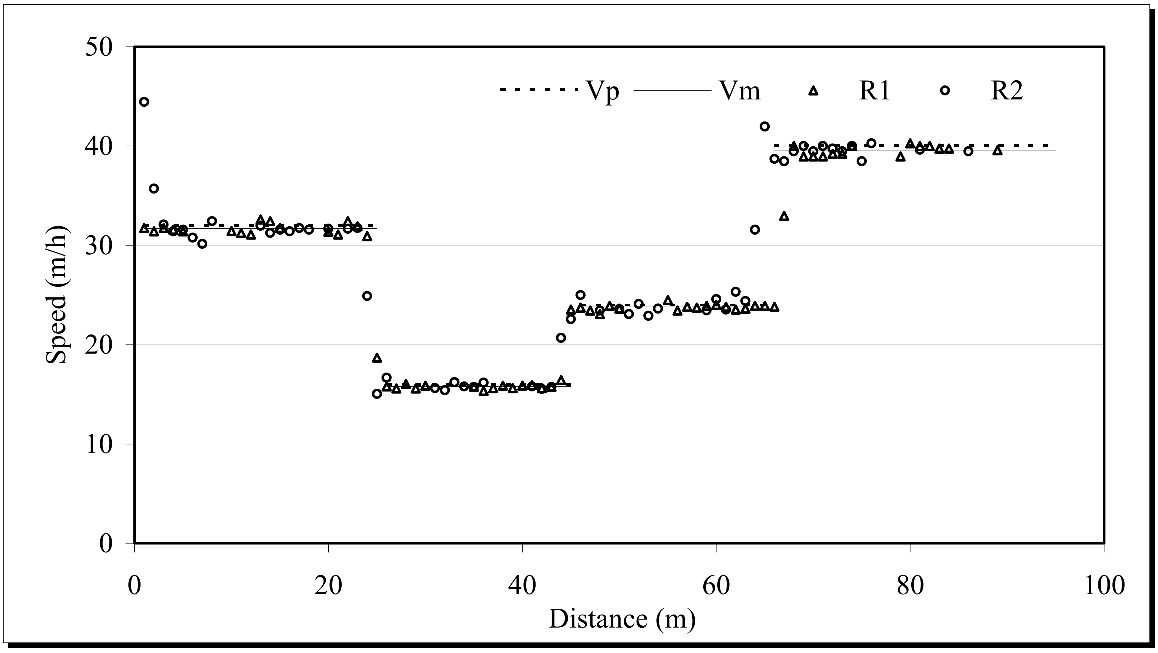

Figure 5.3: Congruence between the averaged of two replicates R1 and R2 of measured (v_m) and programmed (v_p) system speed using IRRIGAMATIC 350 with boom sprinkler system.

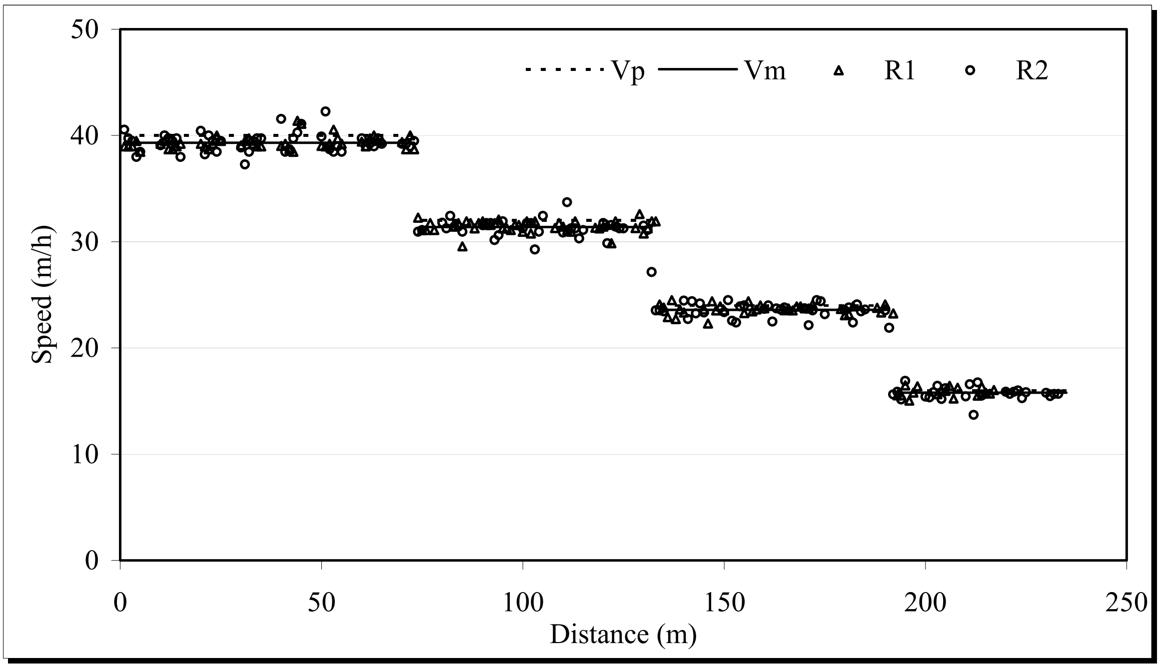

Figure 5.4: Congruence between the averaged of two replicates R1 and R2 of measured (v_m) and programmed (v_p) system speed using IRRIGAMATIC 350 with big gun.

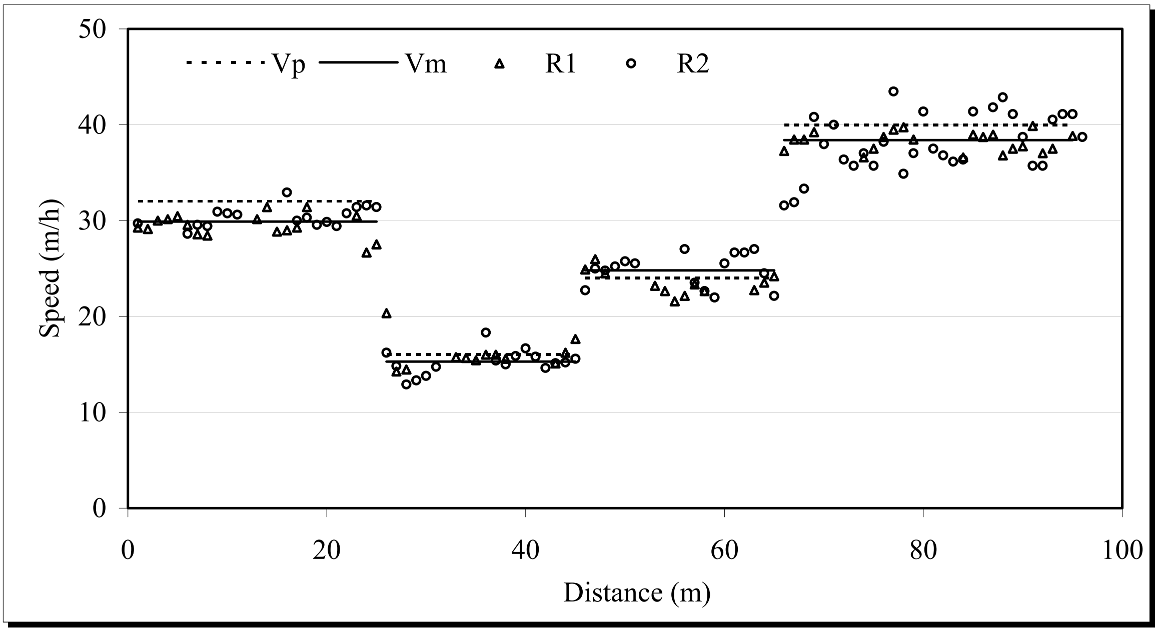

Figure 5.5: Congruence between the averaged of two replicates R1 and R2 of measured (v_m) and programmed (v_p) system speed using PROGRAM RAIN 9 with big gun.

5.2.2. Change in Water Depth (d_n) with Speed (v_m)

Depth of water applied to the area covered by the sprinklers (d_n) was changed due to the change in the travel speed of the irrigation system (v_m). Figures 5.6 through 5.8 show the application depth change by switching the system speed. As results indicated, with increasing system speed, the depth of water applied to the entire area covered by the sprinklers was decreased, since the duration of irrigation over a particular point in the field was decreased (Roth et al., 1989). As shown from the figures, the system needs about 1 m, after the change in speed happened, to reach a constant speed near to v_p. The change in water depth needs about 16 m to reach the constant depth, due to the wetted diameter of sprinklers which is 16 m and the overlap in the travel direction. The radius of the sprinkler wetted diameter should be taken into consideration if the system is to be used for precision irrigation purposes.

The best correlation describing the relationship between d_n and v_m was found to be exponential (figure 5.9). For precision irrigation implementation, the high correlation factor (R^2 = 0.83) means that, this relationship is valid to calculate the appropriate travel speed of the irrigation system to achieve the target depth.

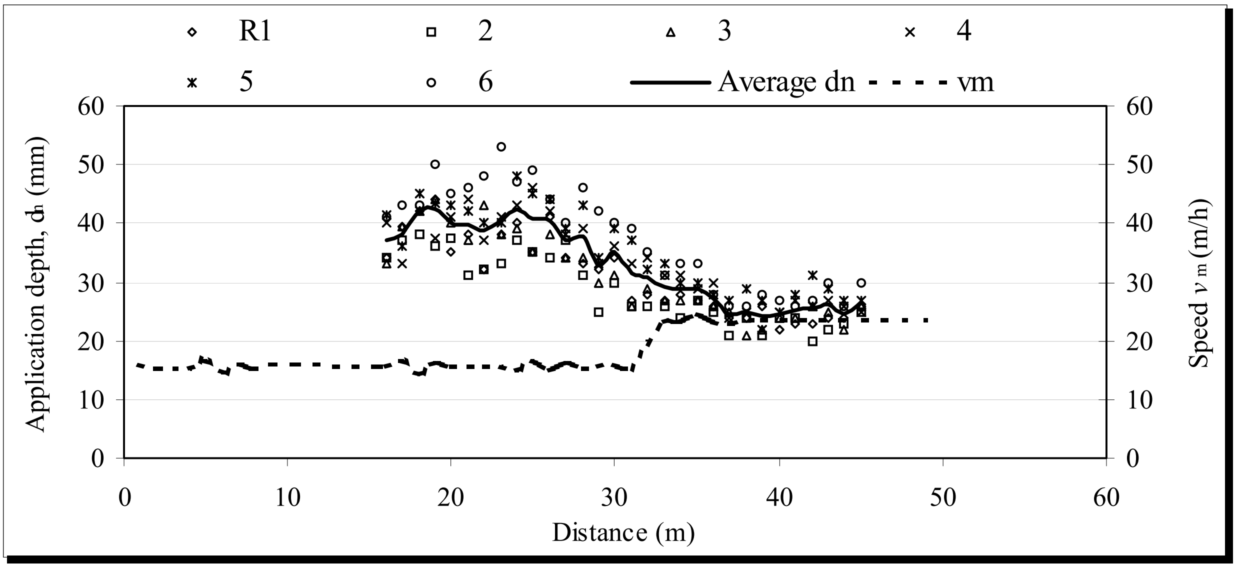

Figure 5.6: Average of six replications, R1 to 6, of measured application depth, d_n (mm) decrease with increase system speed, v_m from 16 to 24 m/h.

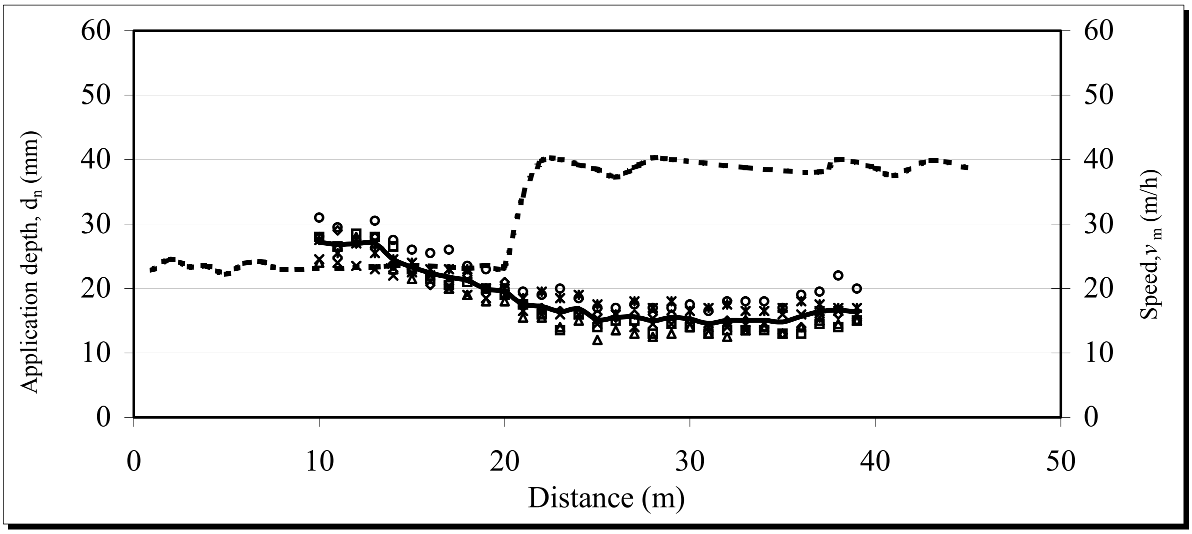

Figure 5.7: Average of six replications, R1 to 6, of measured application depth, d_n (mm), change with changing system speed, v_m from 24 to 40 m/h.

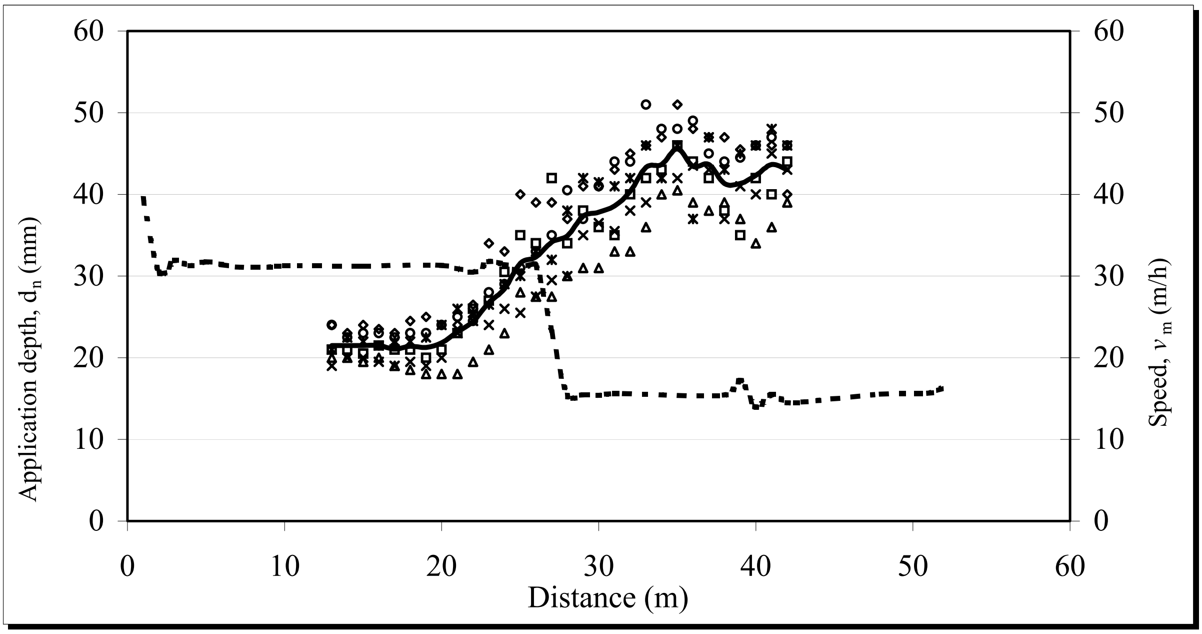

Figure 5.8: Average of six replications, R1 to 6, of measured application depth, d_n (mm), change with changing system speed, v_m from 32 to 16 m/h.

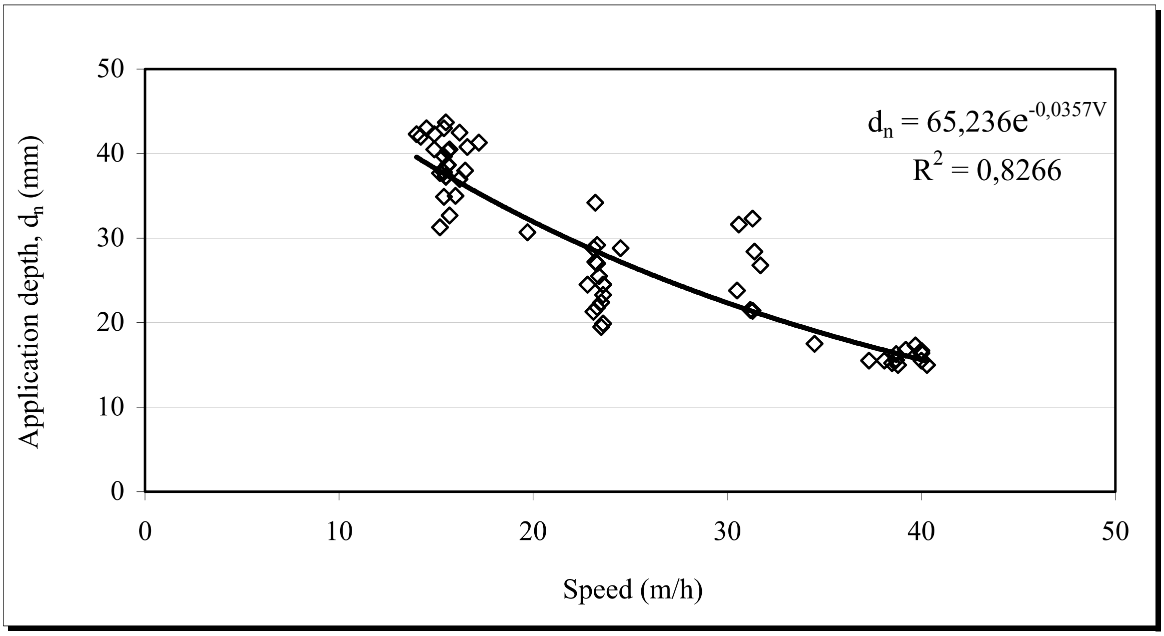

Figure 5.9: Relationship between depths of water applied d_n (mm) and system speeds (m/h).

During the change from one given speed to another, the mode of change in the amount of water applied in the entire area covered by the sprinklers is best described by the exponential relationships shown in Figure (5.10). The high correlation coefficient, R^2 ranged between 0.95-0.98 proved the previous result; the exponential mathematical model (Equation 1) describes the mode of change in water depth applied with change in travel speed for precision irrigation.

$$d_n = a\, e^{b v m} \quad \text{......................................} \quad (1)$$

where,

d_n = Depth of applied water (mm/hr)

a = Constant depends on the sprinkler configuration

b = Constant represents the rate at which the water depth changed with speed

v_m = Measured travel speed (m/h)

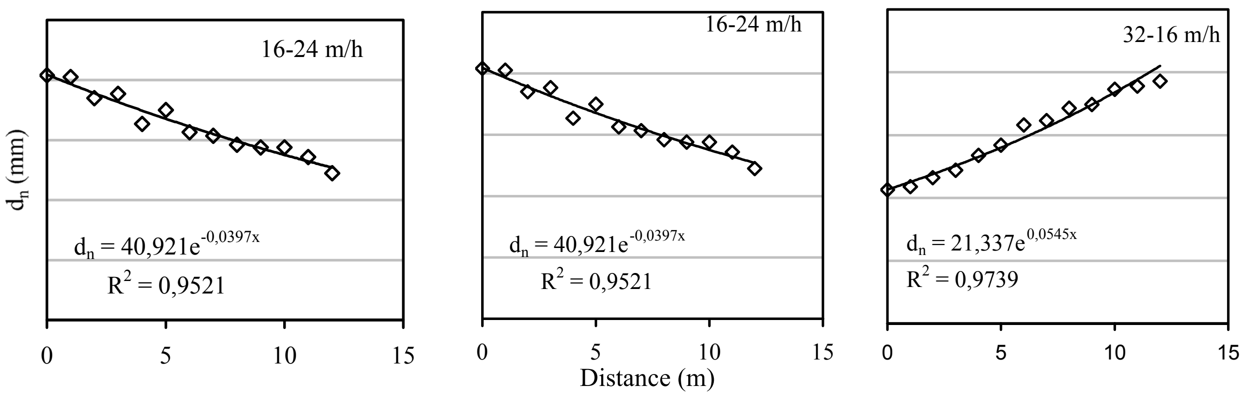

Figure 5.10: Relationships describing the mode of change in the amount of water applied in the entire area covered by the sprinklers, during adjustment from one given speed to another.

According to the suggested hypothesis to build a strategy for precision irrigation, the first suggested solution to achieve variable rate water application is by changing the travel speed, using available technologies of speed control systems. Results indicated this solution is appropriate for changing water depth in the travel direction. This could be used for mobile reel irrigation systems because the irrigation width is small, about 60-75 m, and they do not need high technology like in the second solution, the centre pivot. Another solution is required when the change in water depth in the radial direction is necessary. This solution controls the discharge rate of each sprinkler, using some technologies operating under computer control systems that can detect the position of the irrigation system in the field and regulate the opening time of each sprinkler.

5.3. Centre Pivot System Modifications and Performance

Since this description is of the design and testing of an apparatus, conclusions must be limited to the performance thereof (Sadler et al., 1997). Base water distributions (average of four and five replicates, respectively), before and after the installation of the solenoid valves, along the system radius are shown in Figure 5.11. According to the equation (2) defined by Heermann and Hein 1986 (Heermann et al., 1992) to calculate the uniformity coefficient (CU_{cp}) for centre pivot system, the CU_{cp} after the solenoid valves were installed was 95.8 % compared to 95% before

$$CU_{cp} = 100\left(1 - \left[\left\{\sum S \mid D-(\sum DS/\sum S)\mid\right\}/\sum DS\right]\right) \quad \text{..................................} \quad (2)$$

where:

CU_{cp} = Christiansen’s uniformity for centre pivots,

S = the distance from the pivot to an equally spaced radial can,

D = the depth of water in the catch can at S

installation, as shown in Table 5.3, meaning the installation of the solenoid valves does not influence the uniformity at which the water is distributed, but may improve it. Also, standard deviation and the coefficient of variation before installation of the solenoid valves, 1.66 mm and 7.00 % respectively, were improved after the installation, 0.99 mm and 4.17 % respectively.

Table 5.3: Performance parameters for the centre pivot system, before and after the solenoid valves were installation.

Parameter	**CU_{cp}**	**Mean**	**SD**	**CV**
	%	**mm**		**%**
Before	95.0	23.7	1.66	7.00
After	95.8	23.8	0.99	4.17

This distribution will be used as the baseline for comparison for evaluating the effectiveness of the PLC for variable-rate water application. The insignificant deviation in 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). Using valves with minimum pressure loss across the valve will help in minimising the power costs and also determine the speed of opening and closing. When valves are subjected to higher discharges, the head loss is independent of the diaphragm performance and depends only on the discharge rate and valve construction.

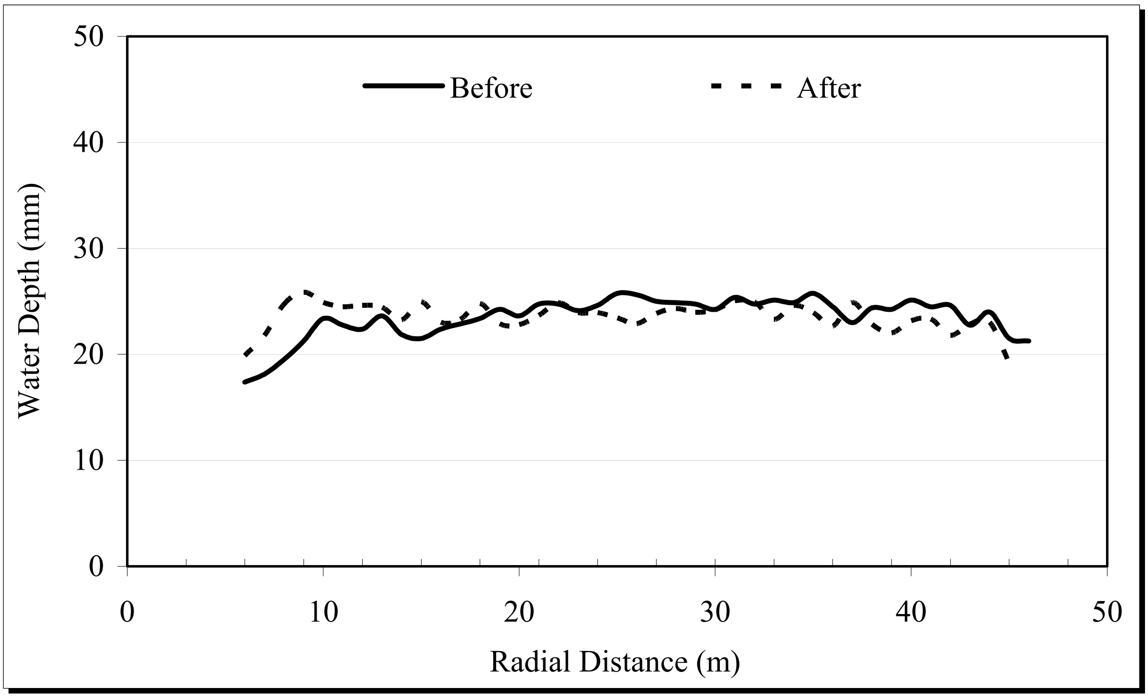

Figure 5.11: Base water distribution along the system radius before and after the solenoid valves installation.

Five test cases (A= 20°, B= 40°, C= 110°, D= 150° and E= Manual) where selected at different application depths to evaluate the PLC in regulating the discharge rate of the sprinkler while the irrigation system moved. This is the suggested solution to achieve a variable rate water application in the radial direction stated in the hypothesis for building a strategy for precision irrigation. . These test cases represented different locations in the application map (different angles in the field) as shown in Figure 5.12. The test case E represented a case of manual programming in order to evaluate this property in the PLC. Under these test cases, the catch cans were distributed according to the procedure described the material and methods, Section 4.5, and the averaged over five replicates.

During the time at which the experiment and the replicate took place, the wind speed was very low and ranged between 0.5-1.5 m/s. This was important to prevent any other factor affecting the water distribution except the open/close time of the solenoid valves.

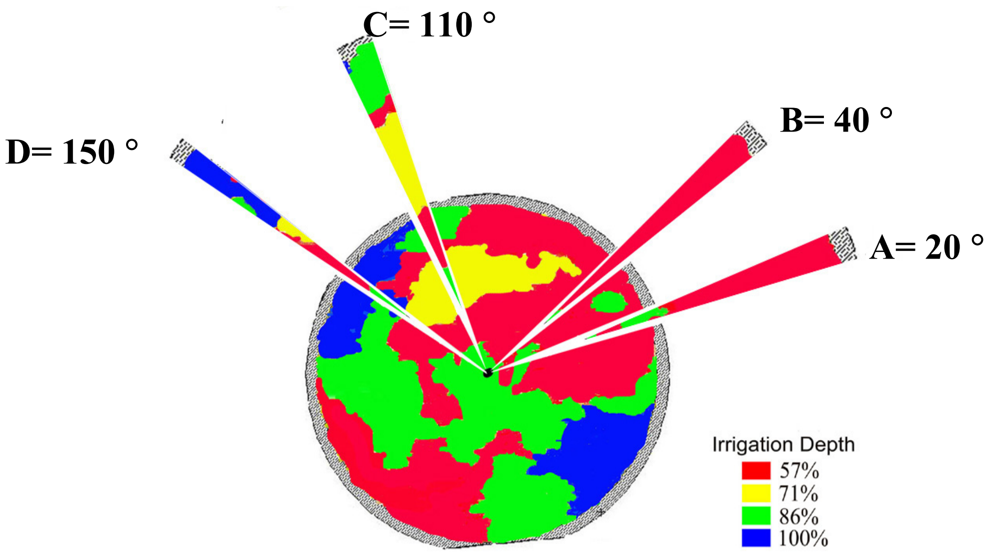

Figure 5.12: Locations of the selected test cases A, B, C and D in the application map.

The pattern of water distribution depths (average of five replicates), for the above selected test cases, along the radius and under the segment installed with the solenoid valves are shown in Figures 5.13 through 5.17. Comparison of the averaged measured application depths with the target in the application map (Figure 5.12) for test case A (Figure 5.13) shows a good agreement with a CU_{cp} ranged 95.6-96.7 %, but with some deviations at the management zone's border. The response of the valves to the signal affected the water distribution patterns, as reported by Fraisse et al., 1995, who observed that these valves have a discrete response time for opening and closing (valves open quickly but required a longer time to close). The solenoid valve functioning (open and close) affects the distribution pattern (water depth) throughout the field but, has no effects on the CU_{cp}. This is shown in test case B (Figure 5.14) where the CU_{cp} was 95.8 %, and is not affected when compared to the base distribution. According to Test Case C (Figure 5.15), the CU_{cp} at which the water is distributed at the beginning and end of the irrigation system is less than the base distribution and the previous test cases, and this attributable to the large wetted area of the sprinkler and the small area of the management. This is also the case in Test Case D (Figure 5.16), where the CU_{cp} was less at the beginning of the system, 94.8 % compared to the base 95.8 %, but in the middle of the system the CU_{cp} was increased to 96.7 %. For the Test Case E (Figure 5.17), the CU_{cp} was similar to that with base distribution, 95.8 %, and the big turn from zero discharge to the maximum required discharge does not affect the CU_{cp}. It does, however, have an effect and increased the distance to reach the required discharge.

Return to the management zone's border spray pattern caused an area between the two zones to be irrigated at depths less/more than the target depths. This is because the sprinklers used in the package had a relatively large wetted radius, which indicates the importance of using sprinklers with smaller wetted radius to reach depths much closer to the target depths. The contrasts between the target and measured depths at the borders were small when the required change in water depth was small (Tests A and C in Figure 5.13 and 5.15) and increased with increases in the required change (Tests D and E). 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.

As previously mentioned, there must be a balance between the small wetted radius and the amount of drift, while selecting the type of sprinklers to be used and installed. The selection of the proper sprinkler packages has also effect on the size of the management unit or zone in the application map, which depends mainly on the ability to measure and manage it (Blackmore, 1994).

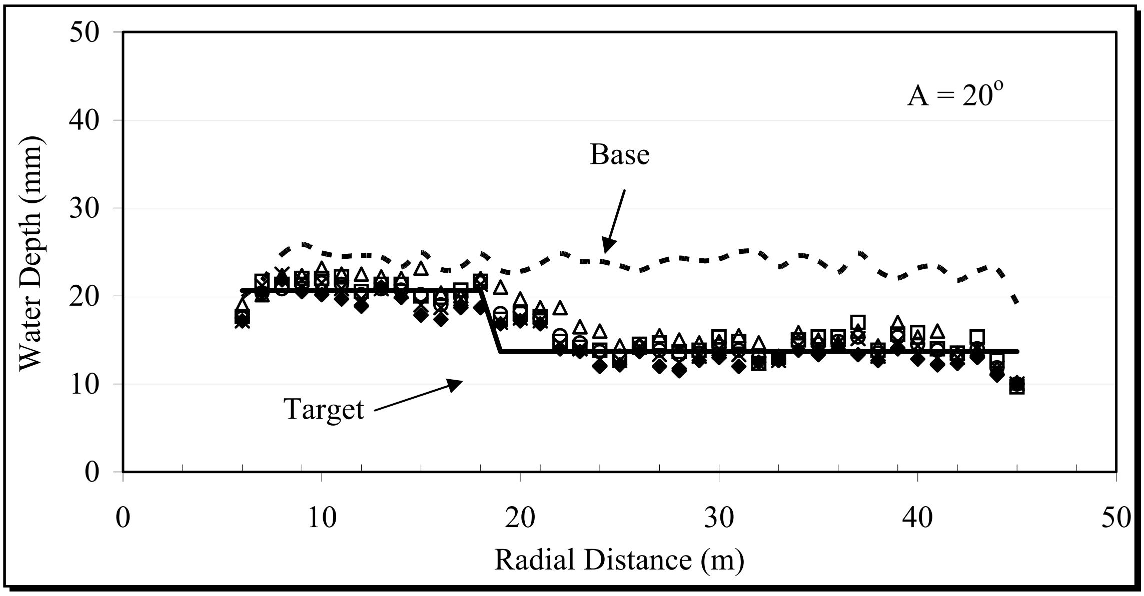

Figure 5.13: Target, measured and base water distribution for the Test Case A= 20°
used to evaluate the PLC developed in FAL

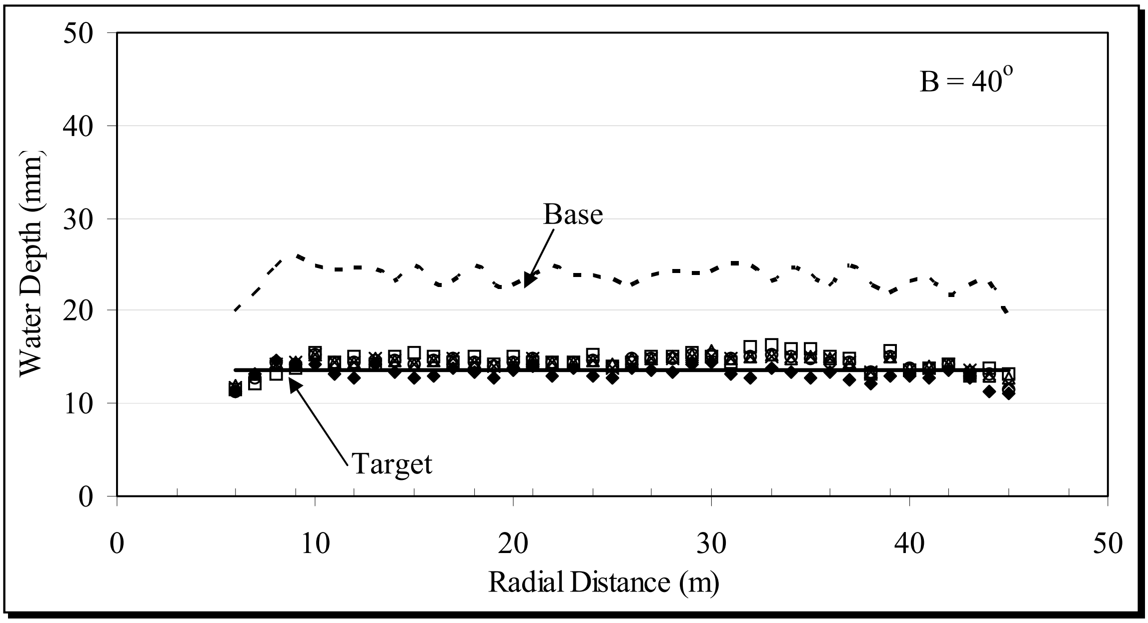

Figure 5.14: Target, measured and base water distribution for the Test Case B= 40°
used to evaluate the PLC developed in FAL

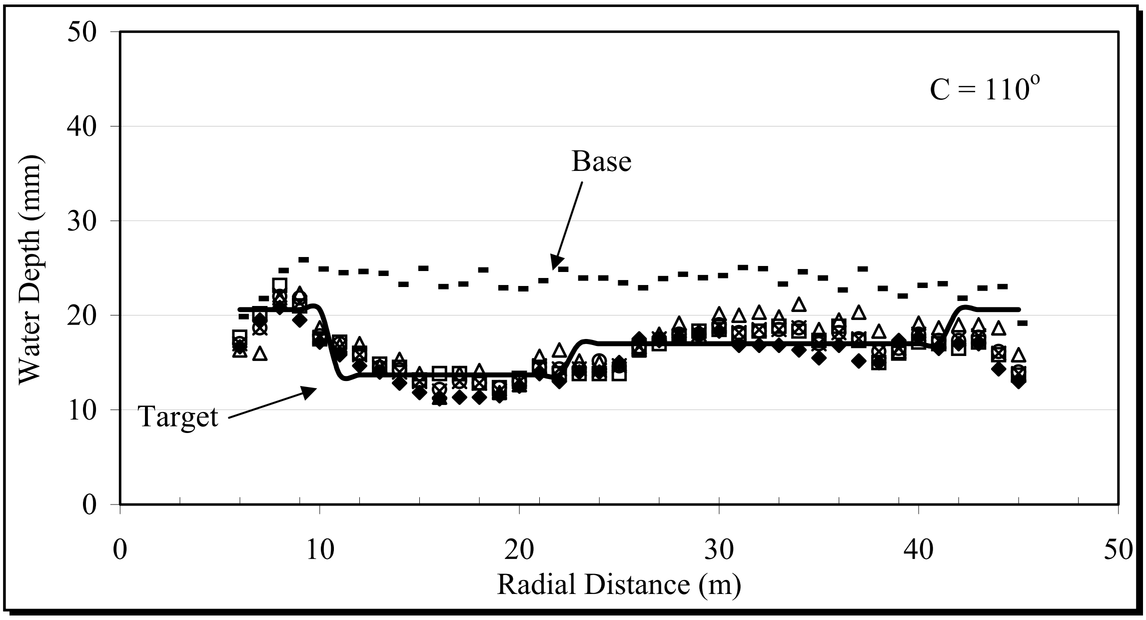

Figure 5.15: Target, measured and base water distribution for the Test Case C= 110°
used to evaluate the PLC developed in FAL

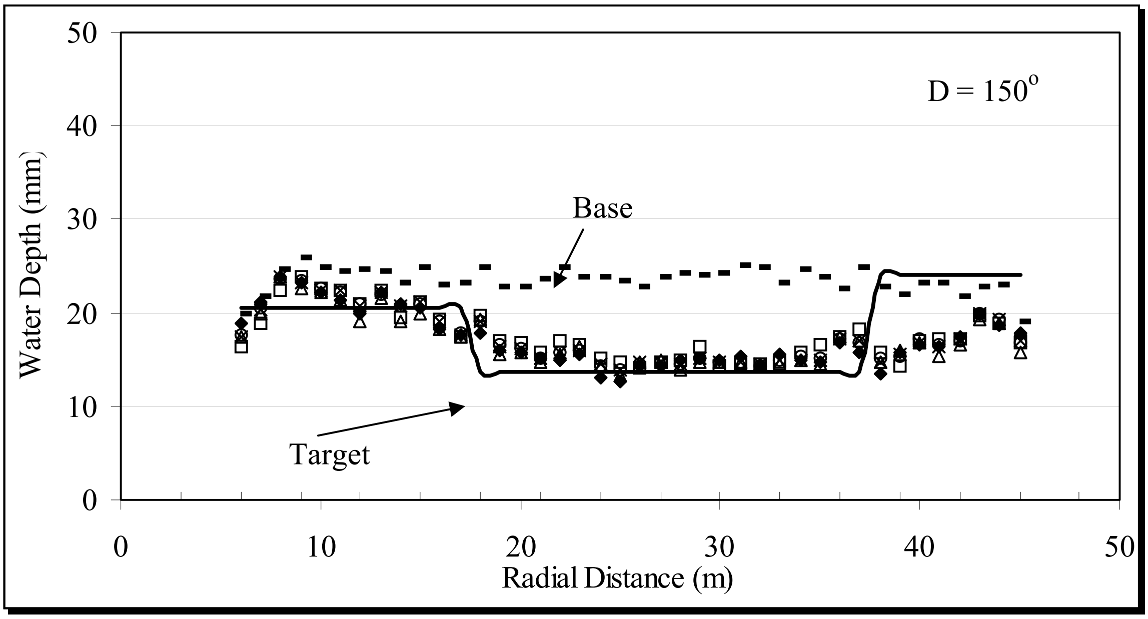

Figure 5.16: Target, measured and base water distribution for the Test Case D= 150°
used to evaluate the PLC developed in FAL

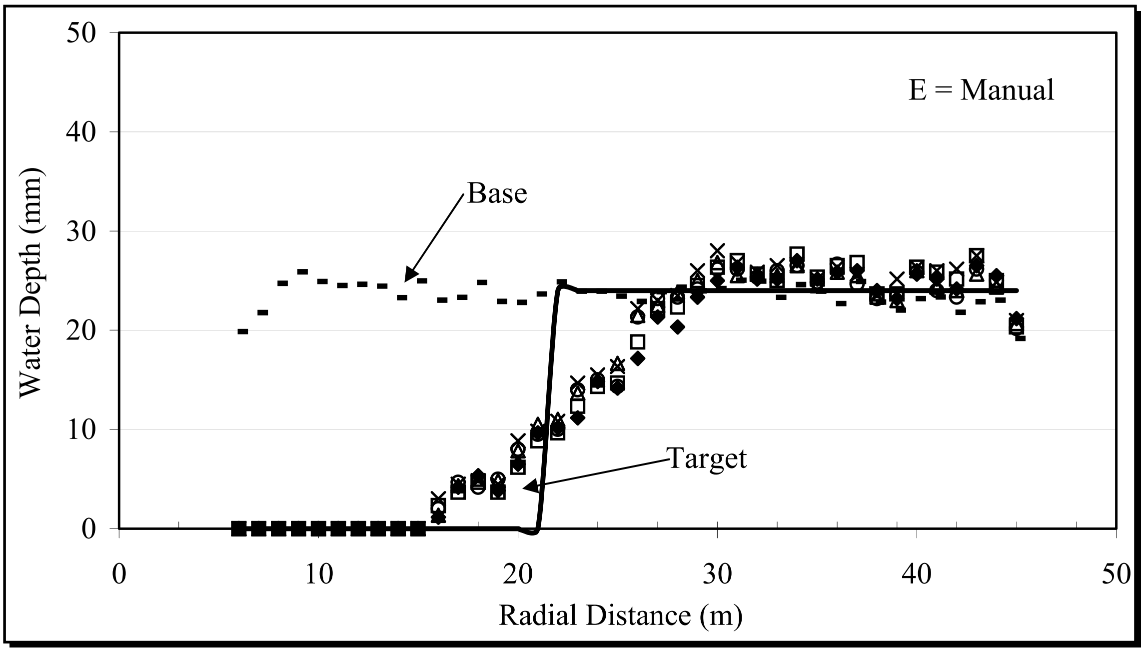

Figure 5.17: Target, measured and base water distribution for the Test Case E= Manual used to evaluate the PLC developed in FAL

As the results show, this variable water application system operated successfully, and the water depth measured reached the target depths. These tests indicated that the pulsed irrigation system will provide a flexible means of applying variable water treatments (Fraisse et al., 1995; Duke et al., 1997). Although the observations and measurements of water application indicate that the control system performance is acceptable, more detailed evaluations and improvements of the fertilisers and chemicals application will be required before definitive conclusions can be reached.

More extensive improvement of the PLC will be required before definitive and applicable conclusions can be reached with regard to system performance. The next improvements in the program should take into consideration:

- Outfitting the system with variable rate for fertilisation and chemigation. A fully functional site-specific centre pivot irrigation system must represent full implementation of variable-rate management to optimise water, nutrients, and pesticides application to small irregular-shaped areas.

- Sensors and techniques to provide real-time or near real-time feedback of crop conditions may be used in the second generation to detect dynamic crop variation during the season to improve crop management and need to be developed, field tested and validated (Camp et al., 1998).
- The ability to create/read a treatment map that is stored on a smartcard (credit-sized memory card) or computer disc that is inserted into the controller in the equipment concerned. This flexibility allows the users to build a central computer room for different fields, each with a different disc of information, and the computer can read the different discs and control different systems simultaneously and independently. Another benefit of this site-specific irrigation system and away from spatial variability is when one field is cultivated with different crops over a whole season (crop rotation) or one field with different crops at one time, a disc for each crop could be established and should be read from the central computer.

Observations and measurement of water application indicate that the system was installed and performed successfully as designed without any significant problems related to the instrumentation or networking. The solenoid valves can be variably actuated to irrigate different quantities. One small-value disadvantage is that the on/off sprinkler may be either in phase or out of phase with the start-stop motion of the irrigation tower, impressing additional variability in application depth (Sadler et al., 1996). This could be minimised when the wetted radius is larger, the alignment of the irrigation machine is controlled very closely, and the base time period (duty cycle) of the sprinkler is small relative to the duration of tower stoppage. 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.

There were no observed system failures or malfunctions that would account to its performance, except that the pressure at the system inlet at the pivot point was increased when more than three sprinklers were closed, and this could be observed at Test Case E, where the measured depths were deviated to be higher than the base. This problem could be overcome by using pumps that change its capacity automatically. Anyhow, this problem has a little impact on sprinkler performance, since the solenoid valves and the sprinklers are pressure regulated.

Regarding the proposed structure to build a strategy for precision irrigation mentioned in Section 3.2, the second suggested solution through which different irrigation depths throughout the field could be reached permit the conclusion that this PLC and the related modifications fulfil this objective.

5.4. Potential Economical Implications

It has been suggested that precision farming is currently at a crossroad (Stafford, 1999; Stafford, 2000). Much of the necessary technology is available commercially, the environmental and economic benefits of implementation are as yet unproven, except in a few cases, e.g., for herbicides (Miller and Paice, 1998), and much development of agronomy is still required to determine optimum recommendation procedures for inputs at the localised level. The potential benefits of precision irrigation include increased crop yield, cost-efficient usage of inputs via variable-rate application and reduced contamination of water supplies by agrochemical deep percolation or runoff (e.g., Beckie et al., 1997; Lindquist et al., 1998). Obviously, these potential benefits should be compared with the extra expense involved in sampling and applying inputs differentially across the field area. These costs are dependent on the accuracy desired and the complexity of the surface under consideration. Therefore, the economic returns of precision irrigation methods need to be improved before wide-range acceptance can be reached. Also, the general introduction of precision irrigation will not take place for several years until the field data for irrigation control are available in manageable forms (Sourell and Sommer, 2002).

Evaluation of the expenses of this system is beyond the scope of this work, and is another important direction toward which this research can be profitably extended, but a brief description for the extra technical costs was conducted. Because of this, a full economic analysis cannot be conducted until full results from research programmes are available and also, because this management system is still in the beginning stages, many industrial accessories are expensive. However, it is possible to make assumptions based on the application map shown in Figure 4.7 and Tables 5.1, and these assumptions include:

- The annual irrigation depth under which the system currently works, including delivery of 850 m^3/ha.
- The kWh/m^3 needed to lift water 100 m is 0.63 (Sourell and Thoermann/FAL, personal communications)
- The crop to be irrigated is wheat with average annual yield 8 ton/ha,
- To simplify the calculation, the field was divided into three management zones with different AWC, therefore needing different quantities of water,
- After the variability delineation using EM38 followed by soil samples, the three zones were: 30% of the area should receive 610 m^3/ha, 60% received 850 m^3/ha and 10% should be irrigated with 940 m^3/ha.
- The system and additional accessories will be amortised over 10 years

5.4.1. Costs

The current capital cost €/(ha.a) for the centre pivot irrigation system together with additional capital costs for precision irrigation are given in Tables 5.4 and 5.5. It should be mentioned that the control system cost is independent from the area.

5.4.1.1. Capital Requirements

The high additional costs 442 €/ha (Table 5.4) are due mainly to the costs of solenoid valves and the control system. It is expected in the coming years, when this new management system becomes familiar, 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.

Table 5.4: Capital requirements for precision irrigation-centre pivot system with 400 m radius (≅ 50 ha)

Item	**No. of Units**	***Price / Unit* €**		**Capital Costs**			
				Machine €		**Area €/ha**	
Irrigation system [a]	1	52,500.00		52,500.00		1,050.00	
Extra items to be installed for precision irrigation system							
Solenoid valves	133		71.34		9,488.00		190.00
Control System [b]	1		10,000.00		10,000.00		200.00
Cables and Boxes	1		1,600.00		1,600.00		32.00
Technical Works	20		50.00		1,000.00		20.00
Sub-Total		***52,500.00***	***11,721.34***	***52,500.00***	***22,088.00***	***1,050.00***	***442.00***
Total				**74,588.00**		**1,492.00**	

[a)] Derbala 2002 (unpublished data)

[b)] This cost is area independent

5.4.1.2. Fixed Costs

By distribution distributing these capital costs for mapping over more land and time and using the skills of precision irrigation specialists, the costs could be decreased and the precision activities increased (Table 5.5). The primary extra costs in the technology are the cost of acquiring data and converting it to information or practical (PLC). While this management system is in early stages, it could be expected in the coming years and increase in technology industry, that these extra costs could be minimised.

Table 5.5: Fixed costs €/ha

Item	**Units**	**Capital Cost €**	Sub-Total
Depreciation	10 years	74,588.00	7,458.80 €/year
Interest Rate	3 %	74,588.00	2,237.64 €
Total			**9,696.44 €/year**
Area	50 ha		**193.93 €/ha.year**

5.4.1.3. Mapping Costs

EM38-Measurements (Service from company *Agricon*): **5 €/ha**

Soil Samples (Service from laboratory of Weather Department): **2.7 €/ha**

Agricultural service providers must be increased and identify a group of customers to justify purchasing their services, and once a service provider is established this will help in reducing the extra costs, through distribution over more land.

5.4.2. Water and Energy Savings

- Amount of water saved that could be saved is calculated as follows:

➢ The amount of water that could be saved = 850 – (0.3*610 + 0.6*850 + 0.1*940)

$$= 850 - 787 = \mathbf{63\ m^3/ha}$$

- Energy Costs (kWh/ton Wheat) that could be saved is calculated as follows:

Without precision irrigation implementation:

(850 m^3/ha * 0.63 kWh/m^3) / **(**8 ton Wheat/ha**) = 66.94 kWh/ton Wheat**

With Precision Irrigation implementation:

In order for the solenoid valve to open 0.0105 kWh are needed and the number of valves needed for one ha is 19. The total kWh needed for the solenoid valves is:

0.0105 * 19 = 0.20 kWh

The amount of water to irrigated is 787 m^3/ha and assuming there is no change in yield

[(787 m^3/ha * 0.63 kWh/m^3) **+** 0.2**]**/ **(**8 ton Wheat/ha**) = 62.00 kWh/ton Wheat**

- The amount of energy that could be saved = 66.94 – 62.00 = **4.94 kWh/ton Wheat**

From such preliminary calculations, both water and energy could be saved with the application of precision irrigation.

5.4.3. Other Advantages

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

- 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).

- No value judgement concerning energy saving could be expressed as to the adoption of this new practice, but there could be some savings.

- To these benefits, other savings could also be included, due to reductions in chemicals and fertilisers applied and/or lost rates, when used for chemical and fertiliser application.

- The attitude toward the use of PI anticipates an improvement in yield quality and quantity, which should be assessed and added to the benefits also.

- This management system would exhibit small, but positive, effects on most of the current concerns for the environment. Therefore, environmental protection, the decrease in ecosystem damage, and sustainability of the agricultural resources should be also evaluated and added to the benefits. Among such environmental benefits are low CO_2 evolved to atmosphere due to low energy needs and controlled NO_2 losses to environment.

In conclusion, the economic returns of precision farming and irrigation methods need to be improved before a wide-scale acceptance is reached (Domsch and Giebel, 2001). Regardless of the economic and practical limitations that emerge at the beginning of this new management system, it is believed that it will help in the sustainability and development of the agricultural resources in the present century and will help in environment protection. As a general result concerning the economical analysis of the application of the precision irrigation, these benefits compared to the expenses, whilst modest, have been calculated on conservative assumptions and could be in fact larger, depending upon individual field conditions. Also, agreed 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. The potential of site specific management is in reducing the cost of inputs and environmental impact, but could increase risks.

5.5. Requirements for Precision Irrigation Implementation

Any changes in agricultural practices that are likely to benefit the environment and help in sustainability of resources are, likely to be encouraged rather than discouraged by the public. The attitude towards increased use of precision irrigation, as well as precision farming, will depend on whether it is perceived as having a positive or negative effect on farming practice by reference to environmental and durability influences. For wide implementation and acceptance of precision irrigation technologies, the starting point that should be considered includes preparing a nationwide agricultural development program. This national program should involve and taking into consideration the following:

- This program must depend on the country's own conditions. Because of the distinct regional imbalance in socio-economic development within countries, Germany and Jordan for instance, each country will have to draw its own strategies for using the opportunities provided by precision irrigation and has to identify its strategies and priorities for its development. Also, while countries with well-developed, large scale agriculture, such as Germany, can rely on economical and environmental incentives to promote precision irrigation, these approaches may not work well in less developed countries, such as Jordan, where financial and technological infrastructures are lacking, so governmental supports must step in to help encourage and foster innovation.

- Start planning for precision irrigation should be, also, based on the domestic conditions. Some trial farm projects and demonstration farms should be established targeted at accumulating experiences, demonstrating ideas and disseminating advanced knowledge.

- Most farmers, especially in developed countries, are still engaged in traditional systems with relatively limited application of modern technologies. As much as possible, they will select a rational and feasible approach based on their production conditions and knowledge for renovating conventional farming tools and technologies.

- Social and material for reconstruction traditional systems should be changed dramatically and can be introduced into farming system without too much difficulties or expenses, and reliable and easy to use.

- The poverty of information has become a problem in restricting new advancement, especially in some developing countries. Therefore, great attention should be paid to speeding up information infrastructure construction and translating management knowledge into easily understood multimedia presentations.

- Use of information technologies involves new skills, although the familiarity with computers should be increased rapidly among many users. This is very important in order to minimise the effect of the level of complication involved in the technology components that may create a major barrier to adoption.

- Because eventual implementation of precision irrigation is largely economically controlled, large-scale agribusiness enterprises profit primarily through economics of scale. It could be suggested that landowner co-operatives can enable groups of small operators to obtain technologies that otherwise might be financially prohibitive.

6. Conclusions And Recommendations

The potential to reduce yield variability on one field, optimize input-output relations and save resources like water and energy, appears to be realizable by changing management strategies in the direction of precision farming. Environmental legislation regarding the optimal benefit of inputs, and market pressures for traceability and audit trails in the new decade will force producers to seriously consider precision farming as a solution. Precision irrigation provides the opportunity to decrease input costs and potentially increase net income by applying water at the right place with the right quantity at the right time. Fields that show spatial variability in AWC would benefit from a precision irrigation system which has the ability to vary the amount of water applied. An important future aspect of precision irrigation is to establish delineation strategies for *in-field* spatial variability, analysis techniques and decision aids that can be used by producers. This study focused on an approach for establishing a strategy for precision irrigation; through examining the suitability of EM38 for AWC delineation in the field, changes in irrigation depth in travel direction with mobile-reel irrigation system and the development and implementation of a demonstration unit of an automated, spatially variable centre pivot irrigation system.

Because the extent of the soil's EC is primarily but not only, attributable to the amount of any free moisture in the soil, the established strategy assumed EC_a measured using EM techniques could be used as indicator or surrogated property to quantify *in-field* spatial variability in order to develop more precise variable-rate water application maps. Though this study did not rely on EC_a measurement *per se*, results shown in Section 5.1 demonstrate how EC_a related to AWC, a soil property that could be of interest in precision irrigation. More work will be needed in areas with a wide range of EC_a differences, such as Jordan, to verify these results and establish a standard related EC_a with AWC. 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.

As proposed in the strategy, the variable-rate water application could be fulfilled by using some available technologies, such as speed control systems and regulating discharge rate. As results in Sections 5.2 and 5.3 indicated, speed control systems succeed in adjusting travelling speeds of mobile-reel machines at acceptable accuracy which, in turn, change the amount of applied water exponentially. Results presented in Section 5.4 justified the modifications established to the commercial centre pivot irrigation system using solenoid valves and controlled with PLC to produce variable–rate water application system to irregular-shaped areas. The PLC obtains the positional information and open/close the addressed solenoid valves to obtain the target depth. The concept of pulse irrigation is technically feasible and a viable method of reducing application of water below that determined by the speed of the parent centre pivot 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. Results showed that the PLC was successful in varying the amount of water throughout the field with some deficiencies at the borders due to large throw radius of the nozzle. Also, it was concluded that the PLC was not adequate in its current configuration for the experiments which were to be performed, including fertilization and chemical treatments.

Precision irrigation gives farmers the ability to more effectively use water and other crop inputs including fertilizers and pesticides, which will improve crop yield and/or quality, without polluting the environment. However, it has proven difficult to determine the cost benefits of precision irrigation, since, at present, many of the technologies used are in their infancy, and pricing of equipment and services are hard to pin down. This can make any current economic statements about a particular technology dated. But, as a general statement, the economical and environmental benefits of taking into account within-field spatial variability appear obvious, although they have yet to be generally proved in field trials and experiments. Considerable research and development are needed to realise the potential benefits of site-specific irrigation and to ensure a net economic return to the producers. Also, it is necessary to recall that the added benefits from variable rate application should be weighed against the additional investment and operation costs involved. Evaluation of these expenses is beyond the scope of this paper, and is another important direction into which this research can be profitably extended (Feinermann and Voet 2000). The environmental benefits of decreased chemical inputs are an important part of management that is minimally factored into many farmer decisions and is likely to be increasingly important in the future. This work, that has been mostly qualitative, should be continued with complementary research of more precise quantitative approaches concerning the environmental and economic benefits.

As a recommendation, precision farming or site-specific management as the process of managing variability which, in turn, has a potential to contribute towards improving the overall efficiency of the agronomic process (Earl et al., 1996). This improved efficiency is beneficial to the farm, both economically and environmentally. The use of precision farming for irrigation water management, precision irrigation, is still in the development stages and requires experimental works to determine its feasibility and applicability. This study has focused on an approach for establishing a strategy for precision irrigation. From the reviewed literature and presented results, the following could be recommended for future works:

- The key lesson is the need to develop decision support tools to support producers with additional information to analyze the situation and change their own management strategies (Heermann et al., 2000).

- EC_a measured with EM38 may be used in the future for developing water application maps. But, development in sensing technology may be required, through which direct information could be collected while the machine moves (feedback) and be integrated to the control system to change the amount of irrigated water.

- The aim of varying the application of water throughout a field suggests, water-soluble fertilizers and chemicals can also be variably applied. Therefore, a continuing part of the site-specific irrigation control system must be the application of fertilisers and chemicals using the precision irrigation control system.

- The control programs need to have automatic records on the amount of water applied through the season, the times at which the systems are irrigating, travelling without irrigating, and maintenance down times as well as storage of treatment area databases.

- Site-specific management is the application of information technology to crop production (Plant, 2001). Information, like any other production factor, has both a value and a cost. More generally, in order for the value of site- specific information to exceed the costs of acquiring it, knowledge must exist of how to use that information to appropriately adjust management practices, and this knowledge is still not available at a sufficiently precise level.

- Some preliminary experience is available that permits speculation on its benefits. But, considerable research and development is needed to realise the potential benefits of site-specific irrigation and ensure a net economic return to the producers, in order to give farmers confidence that the use of these technologies is practical and potentially valuable in improving production.

- Methodology for predicting the potential environmental and economical benefits for a particular site is needed to facilitate the adoption and implementation of this technology where appropriate.

- The area that is likely to need continuing development for the foreseeable future is the software to support the farmer while making decisions concerning appropriate treatments and levels of treatment to be spatially applied (Blackmore et al., 1994). Also, software development should be continued to make it easier for the irrigator to convert real-time sensed data into sprinkler control commands for automated implementation of spatially variable water, fertilisers and chemicals application (Duke et al., 1997). Another aspect in this direction is the ability to create/read a treatment map that is stored on a smartcard (credit-sized memory card) or computer disc that is inserted into the controller in the equipment concerned.

7. German Summary (Kurzfassung):

Möglichkeiten und Entwicklung einer teilflächenspezifischen Beregnung

Einleitung

Viele Felder weisen mehr oder weniger starke kleinräumige Bodenunterschiede auf (Werner, 2002). Diese kleinräumigen Standortunterschiede sowie zusätzlich auch bewirtschaftungsbedingte Einflüsse und Effekte führen zu inhomogen aufgebauten Pflanzenbeständen auf den Schlägen und oft auch zu differenzierten Erträgen. Der Landwirt stimmt seine Maßnahmen (Beregnung, Bodenbearbeitung, Düngung, Pflanzenschutz etc.) auf eine durchschnittliche Standortqualität des Schlages ab. Teilflächenspezifisches Management ermöglicht die Standort- und Bestandesunterschiede innerhalb eines Feldes gezielt zu berücksichtigen (Ehlert, 2001; Werner, 2002; Vosshenrich et al., 2001).

In den vergangenen Jahrzehnten war es das Ziel der Forschung und der Industrie, Wasser mit der Beregnungstechnik so gleichmäßig wie möglich auf dem Feld zu verteilen. Mit heutigen Kenntnissen bezüglich der Bodenheterogenität wird der Bedarf nach teilflächenspezifischer Wasserverteilung offenkundig. Gleichzeitig nimmt die Betriebs- und Schlagsgröße zu. Letztere erfordert, neben Bodenbearbeitung, Düngung und Pflanzenschutz, auch eine teilflächen-spezifischen Beregnung. Ziel der teilflächenspezifischen Beregnung ist es, durch Berücksichtigung der ortspezifischen Heterogenität des Bodens und des Pflanzenbestandes den Produktbezogenen Aufwand, hier Wasser und Energie, zu reduzieren und Umweltziele besser einzubeziehen (Sourell und Sommer, 2002).

Teilflächenspezifische Beregnung und entsprechendes Management erfordern detaillierte Informationen über die Heterogenität von Feldern, um die Beregnungshöhe den lokal variierenden Bodenverhältnissen anpassen zu können. Konventionelle Methoden (Bodenproben, u. anschließende Laboranalyse) sind jedoch zu teuer und zu zeitaufwendig. Es sollten schnelle, berührungsfreie Methoden zur Ermittlung der benötigten Informationen verfügbar sein. Durch elektromagnetische Induktion oder Fernerkundungsaufnahmen könnte dieses Ziel zu erreichen sein (Ehlert, 2001).

Messungen der scheinbaren elektrischen Leitfähigkeit (EC_a) des Bodens stellen eine schnelle Methode zur Ermittlung von Bodenunterschieden dar, und die ermittelten EC-Werte können mit verschiedenen anderen Informationsquellen verglichen werden (Dammer et al., 2001; Domsch, 2001 a und b; Domsch und Giebel, 2001). EC- Messungen werden schon längere Zeit durchgeführt, und die bisherigen Ergebnisse lassen erkennen, daß die EC-Karte direkt in teilflächenspezifische Beregnung umgesetzt werden kann. Dieses Verfahren ist weitgehend unabhängig von den Jahreszeiten, d.h. die Kartierung kann zu jeder Zeit während des Jahres durchgeführt werden (Domsch, 2001 a und b; Domsch und Giebel, 2001).

Mit dieser Arbeit werden erste Schritte zum Aufbau und zur Umsetzung einer Strategie zu *precision irrigation* vorgestellt. Die Einbeziehung ortspezifischer Heterogenität des Bodens und des Pflanzenbestandes soll Aufwand von Wasser und Energie reduzieren und Umweltziele berücksichtigen. Differenzierte Beregnungshöhen sollen über die zu beregnende Fläche verteilt werden. Für Beregnungsmaschinen sind zwei unterschiedliche Lösungswege im Versuchsstadium. Für mobile Beregnungsmaschinen wird eine differenzierte Einzugsgeschwindigkeit und für Kreisberegnungsmaschinen eine differenzierte Ansteuerung jeder Düse untersucht.

Material und Methoden

Der Weg zur Applikationskarte geht über die Hofbodenkarte, die elektrische Leitfähigkeit (EM38) und die Entnahme von Bodenproben zur punktuellen Bestimmung der Bodenwasserspeicherfähigkeit (Abb. 3.1). Die technische Umsetzung erfolgt mit mobilen Beregnungs- und Kreisberegnungsmaschinen. Entsprechend sind zwei unterschiedliche Lösungswege im Versuchsstadium. Für mobile Beregnungsmaschinen wird eine Veränderung der Einzuggeschwindigkeit über die zu beregnende Feldlänge vorgeschlagen. Bei konstantem Durchfluß ergibt sich daraus eine unterschiedliche Beregnungshöhe in Arbeitsrichtung bei relativ geringer Arbeitsbereite. Die differenzierte Einstellung der Geschwindigkeit pro Schlag kann an der Maschine gespeichert oder vom Betriebsleiter eingestellt werden. Der zweite Weg wird für die Kreisberegnungsmaschine beschritten: die Beregnungsgabe ist durch Öffnen und Schließen jeder einzelnen Düse zu variieren.

Variabilitätsbestimmung:

Es wurden drei Felder (je ca. 6 ha) auf der Versuchsstation der FAL ausgewählt. Die Besonderheit von *precision irrigation* gegenüber bisherigen Produktionstechniken besteht in einer sehr intensiven Nutzung von spezifischen und umfangreichen Daten über den Standort und den Pflanzenbestand. Erste Informationen sind in der Hofbodenkarte enthalten. Diese Angaben sind aber zu grob, um sie als teilflächenspezifische Applikationskarte zu nutzen. Für die EM38 Messungen wurden die Felder im 5 m Spurabstand befahren, und jedem EC-Wert wurde ein GPS Wert zugeordnet (Abb. 4.1). Aus diesen Werten wurden Leitfähigkeitskarten erstellt, die Grundlage für die Auswahl von Monitoringpunkten war. An diesen Punkten wurde die Feldkapazität (FK) und der Welkepunkt (WP) bestimmt.

Einzugsgeschwindigkeit

Um die Einzugsgeschwindigkeit einzustellen und zu kontrollieren, sind Steuerungssysteme auf dem Markt verfügbar. Diese Geräte wurden bisher überwiegend nur für die Steuerung einer konstanten Einzugsgeschwindigkeit benutzt. Für die Versuche wurden vier verschiedene Geschwindigkeiten 32, 16, 24, 40 m/h vorprogrammiert. Die Versuche zur Übereinstimmung der Einzugsgeschwindigkeit zwischen programmiert und gemessen wurden über eine Meßstrecke von 100 m durchgeführt und mit der Frage, wie ändert sich die Beregnungshöhe mit der gewählten Geschwindigkeit? In Regenmeßbechern mit einem Gitterabstand von 1x1 m wurde die Beregnungshöhe gemessen.

Durchfluß

Bei Kreisberegnungsmaschinen wurde eine Ansteuerung jeder Düse (Abstand 3 m) durchgeführt. Vor jeder Düse wurde ein Magnetventil installiert (Abb. 4.4). Grundlage für das Öffnen bzw. Schließen der einzelnen Düse ist die Applikationskarte (Abb.4.7). Ein „Programmable Logic Control System (PLC)“ wurde am Institut entwickelt, um die Applikationskarte als Datei zu speichern (Abb. 4.4). Die Postitionsbestimmung der Maschine wird am Zentralturm mit einem Drehsensor bestimmt. Pro Grad wird die Position festgestellt, und in Abhängigkeit von der Entfernung vom Mittelpunkt der Maschine zur Düse werden die Magnetventile geschaltet. Die Fahrgeschwindigkeit der Maschine war konstant. Variiert wurde der Durchfluß und somit die Beregnungshöhe. Die Beregnungshöhe wird in handelsüblichen Messbechern gemessen. Dazu sind die Messbecher im 1 Grad Abstand und dreifacher Wiederholung strahlenförmig aufgebaut.

Ergebnisse

Bodenwasserunterschiede

Die Ergebnisse der elektrischen Leitfähigkeit liegen in mS-Werten vor, die in drei Klassen dargestellt werden. In Abbildung 5.1 werden die Unterschiede in der Leitfähigkeit dargestellt. Die Ergebnisse der FK, WP und nFK für die Monitoringpunkte sind in Tabelle 5.1 enthalten. Es zeigt sich, dass sich die gemessenen Differenzen der Leitfähigkeit auch in den Messergebnissen der nFK widerspiegeln. Ein kausaler Zusammenhang kann noch nicht gegeben werden.

Anpassung der Beregnungshöhen durch Geschwindigkeitswahl

Nach Vorliegen der Applikationskarte sind unterschiedliche Beregnungshöhen über die zu beregnende Fläche zu verteilen, um die ungleiche Wasserspeicherfähigkeit des Bodens zu berücksichtigen.

In Abbildung 5.8 ist beispielhaft ein Geschwindigkeitswechsel für die Linearberegnungsmaschine von 32 auf 16 m/h eingestellt. Die Beregnungshöhe steigt dann von 22 mm auf 45 mm. Es wurden auch Versuche mit andern Einstellungen durchgeführt, die zu ähnlichen guten Ergebnissen führten. Die Geschwindigkeit ändert sich innerhalb von 2 m, dagegen wurde für die Änderung der Beregnungshöhe ein Übergangsbereich von ca. 16 m benötigt. Dieser Bereich wurde unter einem Düsenwagen gemessen. Bei einem Einsatz eines Großflächenregners würde dieser Übergangsbereich größer werden.

Es erscheint möglich, mit mobilen Beregnungsmaschinen unterschiedliche Beregnungshöhen in Abhängigkeit von Boden und/oder Pflanzen zu verteilen.

Anpassung der Beregnungshöhe durch Durchflussveränderung

Grundlage für die differenzierte Beregnung mit einer Kreisberegnungsmaschine ist wieder die Applikationskarte. Auf der Fläche eines ausgewählten Kreissektors wurde die theoretisch berechnete und im PLC programmierte Beregnungshöhe überprüft. In Abbildung 5.13 ist die berechnete und gemessene Beregnungshöhe entlang der Rohrleitung einer Kreisberegnungsmaschine aufgetragen. Diese ersten Versuche zeigen eine gute Übereinstimmung der Soll- und Ist-Werte. Der flache Anstieg oder Abfall der Wasserverteilung ist auf die Wurfweite der Düsen mit ca. 8 m zurückzuführen. Dieser Verlauf ist positiv zu bewerten, da die Bodenunterschiede auch keine Treppenfunktion aufweisen.

Schlußfolgerung

Entsprechend der Zielsetzung der Arbeit konnten für mobile Beregnungsmaschinen und Kreisberegnungsmaschinen technische Lösungen zur teilflächenspezifischen Verteilung von Wasser aufgezeigt werden.

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9. APPENDICES

Appendix A1: Soil available water content at the three fields in the FAL.

Field-Site	Depth cm	FC	PWP	FC-PWP	Bulk Density	Vol.	AWC
		%			g/cm^3	%	mm
F1-1	0-60	15.5	3.4	12.1	1.61	19.50	117.01
F1-1	60-90	9.9	3.1	6.8			
F1-2	0-60	14.2	3.6	10.6	1.61	17.15	102.88
F1-2	60-90	16.4	3.1	13.3			
F1-3	0-60	14.4	2.7	11.7	1.61	18.87	113.20
F1-3	60-90	7.0	2.0	5.0			
F1-4	0-60	12.2	3.0	9.2	1.61	14.76	88.58
F1-4	60-90	8.7	3.5	5.2			
F1-5	0-60	13.8	2.8	11.0	1.61	17.69	106.17
F1-5	60-90	8.4	1.9	6.5			
F1-6	0-60	13.2	3.1	10.1	1.61	16.33	98.00
F1-6	60-90	7.7	1.8	5.9			
F1-7	0-60	14.2	3.4	10.8	1.61	17.44	104.64
F1-7	60-90	7.9	3.2	4.7			
F1-8	0-60	15.3	3.5	11.8	1.61	18.97	113.84
F1-8	60-90	17.8	5.2	12.6			
F1-9	0-60	12.9	3.0	9.9	1.61	15.99	95.96
F1-9	60-90	12.6	2.4	10.2			
F2-1	0-60	15.1	3.5	11.6	1.53	17.72	106.35
F2-1	60-90	12.4	4.9	7.5			
F2-2	0-60	16.4	3.9	12.5	1.53	19.06	114.37
F2-2	60-90	12.7	3.1	9.6			
F2-3	0-60	17.0	3.7	13.3	1.53	20.41	122.46
F2-3	60-90	11.3	6.8	4.5			
F2-4	0-60	17.1	4.1	13.0	1.53	19.86	119.17
F2-4	60-90	14.1	2.3	11.8			
F2-5	0-60	17.2	4.3	12.9	1.53	19.79	118.74
F2-5	60-90	14.0	3.0	11.0			
F2-6	0-60	16.1	3.1	13.0	1.53	19.83	119.01
F2-6	60-90	13.9	2.4	11.5			
F2-7	0-60	15.1	3.5	11.6	1.53	17.81	106.84
F2-7	60-90	12.8	2.5	10.3			
F2-9	0-60	18.9	5.6	13.3	1.53	20.34	122.06
F2-9	60-90	9.5	4.6	4.9			
F2-10	0-60	16.7	3.0	13.7	1.53	21.02	126.14
F2-10	60-90	13.6	2.1	11.5			
F2-11	0-60	17.3	3.5	13.8	1.53	21.12	126.71
F2-11	60-90	15.3	2.7	12.6			
F2-12	0-60	16.7	3.1	13.6	1.53	20.79	124.71
F2-12	60-90	11.9	3.4	8.5			

Appendix A1: Cont'd

F3-2	0-60	11.0	2.3	8.7	1.50	13.03	78.15
F3-2	60-90	8.7	1.5	7.2			
F3-4	0-60	12.2	3.2	9.0	1.50	13.46	80.75
F3-4	60-90	11.2	2.2	9.0			
F3-5	0-60	12.5	3.6	8.9	1.50	13.38	80.27
F3-5	60-90	8.4	3.5	4.9			
F3-8	0-60	10.7	2.9	7.8	1.50	11.69	70.11
F3-8	60-90	6.1	1.0	5.1			
F3-10	0-60	10.1	1.6	8.5	1.50	12.71	76.24
F3-10	60-90	9.7	1.1	8.6			

Appendix B1: Speed measurements using PROGRAM RAIN 9 control system.

Replicate 1			
Distance (m)		Time (min)	Speed (m/h)
1	1	205	29.3
1	2	206	29.1
1	3	200	30.0
1	4	199	30.2
1	5	197	30.5
1	6	203	29.6
1	7	210	28.6
1	8	211	28.4
5	13	995	30.2
1	14	191	31.4
1	15	208	28.8
1	16	207	29.0
1	17	205	29.3
1	18	191	31.4
5	23	984	30.5
1	24	225	26.7
1	25	218	27.5
1	26	295	20.3
1	27	421	14.3
1	28	415	14.5
5	33	1905	15.7
1	34	383	15.7
1	35	389	15.4
1	36	375	16.0
1	37	375	16.0
1	38	385	15.6
5	43	1987	15.1
1	44	370	16.2
1	45	340	17.6
1	46	241	24.9
1	47	231	26.0
1	48	245	24.5
5	53	1293	23.2
1	54	265	22.6
1	55	278	21.6
1	56	271	22.1
1	57	257	23.3
1	58	265	22.6
5	63	1319	22.7
1	64	255	23.5
1	65	248	24.2
1	66	161	37.3
1	67	156	38.5

Replicate 2			
Distance (m)		Time (min)	Speed (m/h)
1	1	202	29.7
5	6	1048	28.6
1	7	203	29.6
1	8	204	29.4
1	9	194	30.9
1	10	195	30.8
1	11	196	30.6
5	16	911	32.9
1	17	200	30.0
1	18	198	30.3
1	19	203	29.6
1	20	201	29.9
1	21	204	29.4
1	22	195	30.8
1	23	191	31.4
1	24	190	31.6
1	25	191	31.4
1	26	370	16.2
1	27	405	14.8
1	28	465	12.9
1	29	450	13.3
1	30	435	13.8
1	31	407	14.7
5	36	1639	18.3
1	37	390	15.4
1	38	400	15.0
1	39	378	15.9
1	40	360	16.7
1	41	380	15.8
1	42	410	14.6
1	43	397	15.1
1	44	395	15.2
1	45	385	15.6
1	46	264	22.7
1	47	240	25.0
1	48	242	24.8
1	49	238	25.2
1	50	233	25.8
1	51	235	25.5
5	56	1110	27.0
1	57	255	23.5
1	58	265	22.6
1	59	273	22.0

Appendix B1: Cont'd

1	68	156	38.5
1	69	153	39.2
5	74	820	36.6
1	75	160	37.5
1	76	155	38.7
1	77	152	39.5
1	78	151	39.7
1	79	156	38.5
5	84	820	36.6
1	85	154	39.0
1	86	155	38.7
1	87	154	39.0
1	88	163	36.8
1	89	160	37.5
1	90	318	37.7
1	91	301	39.9
1	92	162	37.0
1	93	160	37.5
2	95	309	38.8
1	96	200	30.0
1	97	222	27.0
1	98	227	26.4
1	99	225	26.7
1	100	210	28.6
1	101	200	30.0
1	102	205	29.3
1	103	214	28.0
1	104	222	27.0
1	105	226	26.5
1	106	223	26.9

1	60	235	25.5
1	61	225	26.7
1	62	225	26.7
1	63	222	27.0
1	64	245	24.5
1	65	271	22.1
1	66	190	31.6
1	67	188	31.9
1	68	180	33.3
1	69	147	40.8
1	70	158	38.0
1	71	150	40.0
1	72	165	36.4
1	73	168	35.7
1	74	162	37.0
1	75	168	35.7
1	76	157	38.2
1	77	138	43.5
1	78	172	34.9
1	79	162	37.0
1	80	145	41.4
1	81	160	37.5
1	82	163	36.8
1	83	166	36.1
1	84	165	36.4
1	85	145	41.4
2	87	287	41.8
1	88	140	42.9
1	89	146	41.1
1	90	155	38.7
1	91	168	35.7
1	92	168	35.7
1	93	148	40.5
1	94	146	41.1
1	95	146	41.1
1	96	155	38.7
1	97	165	36.4
1	98	168	35.7
1	99	199	30.2
1	100	201	29.9
1	101	210	28.6
1	102	225	26.7
1	103	211	28.4

Appendix B2: Speed measurements using IRRIGMATIC 350 control system

Replicate 1				Replicate 2			
Distance (m)		Time (min)	Speed (m/h)	Distance (m)		Time (min)	Speed (m/h)
1	1	189	31.7	1	1	135	44.4
1	2	191	31.4	1	2	168	35.7
1	3	189	31.7	1	3	187	32.1
1	4	190	31.6	1	4	191	31.4
1	5	191	31.4	1	5	190	31.6
5	10	954	31.4	1	6	195	30.8
1	11	192	31.3	1	7	199	30.2
1	12	193	31.1	1	8	185	32.4
1	13	184	32.6	5	13	938	32.0
1	14	185	32.4	1	14	192	31.3
1	15	189	31.7	1	15	190	31.6
5	20	956	31.4	1	16	191	31.4
1	21	193	31.1	1	17	189	31.7
1	22	185	32.4	1	18	190	31.6
1	23	188	31.9	2	20	379	31.7
1	24	194	30.9	2	22	379	31.7
1	25	321	18.7	1	23	189	31.7
1	26	380	15.8	1	24	241	24.9
1	27	385	15.6	1	25	399	15.0
1	28	374	16.0	1	26	360	16.7
1	29	385	15.6	5	31	1920	15.6
1	30	378	15.9	1	32	389	15.4
5	35	1903	15.8	1	33	370	16.2
1	36	391	15.3	1	34	380	15.8
1	37	384	15.6	1	35	381	15.7
1	38	378	15.9	1	36	371	16.2
1	39	384	15.6	5	41	1900	15.8
1	40	378	15.9	1	42	386	15.5
1	41	377	15.9	1	43	381	15.7
1	42	384	15.6	1	44	290	20.7
1	43	381	15.7	1	45	266	22.6
1	44	365	16.4	1	46	240	25.0
1	45	255	23.5	2	48	512	23.4
1	46	253	23.7	2	50	509	23.6
1	47	256	23.4	1	51	260	23.1
1	48	260	23.1	1	52	249	24.1
1	49	251	23.9	1	53	262	22.9
1	50	254	23.6	1	54	254	23.6
5	55	1225	24.5	5	59	1279	23.5
1	56	256	23.4	1	60	244	24.6
1	57	252	23.8	1	61	255	23.5
1	58	253	23.7	1	62	237	25.3
1	59	251	23.9	1	63	246	24.4
1	60	250	24.0	1	64	190	31.6

Appendix B2: Cont'd

1	61	252	23.8
1	62	255	23.5
1	63	254	23.6
1	64	251	23.9
1	65	251	23.9
1	66	252	23.8
1	67	182	33.0
1	68	150	40.0
1	69	154	39.0
1	70	154	39.0
1	71	154	39.0
1	72	153	39.2
1	73	153	39.2
1	74	150	40.0
5	79	770	39.0
1	80	149	40.3
1	81	150	40.0
1	82	150	40.0
1	83	151	39.7
1	84	151	39.7
5	89	758	39.6

1	65	143	42.0
1	66	155	38.7
1	67	156	38.5
1	68	152	39.5
1	69	150	40.0
1	70	152	39.5
1	71	150	40.0
1	72	151	39.7
1	73	152	39.5
1	74	150	40.0
1	75	156	38.5
1	76	149	40.3
5	81	757	39.6
5	86	760	39.5

Appendix C1: Measurement of change in depth of water applied (mm) with change in speed from 32 to 16 m/h.

Distance (m)	Row 1	2	3	4	5	6	Average (mm)	Distance (m)	Speed (m/h)
13	24.0	21.0	20.0	19.0	21.0	24.0	21.5	1	39.5
14	23.0	21.0	20.0	20.0	22.5	22.5	21.5	2	30.5
15	24.0	20.5	19.5	20.0	22.0	23.0	21.5	3	31.9
16	23.5	21.5	20.0	19.5	21.5	23.0	21.5	4	31.3
17	23.0	21.0	19.0	19.0	22.0	22.5	21.1	5	31.7
18	24.5	21.0	18.5	19.5	22.0	23.0	21.4	6	31.4
19	25.0	20.0	18.0	19.0	22.5	23.0	21.3	7	31.1
20	24.0	21.0	18.0	20.0	24.0	24.0	21.8	8	31.1
21	24.0	23.0	18.0	23.0	26.0	25.0	23.2	9	31.1
22	26.5	26.0	19.5	24.5	25.5	24.5	24.4	10	31.3
23	34.0	27.0	21.0	24.0	26.5	28.0	26.8	15	31.2
24	33.0	30.5	23.0	26.0	29.0	29.0	28.4	20	31.3
25	40.0	35.0	28.0	25.5	30.0	31.0	31.6	22	30.5
26	39.0	34.0	27.5	27.5	33.0	33.0	32.3	23	31.7
27	39.0	42.0	27.5	29.5	32.0	35.0	34.2	24	31.4
28	37.0	34.0	30.0	30.0	38.0	40.5	34.9	25	30.6
29	41.0	38.0	31.0	35.0	42.0	37.0	37.3	26	31.3
30	41.0	36.0	31.0	36.5	41.5	41.0	37.8	27	23.2
31	43.0	35.0	33.0	35.5	41.0	44.0	38.6	28	15.4
32	45.0	40.0	33.0	38.0	42.0	44.0	40.3	29	15.5
33	46.0	42.0	36.0	39.0	46.0	51.0	43.3	30	15.4
34	47.0	43.0	40.0	42.0	42.0	48.0	43.7	31	15.6
35	51.0	46.0	40.5	42.0	46.0	48.0	45.6	38	15.4
36	48.0	44.0	39.0	43.5	37.0	49.0	43.4	39	17.2
37	47.0	42.0	38.0	43.0	47.0	45.0	43.7	40	14.0
38	47.0	38.0	39.0	37.0	43.0	44.0	41.3	41	15.5
39	45.5	35.0	37.0	41.0	45.0	44.5	41.3	42	14.5
40	46.0	42.0	34.0	40.0	46.0	46.0	42.3	43	14.6
41	46.0	40.0	36.0	45.0	48.0	47.0	43.7	48	15.5
42	40.0	44.0	39.0	43.0	46.0	46.0	43.0	51	15.7
								52	16.4

Appendix C2: Measurement of change in depth of water applied (mm) with change in speed from 24 to 40 m/h.

Distance (m)	Row 1	2	3	4	5	6	Average (mm)	Distance (m)	Speed (m/h)
10	28.0	28.0	24.0	24.5	27.5	31.0	27.2	1	22.8
11	29.0	26.5	26.5	24.0	25.5	29.5	26.8	2	24.6
12	27.0	28.5	28.0	23.5	27.0	27.5	26.9	3	23.3
13	28.0	28.0	27.0	23.0	25.5	30.5	27.0	4	23.4
14	23.5	26.5	23.0	22.0	24.5	27.5	24.5	5	22.2
15	23.0	23.0	21.5	22.5	24.0	26.0	23.3	6	23.9
16	20.5	21.5	22.0	22.0	23.0	25.5	22.4	7	24.1
17	21.0	20.5	20.0	20.0	23.0	26.0	21.8	8	23.0
18	22.0	21.0	19.0	19.0	23.0	23.5	21.3	13	23.3
19	20.0	20.0	18.0	18.5	20.0	23.0	19.9	14	23.6
20	21.0	19.0	18.0	19.0	20.0	20.0	19.5	15	23.6
21	17.5	17.5	15.5	16.5	18.5	19.5	17.5	16	23.5
22	17.0	16.0	15.5	16.5	19.5	19.0	17.3	17	23.3
23	16.5	13.5	14.0	16.0	18.5	20.0	16.4	18	23.1
24	16.5	16.0	15.0	16.0	19.0	18.5	16.8	19	23.6
25	16.0	14.0	12.0	14.5	17.5	17.0	15.2	20	23.5
26	15.5	15.0	13.5	16.0	16.0	17.0	15.5	21	34.5
27	16.0	15.0	13.0	14.0	18.0	17.5	15.6	22	39.7
28	16.0	13.0	12.5	14.5	17.0	17.0	15.0	23	40.0
29	16.0	14.5	13.0	14.5	18.0	17.0	15.5	24	39.2
30	15.0	14.0	14.0	14.5	16.5	17.5	15.3	25	38.5
31	14.0	13.0	13.0	14.0	17.0	16.5	14.6	26	37.3
32	15.0	13.5	12.5	14.0	17.5	18.0	15.1	27	38.7
33	15.0	13.5	13.5	13.5	16.5	18.0	15.0	28	40.3
34	14.0	13.5	14.0	14.5	16.5	18.0	15.1	29	40.0
35	13.0	13.0	13.0	16.0	17.0	17.0	14.8	33	38.8
36	14.0	13.0	14.0	16.0	18.0	19.0	15.7	37	38.1
37	15.5	14.5	15.0	16.5	17.5	19.5	16.4	38	40.0
38	16.0	14.0	14.5	16.5	17.0	22.0	16.7	40	38.7
39	15.0	15.0	15.0	16.0	17.0	20.0	16.3	41	37.5
								43	39.9

Appendix C3: Measurement of change in depth of water applied (mm) with change in speed from 16 to 24 m/h.

Distance (m)	Row 1	2	3	4	5	6	Average (mm)	Distance (m)	Speed (m/h)
16	34.0	34.0	33.0	40.0	41.5	41.0	37.3	1	15.9
17	39.5	37.0	39.5	33.0	36.0	43.0	38.0	2	15.4
18	42.0	38.0	42.0	42.0	45.0	43.0	42.0	4	15.4
19	44.0	36.0	44.0	37.5	43.5	50.0	42.5	5	16.7
20	35.0	37.5	40.0	41.0	43.0	45.0	40.3	6	14.6
21	38.0	31.0	37.0	44.0	42.0	46.0	39.7	7	15.9
22	32.0	32.0	43.0	37.0	40.0	48.0	38.7	8	15.3
23	38.0	33.0	38.0	41.0	40.0	53.0	40.5	9	16.0
24	40.0	37.0	39.0	43.0	48.0	47.0	42.3	16	15.5
25	35.0	35.0	35.0	46.0	45.0	49.0	40.8	17	16.5
26	41.0	34.0	38.0	42.0	44.0	44.0	40.5	18	14.2
27	34.0	37.0	34.0	38.0	39.0	40.0	37.0	19	16.2
28	33.0	31.0	34.0	39.0	43.0	46.0	37.7	20	15.6
29	32.0	25.0	30.0	33.0	34.0	42.0	32.7	21	15.4
30	34.0	30.0	31.0	36.0	39.0	40.0	35.0	22	15.6
31	27.0	26.0	26.0	33.0	37.0	39.0	31.3	23	15.7
32	28.0	26.0	29.0	34.0	32.0	35.0	30.7	24	14.9
33	27.0	26.0	27.0	31.0	33.0	31.0	29.2	25	16.6
34	28.0	24.0	27.0	31.0	30.0	33.0	28.8	26	14.9
35	27.0	27.0	27.0	29.0	30.0	33.0	28.8	27	16.2
36	26.0	25.0	26.0	30.0	28.0	28.0	27.2	28	15.2
37	24.0	21.0	25.0	24.0	27.0	26.0	24.5	29	15.7
38	24.0	24.0	21.0	25.0	29.0	26.0	24.8	30	16.0
39	26.0	21.0	22.0	22.0	27.0	28.0	24.3	31	15.2
40	22.0	24.0	24.0	25.0	25.0	27.0	24.5	32	19.7
41	23.0	24.0	24.0	27.0	28.0	26.0	25.3	33	23.3
42	23.0	20.0	26.0	26.0	31.0	27.0	25.5	34	23.1
43	24.0	22.0	25.0	27.0	29.0	30.0	26.2	35	24.5
44	24.0	23.0	22.0	26.0	27.0	26.0	24.7	36	23.2
45	26.0	25.0	26.0	25.0	27.0	30.0	26.5	37	22.8
								39	23.6
								49	23.4

Appendix D1: Radial water distribution after installation the Solenoid valves.

Distance (m)	Rep. 1 (mm)				Rep. 2 (mm)			
	Row 1	2	3	Average	Row 1	2	3	Average
6	18.5	18.5	18.0	18.3	20.0	20.5	19.0	19.8
7	19.5	21.0	20.5	20.3	22.0	22.0	21.0	21.7
8	25.5	25.5	25.5	25.5	25.0	24.5	24.5	24.7
9	25.5	25.0	24.0	24.8	26.0	26.0	25.5	25.8
10	24.5	25.5	23.5	24.5	24.0	25.0	25.5	24.8
11	25.0	25.5	23.5	24.7	25.0	25.0	23.5	24.5
12	22.5	22.5	22.5	22.5	25.5	24.0	24.5	24.7
13	25.5	25.5	25.0	25.3	24.5	24.0	24.5	24.3
14	23.5	22.5	23.0	23.0	24.0	23.5	23.0	23.5
15	25.0	23.5	23.0	23.8	26.0	24.5	24.5	25.0
16	22.5	22.5	23.0	22.7	23.0	23.0	23.0	23.0
17	24.0	24.5	23.5	24.0	24.0	23.0	23.5	23.5
18	22.5	25.5	25.5	24.5	24.5	24.5	25.0	24.7
19	21.5	21.5	21.5	21.5	24.0	22.5	23.0	23.2
20	23.0	22.5	23.5	23.0	23.5	22.5	22.5	22.8
21	25.5	24.5	25.5	25.2	24.0	23.5	23.5	23.7
22	23.5	23.5	23.5	23.5	25.5	25.0	24.0	24.8
23	25.0	24.5	25.5	25.0	24.0	24.5	24.0	24.2
24	24.0	23.5	24.5	24.0	24.0	24.5	23.5	24.0
25	22.5	23.0	21.5	22.3	23.0	24.5	23.0	23.5
26	24.5	25.5	25.5	25.2	22.5	23.5	23.0	23.0
27	24.0	24.5	25.5	24.7	24.0	23.5	24.5	24.0
28	23.0	24.5	22.5	23.3	24.5	24.5	24.0	24.3
29	24.5	25.5	24.0	24.7	24.0	24.5	23.5	24.0
30	24.5	25.5	25.5	25.2	24.0	24.0	24.5	24.2
31	24.5	25.5	24.5	24.8	25.0	25.5	24.5	25.0
32	23.5	23.5	22.5	23.2	25.0	25.5	24.5	25.0
33	23.5	24.0	22.5	23.3	24.0	23.5	23.0	23.5
34	25.0	25.5	24.5	25.0	25.0	24.5	24.5	24.7
35	22.5	23.5	23.0	23.0	24.0	24.5	24.0	24.2
36	25.0	23.0	24.5	24.2	23.0	22.5	23.0	22.8
37	25.5	27.5	28.5	27.2	24.0	25.0	25.5	24.8
38	22.5	22.0	21.5	22.0	23.0	23.0	22.5	22.8
39	21.5	22.0	23.5	22.3	22.0	22.5	22.0	22.2
40	25.0	23.0	23.5	23.8	23.5	22.0	23.5	23.0
41	22.0	23.5	24.5	23.3	22.0	24.0	23.5	23.2
42	21.5	22.0	22.0	21.8	22.0	22.0	21.0	21.7
43	23.5	24.0	23.5	23.7	23.0	23.0	22.0	22.7
44	21.5	21.5	23.5	22.2	23.0	23.0	23.0	23.0
45	17.5	18.5	18.5	18.2	18.0	19.5	19.0	18.8

Appendix D1: Cont'd

Rep. 3 (mm)				Rep. 4 (mm)			
Row 1	2	3	Average	Row 1	2	3	Average
21.5	23.0	18.5	21.0	20.0	20.5	18.0	19.5
23.5	23.5	22.5	23.2	21.5	22.0	21.5	21.7
25.5	24.5	24.5	24.8	25.5	25.0	25.0	25.2
26.0	25.5	26.5	26.0	25.0	25.5	25.0	25.2
24.5	25.5	27.5	25.8	24.5	25.5	25.5	25.2
26.0	24.5	23.5	24.7	25.5	25.0	23.5	24.7
28.5	24.5	24.0	25.7	25.5	23.5	23.5	24.2
25.0	24.5	24.5	24.7	25.5	25.0	24.5	25.0
23.0	23.5	22.0	22.8	23.5	23.0	22.5	23.0
27.5	24.5	24.0	25.3	26.0	24.0	23.5	24.5
24.0	23.0	23.0	23.3	23.5	23.0	23.0	23.2
24.5	21.5	21.5	22.5	24.0	23.0	22.5	23.2
26.0	25.0	24.0	25.0	24.0	25.0	24.5	24.5
26.0	21.0	21.5	22.8	23.5	22.0	21.5	22.3
24.0	22.0	21.5	22.5	23.5	23.0	22.5	23.0
23.5	21.5	20.5	21.8	24.5	23.0	23.0	23.5
27.5	25.5	21.5	24.8	25.5	24.5	22.5	24.2
22.0	22.5	22.0	22.2	23.5	23.5	24.0	23.7
22.5	24.0	21.5	22.7	23.0	24.0	23.0	23.3
24.5	25.5	21.5	23.8	23.5	24.0	21.5	23.0
20.5	21.5	19.5	20.5	22.5	23.5	22.5	22.8
22.5	21.5	21.5	21.8	23.5	23.0	23.5	23.3
25.5	23.5	24.5	24.5	24.5	24.0	23.5	24.0
24.5	22.5	21.5	22.8	24.5	24.0	23.0	23.8
23.5	22.5	23.0	23.0	24.0	24.0	24.5	24.2
25.0	25.0	23.5	24.5	25.0	25.0	24.0	24.7
26.0	25.5	24.0	25.2	25.0	24.5	23.5	24.3
23.5	22.0	22.5	22.7	23.5	23.0	22.5	23.0
24.0	22.5	23.5	23.3	24.5	24.0	24.0	24.2
23.5	24.5	23.5	23.8	23.0	24.0	23.5	23.5
20.5	21.0	20.5	20.7	23.0	22.0	22.5	22.5
22.5	22.5	23.5	22.8	24.0	25.0	26.0	25.0
24.0	22.5	22.5	23.0	23.0	23.0	22.0	22.7
24.5	22.0	21.0	22.5	23.0	22.0	22.5	22.5
22.5	20.5	24.5	22.5	23.5	22.0	24.0	23.2
22.5	24.5	22.5	23.2	22.5	24.0	23.5	23.3
22.0	22.0	20.5	21.5	22.0	22.0	21.0	21.7
22.5	21.5	21.5	21.8	23.0	23.0	22.5	22.8
24.5	23.5	22.5	23.5	23.0	22.5	23.0	22.8
19.5	20.5	19.5	19.8	18.5	19.5	19.0	19.0

Appendix D1: Cont'd

Rep. 5 (mm)				**Base (mm)**
Row 1	2	3	Average	
21.0	20.0	21.0	20.7	**19.9**
22.0	22.0	22.0	22.0	**21.8**
23.0	23.5	24.0	23.5	**24.7**
27.5	28.0	27.0	27.5	**25.9**
24.0	23.5	25.0	24.2	**24.9**
25.0	24.0	23.0	24.0	**24.5**
26.5	25.5	26.5	26.2	**24.6**
22.5	22.5	23.5	22.8	**24.4**
25.0	23.5	23.5	24.0	**23.3**
26.0	26.0	26.5	26.2	**25.0**
23.0	23.0	23.0	23.0	**23.0**
23.5	23.5	23.0	23.3	**23.3**
25.0	26.0	25.0	25.3	**24.8**
25.0	24.5	24.5	24.7	**22.9**
23.5	22.0	22.5	22.7	**22.8**
23.0	25.0	24.5	24.2	**23.7**
26.0	27.5	27.5	27.0	**24.9**
25.0	24.5	24.5	24.7	**23.9**
25.5	26.5	25.0	25.7	**23.9**
23.0	26.0	24.5	24.5	**23.4**
23.0	23.0	23.0	23.0	**22.9**
25.0	25.5	26.0	25.5	**23.9**
25.0	25.5	26.0	25.5	**24.3**
23.5	25.0	25.0	24.5	**24.0**
24.5	24.0	25.0	24.5	**24.2**
25.5	26.5	26.5	26.2	**25.0**
26.5	27.5	27.0	27.0	**24.9**
24.0	23.5	24.5	24.0	**23.3**
26.0	25.0	26.5	25.8	**24.6**
26.0	25.0	24.5	25.2	**23.9**
23.5	23.0	23.0	23.2	**22.7**
25.0	24.0	25.0	24.7	**24.9**
23.5	23.5	24.0	23.7	**22.8**
20.5	21.0	20.5	20.7	**22.0**
24.0	22.5	23.5	23.3	**23.2**
23.5	24.0	23.5	23.7	**23.3**
22.0	22.0	23.0	22.3	**21.8**
23.0	23.5	23.5	23.3	**22.9**
23.5	24.0	23.5	23.7	**23.0**
19.5	20.0	20.5	20.0	**19.2**

Appendix D2: Radial water distribution pattern (mm) at test case A = 20°

Distance (m)	Rep. 1 (mm)				Rep. 2 (mm)			
	Row 1	2	3	Average	Row 1	2	3	Average
6	17.0	17.0	17.5	17.2	19.5	17.5	16.0	17.7
7	21.0	20.5	20.0	20.5	22.0	21.5	21.5	21.7
8	21.0	21.5	23.0	21.8	24.0	23.0	23.0	23.3
9	21.0	20.5	20.0	20.5	23.5	23.5	23.0	23.3
10	19.0	21.0	20.5	20.2	23.0	22.5	22.5	22.7
11	20.0	19.0	20.0	19.7	22.5	22.0	22.0	22.2
12	18.5	19.0	19.0	18.8	21.0	20.5	20.0	20.5
13	20.0	21.5	21.5	21.0	21.5	21.5	21.0	21.3
14	20.0	20.0	19.5	19.8	21.5	21.0	21.5	21.3
15	18.0	18.0	17.5	17.8	21.0	19.5	19.5	20.0
16	16.5	18.0	17.5	17.3	19.5	20.0	20.0	19.8
17	19.0	18.0	19.0	18.7	20.0	21.0	21.0	20.7
18	18.0	19.0	19.0	18.7	25.0	22.5	24.0	23.8
19	17.0	17.0	16.5	16.8	17.0	17.0	18.0	17.3
20	17.5	17.0	17.0	17.2	17.0	18.0	19.0	18.0
21	16.0	16.5	18.0	16.8	17.0	17.5	18.5	17.7
22	14.0	14.0	14.0	14.0	14.0	15.0	15.5	14.8
23	14.0	13.5	13.5	13.7	13.5	14.0	15.0	14.2
24	11.5	12.0	12.5	12.0	13.0	14.0	14.5	13.8
25	12.0	12.5	12.0	12.2	13.0	13.0	13.0	13.0
26	14.0	13.0	14.0	13.7	14.0	14.5	15.0	14.5
27	12.0	12.0	12.0	12.0	14.0	15.5	14.5	14.7
28	11.5	12.0	11.0	11.5	13.0	14.0	14.0	13.7
29	12.5	12.5	13.0	12.7	14.0	13.5	14.0	13.8
30	13.0	13.0	13.0	13.0	15.0	15.5	15.5	15.3
31	12.0	11.0	13.0	12.0	14.5	15.0	15.0	14.8
32	13.0	12.5	12.0	12.5	12.5	12.5	12.0	12.3
33	12.0	12.5	13.5	12.7	12.5	13.5	13.0	13.0
34	14.0	13.5	14.0	13.8	14.5	15.5	15.0	15.0
35	13.0	13.0	14.0	13.3	15.0	16.0	15.0	15.3
36	15.0	13.5	14.5	14.3	15.0	15.0	16.0	15.3
37	13.0	13.0	14.0	13.3	16.0	17.0	18.0	17.0
38	13.0	13.0	12.0	12.7	13.5	14.0	14.0	13.8
39	14.0	13.0	15.0	14.0	15.5	15.5	16.0	15.7
40	13.0	13.0	12.5	12.8	15.5	16.5	15.5	15.8
41	11.5	12.0	13.0	12.2	13.5	14.0	14.5	14.0
42	12.0	12.0	13.0	12.3	13.5	13.5	13.5	13.5
43	13.0	13.0	13.0	13.0	15.5	15.0	15.5	15.3
44	11.0	11.0	11.0	11.0	12.0	12.5	13.5	12.7
45	10.0	10.0	10.0	10.0	9.5	9.5	10.0	9.7

Appendix D2: Cont'd

Rep. 3 (mm)				Rep. 4 (mm)			
Row 1	2	3	Average	Row 1	2	3	Average
19.0	19.5	18.5	19.0	18.0	17.0	16.5	17.2
20.0	20.0	20.5	20.2	21.5	21.0	21.0	21.2
22.0	23.0	22.5	22.5	22.5	22.0	23.0	22.5
24.5	25.0	24.0	24.5	22.0	22.0	21.5	21.8
23.5	23.0	23.0	23.2	21.0	22.0	21.5	21.5
23.0	22.5	23.0	22.8	21.0	20.5	21.0	20.8
22.0	22.5	23.0	22.5	19.5	20.0	19.5	19.7
22.0	23.0	21.5	22.2	20.0	21.5	21.0	20.8
22.5	22.0	21.5	22.0	20.5	20.5	20.5	20.5
24.0	24.0	24.0	24.0	19.5	19.0	18.5	19.0
20.0	20.0	21.0	20.3	18.0	19.0	19.0	18.7
20.0	20.0	20.0	20.0	19.5	19.5	20.0	19.7
21.5	22.0	22.5	22.0	21.5	21.0	21.5	21.3
20.5	21.0	21.5	21.0	17.0	17.0	17.0	17.0
20.0	19.0	20.0	19.7	17.0	17.5	18.0	17.5
19.0	18.5	18.5	18.7	16.5	17.0	18.0	17.2
18.0	19.0	19.0	18.7	14.0	14.5	15.0	14.5
16.5	16.5	16.5	16.5	14.0	14.0	14.0	14.0
15.5	16.5	16.0	16.0	12.0	13.0	13.5	12.8
13.5	14.5	15.0	14.3	12.5	13.0	12.5	12.7
15.0	14.5	14.0	14.5	14.0	14.0	14.5	14.2
15.5	16.0	15.0	15.5	13.0	14.0	13.0	13.3
14.5	15.5	15.0	15.0	12.0	13.0	12.5	12.5
15.0	14.0	15.0	14.7	13.0	13.0	13.5	13.2
14.5	15.0	15.0	14.8	14.0	14.0	14.0	14.0
15.0	15.5	16.0	15.5	13.0	13.0	14.0	13.3
15.0	14.5	14.5	14.7	12.5	12.5	12.0	12.3
13.0	13.0	13.5	13.2	12.0	13.0	13.0	12.7
15.0	15.0	17.5	15.8	14.0	14.5	14.5	14.3
15.0	15.5	14.5	15.0	14.0	14.5	14.5	14.3
15.0	14.5	14.5	14.7	15.0	14.0	15.0	14.7
16.0	16.0	16.0	16.0	14.5	15.0	16.0	15.2
14.0	14.0	15.0	14.3	13.0	13.5	13.0	13.2
15.5	17.5	18.0	17.0	15.0	14.0	15.5	14.8
15.5	16.0	14.5	15.3	14.0	15.0	14.0	14.3
15.5	16.0	16.5	16.0	12.5	13.0	13.5	13.0
13.0	13.5	14.0	13.5	13.0	13.0	13.0	13.0
13.0	14.0	14.5	13.8	14.0	14.0	14.0	14.0
13.5	11.0	11.0	11.8	11.5	12.0	12.0	11.8
9.5	10.5	10.5	10.2	10.0	10.0	10.0	10.0

Appendix D2: Cont'd

Rep. 5				Target (mm)	Base (mm)
Row 1	2	3	Average		
19.0	18.5	17.0	18.2	**20.6**	**19.9**
20.5	19.5	18.5	19.5	**20.6**	**21.8**
21.0	21.0	20.5	20.8	**20.6**	**24.7**
19.5	19.5	19.5	19.5	**20.6**	**25.9**
17.5	17.0	17.0	17.2	**20.6**	**24.9**
15.5	16.0	16.0	15.8	**20.6**	**24.5**
15.0	14.5	14.5	14.7	**20.6**	**24.6**
14.0	14.0	14.0	14.0	**20.6**	**24.4**
13.5	12.0	13.0	12.8	**20.6**	**23.3**
12.0	11.5	12.0	11.8	**20.6**	**25.0**
11.0	11.5	11.0	11.2	**20.6**	**23.0**
11.5	11.0	11.5	11.3	**20.6**	**23.3**
11.5	11.0	11.5	11.3	**20.6**	**24.8**
12.0	11.5	11.0	11.5	**13.7**	**22.9**
13.0	12.5	12.0	12.5	**13.7**	**22.8**
14.5	13.0	14.0	13.8	**13.7**	**23.7**
13.0	12.5	13.5	13.0	**13.7**	**24.9**
14.5	13.5	14.0	14.0	**13.7**	**23.9**
14.5	14.0	13.5	14.0	**13.7**	**23.9**
15.0	15.5	14.5	15.0	**13.7**	**23.4**
18.0	17.0	17.5	17.5	**13.7**	**22.9**
18.0	17.5	16.5	17.3	**13.7**	**23.9**
17.0	18.0	18.0	17.7	**13.7**	**24.3**
18.0	18.0	18.0	18.0	**13.7**	**24.0**
19.0	18.0	18.0	18.3	**13.7**	**24.2**
17.5	16.5	16.5	16.8	**13.7**	**25.0**
16.5	17.0	17.0	16.8	**13.7**	**24.9**
16.5	17.0	17.0	16.8	**13.7**	**23.3**
17.0	15.5	16.5	16.3	**13.7**	**24.6**
15.0	15.5	16.0	15.5	**13.7**	**23.9**
16.5	17.0	17.0	16.8	**13.7**	**22.7**
15.5	14.5	15.5	15.2	**13.7**	**24.9**
14.5	15.0	15.5	15.0	**13.7**	**22.8**
18.0	16.0	18.0	17.3	**13.7**	**22.0**
17.5	18.0	17.5	17.7	**13.7**	**23.2**
17.0	16.0	16.5	16.5	**13.7**	**23.3**
17.5	16.5	17.0	17.0	**13.7**	**21.8**
17.0	17.0	17.0	17.0	**13.7**	**22.9**
14.5	14.0	14.5	14.3	**13.7**	**23.0**
12.0	13.0	12.5	12.5	**13.7**	**19.2**

Appendix D3: Radial water distribution pattern (mm) at test case B = 40°.

Distance m	Rep. 1 (mm)				Rep. 2 (mm)			
	Row 1	2	3	Average	Row 1	2	3	Average
6	11.0	11.5	11.5	11.3	12.0	12.5	13.0	12.5
7	13.0	13.5	13.0	13.2	14.0	12.5	13.0	13.2
8	14.0	15.0	15.0	14.7	14.0	14.0	14.5	14.2
9	14.0	15.0	13.5	14.2	15.0	15.5	14.0	14.8
10	14.0	14.0	14.5	14.2	17.0	17.0	16.0	16.7
11	13.5	13.0	13.0	13.2	16.0	16.0	15.5	15.8
12	13.5	12.5	12.0	12.7	16.5	15.5	16.0	16.0
13	14.0	14.0	14.5	14.2	15.5	15.0	15.5	15.3
14	13.5	13.5	13.0	13.3	16.5	16.5	15.0	16.0
15	13.0	12.5	12.5	12.7	16.0	16.0	15.5	15.8
16	13.5	13.0	12.5	13.0	15.5	17.0	16.5	16.3
17	14.0	14.0	13.5	13.8	16.0	16.0	15.5	15.8
18	14.0	13.5	12.5	13.3	16.5	16.0	15.5	16.0
19	13.0	12.5	12.5	12.7	15.0	15.5	15.0	15.2
20	14.0	13.0	13.5	13.5	16.5	15.5	16.0	16.0
21	14.5	14.0	13.5	14.0	15.5	15.0	17.0	15.8
22	13.0	13.0	13.0	13.0	15.0	16.0	16.0	15.7
23	14.0	14.0	13.5	13.8	16.5	14.5	15.5	15.5
24	13.5	12.5	13.0	13.0	16.0	16.5	16.5	16.3
25	12.5	13.0	12.5	12.7	15.0	15.5	15.0	15.2
26	13.5	14.0	14.0	13.8	15.5	15.5	15.5	15.5
27	14.0	13.5	13.5	13.7	16.5	15.5	16.5	16.2
28	13.0	13.5	13.5	13.3	16.5	16.5	16.5	16.5
29	14.0	14.5	14.0	14.2	16.5	16.5	17.0	16.7
30	14.5	14.5	14.0	14.3	17.0	17.0	18.5	17.5
31	13.0	13.5	13.0	13.2	16.0	17.0	16.5	16.5
32	12.5	12.5	13.0	12.7	16.5	18.0	18.0	17.5
33	14.5	14.0	13.0	13.8	17.0	17.5	17.5	17.3
34	13.0	13.5	13.5	13.3	16.5	17.0	17.0	16.8
35	13.0	12.5	13.0	12.8	16.5	16.5	18.0	17.0
36	13.5	13.5	13.0	13.3	15.5	16.0	17.0	16.2
37	13.0	12.0	12.5	12.5	19.0	15.0	16.0	16.7
38	12.0	12.0	12.5	12.2	14.0	14.0	15.0	14.3
39	12.5	13.0	13.5	13.0	15.0	19.0	18.0	17.3
40	12.5	13.5	13.0	13.0	14.0	14.0	15.5	14.5
41	12.5	13.0	12.5	12.7	14.0	15.0	15.5	14.8
42	14.0	13.0	13.5	13.5	14.5	16.0	15.0	15.2
43	13.0	12.5	13.0	12.8	13.0	15.0	14.0	14.0
44	11.0	12.0	11.0	11.3	14.0	15.5	15.0	14.8
45	11.0	11.5	11.0	11.2	15.0	15.5	14.5	15.0

Appendix D3: Cont'd.

Rep. 3 (mm)				Rep. 4 (mm)			
Row 1	2	3	Average	Row 1	2	3	Average
11.5	12.0	12.0	11.8	11.5	11.5	12.0	11.7
13.5	13.0	13.0	13.2	13.5	12.5	13.0	13.0
14.0	14.5	14.5	14.3	14.0	14.5	14.0	14.2
14.5	15.0	14.0	14.5	14.5	15.0	14.0	14.5
15.5	15.5	15.0	15.3	15.5	15.5	15.0	15.3
15.0	14.5	14.0	14.5	15.0	14.5	14.0	14.5
15.0	14.0	14.0	14.3	15.0	14.0	14.0	14.3
15.0	14.5	15.0	14.8	15.0	14.5	15.0	14.8
15.0	15.0	14.0	14.7	15.0	15.0	14.0	14.7
14.5	14.0	14.0	14.2	14.5	14.0	14.0	14.2
14.5	15.0	14.5	14.7	14.5	15.0	14.5	14.7
15.0	15.0	14.5	14.8	15.0	15.0	14.5	14.8
15.0	14.5	14.0	14.5	15.0	14.5	14.0	14.5
14.0	14.0	14.5	14.2	14.0	14.0	14.0	14.0
15.0	14.0	14.5	14.5	15.0	14.0	14.5	14.5
15.0	14.5	15.0	14.8	15.0	14.5	15.0	14.8
14.0	14.5	14.5	14.3	14.0	14.5	14.5	14.3
15.0	14.0	14.5	14.5	15.0	14.0	14.5	14.5
14.5	14.5	15.0	14.7	14.5	14.5	15.0	14.7
14.0	14.5	14.0	14.2	14.0	13.5	14.0	13.8
14.5	15.0	15.0	14.8	14.5	15.0	14.0	14.5
15.0	14.5	15.0	14.8	15.0	14.5	15.0	14.8
15.0	15.0	15.0	15.0	14.5	15.0	15.0	14.8
15.0	15.5	15.5	15.3	14.5	15.5	15.5	15.2
15.5	15.5	16.0	15.7	15.5	15.0	15.0	15.2
14.5	15.0	15.0	14.8	14.5	15.0	15.0	14.8
14.5	15.0	15.5	15.0	14.5	15.0	15.5	15.0
15.5	15.5	15.0	15.3	15.5	15.0	14.5	15.0
15.0	15.0	14.5	14.8	15.0	15.0	15.0	15.0
15.0	14.5	15.5	15.0	15.0	14.5	15.5	15.0
14.5	15.0	15.0	14.8	14.5	15.0	15.0	14.8
16.0	13.5	14.0	14.5	16.0	13.5	14.0	14.5
13.0	13.0	14.0	13.3	13.0	13.0	14.0	13.3
14.0	16.0	15.5	15.2	14.0	16.0	15.0	15.0
13.5	14.0	14.0	13.8	13.0	14.0	14.0	13.7
14.0	14.0	14.0	14.0	13.5	14.0	14.0	13.8
14.0	14.5	14.0	14.2	14.0	14.5	14.0	14.2
13.0	14.0	13.5	13.5	13.0	14.0	13.5	13.5
12.5	13.5	13.0	13.0	12.5	14.0	13.0	13.2
13.0	13.5	12.0	12.8	12.0	12.5	12.0	12.2

Appendix D3: Cont'd

Rep. 5 (mm)				**Target (mm)**	**Base (mm)**
Row 1	2	3	Average		
11.5	12.0	10.5	11.3	**13.7**	**19.9**
13.5	12.0	12.5	12.7	**13.7**	**21.8**
14.0	14.5	14.5	14.3	**13.7**	**24.7**
14.5	14.0	14.0	14.2	**13.7**	**25.9**
15.5	15.5	15.0	15.3	**13.7**	**24.9**
15.0	14.5	14.0	14.5	**13.7**	**24.5**
15.0	14.0	14.0	14.3	**13.7**	**24.6**
14.5	14.5	15.0	14.7	**13.7**	**24.4**
15.0	15.0	14.0	14.7	**13.7**	**23.3**
14.5	14.0	14.0	14.2	**13.7**	**25.0**
14.5	15.0	14.5	14.7	**13.7**	**23.0**
15.0	15.0	14.5	14.8	**13.7**	**23.3**
14.5	15.0	14.0	14.5	**13.7**	**24.8**
14.0	14.0	14.0	14.0	**13.7**	**22.9**
14.5	14.0	14.5	14.3	**13.7**	**22.8**
15.0	14.5	15.0	14.8	**13.7**	**23.7**
14.0	14.5	14.5	14.3	**13.7**	**24.9**
15.0	14.0	14.5	14.5	**13.7**	**23.9**
14.5	14.5	15.0	14.7	**13.7**	**23.9**
14.0	14.0	14.0	14.0	**13.7**	**23.4**
14.5	15.5	14.5	14.8	**13.7**	**22.9**
15.0	14.5	15.0	14.8	**13.7**	**23.9**
14.5	15.0	15.0	14.8	**13.7**	**24.3**
15.0	15.5	15.5	15.3	**13.7**	**24.0**
16.0	15.5	14.5	15.3	**13.7**	**24.2**
14.5	15.0	15.0	14.8	**13.7**	**25.0**
14.5	15.0	15.5	15.0	**13.7**	**24.9**
15.5	15.5	15.0	15.3	**13.7**	**23.3**
15.0	15.0	15.0	15.0	**13.7**	**24.6**
14.5	14.5	15.5	14.8	**13.7**	**23.9**
14.5	13.5	15.0	14.3	**13.7**	**22.7**
16.0	13.5	14.0	14.5	**13.7**	**24.9**
13.0	13.0	14.0	13.3	**13.7**	**22.8**
14.0	16.0	15.5	15.2	**13.7**	**22.0**
13.5	14.0	14.0	13.8	**13.7**	**23.2**
13.5	14.0	14.0	13.8	**13.7**	**23.3**
14.0	14.5	14.0	14.2	**13.7**	**21.8**
13.0	13.5	13.5	13.3	**13.7**	**22.9**
12.5	14.0	13.0	13.2	**13.7**	**23.0**
11.0	12.5	11.0	11.5	**13.7**	**19.2**

Appendix D4: Radial water distribution pattern (mm) at test case C = 110^o.

Distance m	Rep. 1 (mm)				Rep. 2 (mm)			
	Row 1	2	3	Average	Row 1	2	3	Average
6	17.0	16.5	16.5	16.7	18.0	17.5	17.5	17.7
7	20.5	19.5	18.5	19.5	20.5	20.0	20.0	20.2
8	21.0	21.0	20.5	20.8	22.5	23.0	24.0	23.2
9	19.5	19.5	19.5	19.5	21.0	21.0	21.0	21.0
10	17.5	17.0	17.0	17.2	17.5	17.0	18.0	17.5
11	15.5	16.0	16.0	15.8	17.5	17.5	16.5	17.2
12	15.0	14.5	14.5	14.7	17.0	15.0	16.0	16.0
13	14.0	14.0	14.0	14.0	15.0	15.0	14.5	14.8
14	13.5	12.0	13.0	12.8	15.0	14.0	14.5	14.5
15	12.0	11.5	12.0	11.8	13.0	13.0	13.5	13.2
16	11.0	11.5	11.0	11.2	14.0	13.5	14.0	13.8
17	11.5	11.0	11.5	11.3	13.5	14.0	14.0	13.8
18	11.5	11.0	11.5	11.3	12.5	13.0	13.0	12.8
19	12.0	11.5	11.0	11.5	12.5	12.0	12.5	12.3
20	13.0	12.5	12.0	12.5	13.0	13.5	13.5	13.3
21	14.5	13.0	14.0	13.8	14.0	15.0	14.5	14.5
22	13.0	12.5	13.5	13.0	13.5	14.0	14.0	13.8
23	14.5	13.5	14.0	14.0	14.0	14.0	13.5	13.8
24	14.5	14.0	13.5	14.0	14.0	14.0	13.5	13.8
25	15.0	15.5	14.5	15.0	13.5	14.0	14.0	13.8
26	18.0	17.0	17.5	17.5	16.0	16.5	17.0	16.5
27	18.0	17.5	16.5	17.3	17.0	17.0	17.0	17.0
28	17.0	18.0	18.0	17.7	18.0	17.0	18.0	17.7
29	18.0	18.0	18.0	18.0	18.0	18.0	19.0	18.3
30	19.0	18.0	18.0	18.3	18.0	18.0	19.5	18.5
31	17.5	16.5	16.5	16.8	17.5	18.0	18.5	18.0
32	16.5	17.0	17.0	16.8	18.0	18.5	18.5	18.3
33	16.5	17.0	17.0	16.8	19.0	19.0	18.5	18.8
34	17.0	15.5	16.5	16.3	18.5	18.0	18.5	18.3
35	15.0	15.5	16.0	15.5	18.0	17.0	17.0	17.3
36	16.5	17.0	17.0	16.8	20.0	19.0	17.5	18.8
37	15.5	14.5	15.5	15.2	18.0	17.0	17.0	17.3
38	14.5	15.0	15.5	15.0	15.0	15.0	15.0	15.0
39	18.0	16.0	18.0	17.3	16.0	16.0	16.0	16.0
40	17.5	18.0	17.5	17.7	17.0	17.0	17.5	17.2
41	17.0	16.0	16.5	16.5	16.0	17.5	17.5	17.0
42	17.5	16.5	17.0	17.0	16.0	16.5	17.0	16.5
43	17.0	17.0	17.0	17.0	17.0	17.0	17.5	17.2
44	14.5	14.0	14.5	14.3	16.0	15.5	16.0	15.8
45	13.5	13.0	12.5	13.0	13.5	13.5	14.0	13.7

Appendix D4: Cont'd

Rep. 3 (mm)				Rep. 4 (mm)			
Row 1	2	3	Average	Row 1	2	3	Average
16.0	16.0	17.0	16.3	17.0	17.0	17.0	17.0
15.0	16.0	17.0	16.0	19.0	18.5	18.5	18.7
21.0	22.0	22.5	21.8	21.5	22.0	23.0	22.2
22.0	23.0	22.0	22.3	21.0	22.0	21.0	21.3
19.0	18.0	19.0	18.7	18.0	17.0	18.0	17.7
17.5	17.0	16.0	16.8	17.0	17.0	16.0	16.7
17.5	16.0	17.5	17.0	16.5	15.0	16.0	15.8
15.0	14.0	15.0	14.7	15.0	14.0	14.5	14.5
15.0	15.5	15.5	15.3	14.5	13.5	14.0	14.0
14.0	13.5	14.0	13.8	13.0	13.0	13.0	13.0
11.0	11.0	12.0	11.3	12.0	12.0	12.0	12.0
13.5	14.0	14.0	13.8	13.0	13.0	13.0	13.0
14.5	14.0	14.0	14.2	13.0	12.5	13.0	12.8
12.5	11.0	12.0	11.8	12.5	11.5	12.0	12.0
13.0	12.5	12.5	12.7	13.0	13.0	13.0	13.0
16.0	16.0	15.0	15.7	15.0	14.5	14.5	14.7
16.0	17.0	16.0	16.3	14.0	14.5	14.5	14.3
15.0	16.0	14.5	15.2	14.5	14.5	14.0	14.3
15.0	15.0	15.0	15.0	14.5	14.0	14.0	14.2
15.5	15.0	14.0	14.8	15.0	15.0	14.0	14.7
17.0	16.5	15.5	16.3	17.0	16.5	16.5	16.7
18.5	18.0	17.5	18.0	18.0	17.5	17.0	17.5
20.0	18.0	19.5	19.2	18.0	17.0	18.5	17.8
18.5	18.5	18.0	18.3	18.0	18.0	18.0	18.0
20.0	20.0	20.5	20.2	19.0	18.5	19.0	18.8
20.5	20.5	19.0	20.0	18.5	18.0	18.0	18.2
20.5	21.0	19.5	20.3	18.5	19.0	18.0	18.5
20.0	19.5	20.0	19.8	18.5	18.5	18.5	18.5
21.5	20.0	22.0	21.2	19.0	18.0	19.0	18.7
18.5	19.0	18.0	18.5	17.0	17.0	17.0	17.0
18.5	20.0	20.0	19.5	18.0	18.5	18.0	18.2
19.5	20.0	21.5	20.3	17.5	17.0	18.0	17.5
18.0	18.0	19.0	18.3	16.0	16.0	16.5	16.2
17.0	16.0	15.5	16.2	17.0	16.0	16.5	16.5
19.5	19.0	19.0	19.2	18.0	18.0	18.0	18.0
18.5	19.0	18.5	18.7	17.0	17.5	17.5	17.3
18.0	19.5	19.5	19.0	17.0	17.5	18.0	17.5
19.0	19.0	19.0	19.0	17.5	18.0	18.0	17.8
19.0	19.0	18.0	18.7	16.5	16.0	15.5	16.0
15.5	16.0	16.0	15.8	14.0	14.0	13.5	13.8

Appendix D4: Cont'd

Rep. 5 (mm)				**Target (mm)**	**Base (mm)**
Row 1	2	3	Average		
17.0	17.0	17.0	17.0	**20.6**	**19.9**
19.0	18.5	18.5	18.7	**20.6**	**21.8**
21.5	22.0	22.5	22.0	**20.6**	**24.7**
22.0	22.0	21.5	21.8	**20.6**	**25.9**
18.0	17.5	18.0	17.8	**20.6**	**24.9**
17.0	17.0	17.0	17.0	**13.7**	**24.5**
16.5	15.0	16.0	15.8	**13.7**	**24.6**
15.0	14.0	14.5	14.5	**13.7**	**24.4**
14.5	14.0	14.3	14.3	**13.7**	**23.3**
13.0	13.0	13.0	13.0	**13.7**	**25.0**
12.0	12.0	12.5	12.2	**13.7**	**23.0**
13.0	13.0	13.0	13.0	**13.7**	**23.3**
13.0	12.5	13.0	12.8	**13.7**	**24.8**
13.0	11.5	12.5	12.3	**13.7**	**22.9**
13.0	13.5	12.5	13.0	**13.7**	**22.8**
14.5	14.5	14.5	14.5	**13.7**	**23.7**
14.0	14.5	14.5	14.3	**13.7**	**24.9**
14.5	14.5	14.0	14.3	**17.0**	**23.9**
14.5	17.0	14.0	15.2	**17.0**	**23.9**
14.5	15.5	14.0	14.7	**17.0**	**23.4**
17.0	17.0	16.0	16.7	**17.0**	**22.9**
18.0	17.5	17.0	17.5	**17.0**	**23.9**
18.0	17.5	18.5	18.0	**17.0**	**24.3**
18.0	18.0	18.0	18.0	**17.0**	**24.0**
19.0	19.0	19.0	19.0	**17.0**	**24.2**
18.5	18.0	18.0	18.2	**17.0**	**25.0**
18.5	18.5	18.0	18.3	**17.0**	**24.9**
18.5	18.5	18.5	18.5	**17.0**	**23.3**
19.0	18.0	19.0	18.7	**17.0**	**24.6**
17.0	17.0	17.0	17.0	**17.0**	**23.9**
18.0	18.5	18.0	18.2	**17.0**	**22.7**
17.5	17.0	18.0	17.5	**17.0**	**24.9**
16.0	16.0	16.5	16.2	**17.0**	**22.8**
17.0	16.0	16.5	16.5	**17.0**	**22.0**
18.0	18.0	18.0	18.0	**17.0**	**23.2**
17.0	17.5	17.5	17.3	**17.0**	**23.3**
17.0	17.5	17.5	17.3	**20.6**	**21.8**
17.5	17.5	18.0	17.7	**20.6**	**22.9**
16.5	16.0	16.0	16.2	**20.6**	**23.0**
14.0	14.0	14.0	14.0	**20.6**	**19.2**

Appendix D5: Radial water distribution pattern (mm) at test case D = 150^o.

Distance m	Rep. 1 (mm)				Rep. 2 (mm)			
	Row 1	2	3	Average	Row 1	2	3	Average
6	19.0	19.0	18.5	18.8	16.0	16.0	17.0	16.3
7	21.0	21.5	21.0	21.2	18.5	18.0	20.0	18.8
8	23.5	24.5	23.5	23.8	21.0	23.0	23.5	22.5
9	23.0	24.0	23.0	23.3	24.0	24.0	23.5	23.8
10	21.5	22.5	22.5	22.2	22.0	23.0	23.0	22.7
11	21.5	21.0	21.5	21.3	22.0	22.5	23.0	22.5
12	20.0	20.0	20.0	20.0	20.5	21.0	21.5	21.0
13	22.0	22.0	22.5	22.2	22.0	22.5	23.0	22.5
14	21.0	20.5	21.5	21.0	19.0	19.0	20.5	19.5
15	20.0	20.0	21.5	20.5	21.0	21.0	21.5	21.2
16	18.0	18.5	18.5	18.3	19.0	19.0	20.0	19.3
17	17.5	18.0	17.5	17.7	17.0	18.0	17.0	17.3
18	18.0	18.0	17.5	17.8	17.0	23.0	19.0	19.7
19	16.0	16.0	16.0	16.0	16.5	17.0	17.5	17.0
20	15.5	15.0	16.5	15.7	16.5	17.0	17.0	16.8
21	15.0	15.5	15.0	15.2	16.0	16.5	15.0	15.8
22	14.5	15.5	15.0	15.0	17.5	16.5	17.0	17.0
23	15.5	15.5	15.5	15.5	16.0	16.5	17.0	16.5
24	12.5	13.5	13.5	13.2	15.5	15.0	15.0	15.2
25	12.0	13.0	13.0	12.7	15.5	14.5	14.5	14.8
26	14.0	15.0	14.0	14.3	13.0	14.5	15.0	14.2
27	14.0	14.5	14.5	14.3	14.0	15.0	15.0	14.7
28	15.0	15.5	14.5	15.0	15.5	15.0	14.5	15.0
29	15.0	15.5	15.0	15.2	17.0	16.0	16.0	16.3
30	14.5	15.5	15.0	15.0	14.0	14.0	15.0	14.3
31	15.0	15.5	15.5	15.3	14.5	14.5	14.5	14.5
32	14.0	14.5	14.5	14.3	15.0	14.0	14.5	14.5
33	15.5	15.5	15.5	15.5	14.0	15.0	15.5	14.8
34	14.0	16.0	15.0	15.0	15.0	15.5	17.0	15.8
35	14.5	14.5	15.0	14.7	17.0	17.0	15.5	16.5
36	16.0	17.0	17.5	16.8	15.5	17.0	20.0	17.5
37	16.5	15.5	15.5	15.8	16.5	17.5	21.0	18.3
38	13.5	13.5	13.5	13.5	15.0	16.0	16.0	15.7
39	14.0	18.0	15.5	15.8	14.0	14.0	15.0	14.3
40	16.0	17.5	16.5	16.7	16.0	17.0	18.0	17.0
41	16.5	16.0	16.5	16.3	17.5	17.0	17.0	17.2
42	17.5	17.0	18.0	17.5	17.0	17.5	17.0	17.2
43	20.5	19.0	20.0	19.8	18.5	19.5	21.0	19.7
44	19.0	18.5	18.5	18.7	18.0	19.0	19.5	18.8
45	18.0	18.0	17.5	17.8	16.5	17.0	17.0	16.8

Appendix D5: Cont'd.

Rep. 3 (mm)				Rep. 4 (mm)			
Row 1	2	3	Average	Row 1	2	3	Average
19.0	17.0	16.0	17.3	18.0	17.0	17.0	17.3
20.0	19.5	20.0	19.8	19.5	20.5	21.0	20.3
23.5	24.0	24.0	23.8	23.0	24.0	24.5	23.8
23.0	23.0	22.0	22.7	23.0	23.5	23.5	23.3
22.0	22.5	22.0	22.2	22.0	23.0	22.5	22.5
21.5	20.5	22.0	21.3	22.0	22.5	22.5	22.3
19.0	19.5	19.0	19.2	20.0	21.0	21.0	20.7
22.0	21.5	21.0	21.5	22.0	22.0	22.5	22.2
19.0	18.5	20.0	19.2	20.0	20.5	21.5	20.7
19.5	19.5	21.0	20.0	21.0	21.0	21.5	21.2
18.0	18.0	19.0	18.3	19.0	18.5	20.0	19.2
17.0	17.0	18.0	17.3	17.0	18.5	17.5	17.7
16.0	21.0	21.0	19.3	17.0	21.0	19.5	19.2
14.5	16.0	16.0	15.5	16.0	16.5	16.5	16.3
16.0	15.5	16.0	15.8	16.0	16.0	16.5	16.2
15.0	14.5	15.0	14.8	15.0	15.5	15.0	15.2
15.0	16.0	15.5	15.5	15.5	16.0	15.5	15.7
16.5	16.5	16.0	16.3	16.0	16.0	16.0	16.0
14.5	14.5	14.0	14.3	14.0	14.5	15.0	14.5
12.5	13.5	14.0	13.3	13.0	14.5	14.0	13.8
14.5	16.0	14.0	14.8	14.0	15.5	14.5	14.7
15.5	15.5	14.0	15.0	14.5	15.0	14.5	14.7
14.0	14.5	13.5	14.0	14.5	15.0	14.0	14.5
14.5	14.5	15.0	14.7	15.5	15.0	15.0	15.2
14.5	15.0	14.5	14.7	14.5	15.0	14.5	14.7
15.5	15.0	14.0	14.8	15.0	15.0	14.5	14.8
15.5	15.0	13.0	14.5	15.0	14.5	14.0	14.5
15.0	15.0	13.5	14.5	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	14.5	15.5	15.0	15.0
14.0	14.5	15.0	14.5	15.0	15.5	14.5	15.0
18.5	17.0	17.0	17.5	16.5	17.0	18.0	17.2
16.5	17.0	17.5	17.0	16.5	16.5	18.0	17.0
14.5	15.0	15.0	14.8	14.5	15.0	15.0	14.8
15.5	16.5	16.0	16.0	14.5	16.5	15.5	15.5
17.0	17.5	16.0	16.8	16.0	17.5	17.0	16.8
15.5	15.0	15.5	15.3	16.5	16.0	16.5	16.3
17.0	16.0	17.0	16.7	17.0	17.0	17.5	17.2
20.0	18.5	19.5	19.3	20.0	19.0	21.0	20.0
19.0	18.5	19.0	18.8	19.5	19.0	19.5	19.3
16.0	16.5	15.0	15.8	17.5	17.0	16.5	17.0

Appendix D5: Cont'd.

Rep. 5 (mm)				**Target (mm)**	**Base (mm)**
Row 1	2	3	Average		
18.0	17.5	17.5	17.7	**20.6**	**19.9**
20.0	21.0	20.5	20.5	**20.6**	**21.8**
23.0	24.5	23.5	23.7	**20.6**	**24.7**
23.5	24.0	23.0	23.5	**20.6**	**25.9**
22.5	23.0	22.5	22.7	**20.6**	**24.9**
22.0	22.5	22.0	22.2	**20.6**	**24.5**
20.0	22.0	21.0	21.0	**20.6**	**24.6**
22.0	22.0	22.0	22.0	**20.6**	**24.4**
20.0	21.0	21.0	20.7	**20.6**	**23.3**
21.0	21.0	21.0	21.0	**20.6**	**25.0**
18.5	18.5	20.0	19.0	**20.6**	**23.0**
17.5	18.5	17.5	17.8	**20.6**	**23.3**
17.0	21.0	19.0	19.0	**13.7**	**24.8**
16.0	17.5	16.5	16.7	**13.7**	**22.9**
16.0	16.0	16.5	16.2	**13.7**	**22.8**
15.0	15.5	15.0	15.2	**13.7**	**23.7**
15.5	16.0	15.5	15.7	**13.7**	**24.9**
16.0	16.0	16.0	16.0	**13.7**	**23.9**
14.0	14.5	14.5	14.3	**13.7**	**23.9**
13.5	14.0	14.0	13.8	**13.7**	**23.4**
14.0	15.0	14.5	14.5	**13.7**	**22.9**
14.5	15.0	14.5	14.7	**13.7**	**23.9**
14.5	15.0	14.0	14.5	**13.7**	**24.3**
15.5	15.0	15.0	15.2	**13.7**	**24.0**
14.0	15.0	15.0	14.7	**13.7**	**24.2**
15.0	15.0	14.5	14.8	**13.7**	**25.0**
14.5	14.5	14.0	14.3	**13.7**	**24.9**
15.0	15.0	15.0	15.0	**13.7**	**23.3**
15.0	15.5	15.5	15.3	**13.7**	**24.6**
15.0	15.5	15.0	15.2	**13.7**	**23.9**
16.5	17.0	18.0	17.2	**13.7**	**22.7**
16.5	16.0	18.0	16.8	**13.7**	**24.9**
14.5	15.0	16.0	15.2	**24.0**	**22.8**
14.5	16.0	15.5	15.3	**24.0**	**22.0**
16.5	17.5	17.5	17.2	**24.0**	**23.2**
16.5	16.0	17.5	16.7	**24.0**	**23.3**
17.0	17.0	17.0	17.0	**24.0**	**21.8**
20.0	19.0	21.0	20.0	**24.0**	**22.9**
19.5	18.5	20.0	19.3	**24.0**	**23.0**
17.0	16.5	17.0	16.8	**24.0**	**19.2**

Appendix D6: Radial water distribution pattern (mm) at test case E = Manual.

Distance m	Rep. 1 (mm)				Rep. 2 (mm)			
	Row 1	2	3	Average	Row 1	2	3	Average
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1.0	1.5	1.0	1.2	2.0	2.0	3.0	2.3
17	4.5	4.0	4.0	4.2	4.0	3.5	3.5	3.7
18	5.0	5.5	5.5	5.3	4.0	5.0	5.0	4.7
19	4.0	3.5	4.0	3.8	3.5	3.5	4.0	3.7
20	6.0	7.0	6.5	6.5	5.5	6.0	7.0	6.2
21	9.0	9.5	10.5	9.7	9.0	8.5	9.0	8.8
22	10.0	10.0	10.5	10.2	10.0	9.0	10.0	9.7
23	11.0	11.5	11.0	11.2	11.5	12.5	13.0	12.3
24	15.0	14.5	15.0	14.8	14.0	14.5	14.5	14.3
25	14.0	13.5	15.0	14.2	15.0	14.0	15.0	14.7
26	17.0	17.0	17.5	17.2	18.0	19.0	19.5	18.8
27	21.0	21.0	22.0	21.3	21.5	23.0	22.0	22.2
28	20.0	20.0	21.0	20.3	21.0	23.0	23.0	22.3
29	23.5	22.5	24.0	23.3	25.0	23.5	25.0	24.5
30	24.0	25.5	25.5	25.0	26.0	27.0	26.0	26.3
31	26.0	26.5	26.5	26.3	27.0	27.0	27.0	27.0
32	25.5	25.5	24.5	25.2	26.5	25.5	25.0	25.7
33	25.0	25.5	25.0	25.2	25.0	25.0	25.0	25.0
34	26.5	26.5	28.0	27.0	28.0	27.0	28.0	27.7
35	25.5	26.0	24.0	25.2	25.5	25.5	25.0	25.3
36	26.0	25.5	26.0	25.8	27.5	25.5	26.5	26.5
37	26.5	26.0	25.5	26.0	28.0	26.5	26.0	26.8
38	24.5	24.0	23.5	24.0	23.5	23.5	24.0	23.7
39	23.0	23.0	23.5	23.2	23.0	24.0	24.0	23.7
40	26.0	25.5	25.5	25.7	27.0	26.5	25.5	26.3
41	26.0	25.0	24.5	25.2	25.5	26.5	25.5	25.8
42	24.5	24.0	24.0	24.2	24.5	26.0	25.0	25.2
43	27.0	26.5	26.0	26.5	27.0	27.5	28.0	27.5
44	25.5	25.0	26.0	25.5	24.5	25.5	25.0	25.0
45	22.0	21.0	20.5	21.2	20.0	21.0	20.0	20.3

Appendix D6: Cont'd

Rep. 3 (mm)				Rep. 4 (mm)			
Row 1	2	3	Average	Row 1	2	3	Average
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0	1.5	1.5	1.3	2.5	3.5	3.0	3.0
4.0	5.0	4.0	4.3	4.5	4.0	5.0	4.5
4.0	5.5	5.5	5.0	4.0	5.0	5.5	4.8
4.5	5.0	5.0	4.8	4.5	5.0	4.0	4.5
9.0	8.0	6.5	7.8	9.0	9.0	8.5	8.8
11.0	11.0	9.5	10.5	10.0	9.5	10.0	9.8
11.0	11.5	10.5	11.0	11.0	10.5	11.0	10.8
13.0	15.0	13.0	13.7	14.0	15.0	15.0	14.7
15.5	15.5	14.0	15.0	15.5	15.0	16.0	15.5
18.0	16.5	15.5	16.7	16.5	16.0	16.5	16.3
22.5	22.0	20.0	21.5	21.0	23.5	22.0	22.2
23.0	23.5	21.0	22.5	23.5	23.5	22.0	23.0
24.5	24.0	23.0	23.8	23.5	24.0	23.0	23.5
25.5	25.0	24.5	25.0	26.0	25.5	26.5	26.0
26.5	26.5	27.5	26.8	27.0	29.0	28.0	28.0
25.0	26.5	25.0	25.5	26.0	28.0	26.5	26.8
25.5	26.5	25.0	25.7	27.0	26.0	24.5	25.8
26.0	25.5	25.0	25.5	26.0	26.5	27.0	26.5
27.0	26.0	26.5	26.5	26.5	26.5	27.0	26.7
25.0	24.5	24.0	24.5	25.5	26.0	24.0	25.2
26.0	26.0	25.5	25.8	26.0	26.0	27.0	26.3
26.0	25.5	25.0	25.5	26.5	25.5	25.0	25.7
23.0	23.0	24.0	23.3	23.5	24.0	23.0	23.5
23.0	23.0	23.0	23.0	25.0	25.5	25.0	25.2
26.5	24.5	27.0	26.0	26.0	26.5	26.5	26.3
23.5	24.5	25.0	24.3	25.0	26.0	27.0	26.0
24.0	24.0	24.0	24.0	26.0	26.0	26.5	26.2
26.5	25.5	25.0	25.7	27.5	27.0	28.0	27.5
24.5	24.0	24.5	24.3	24.5	24.5	25.5	24.8
20.5	21.0	20.5	20.7	21.0	21.0	21.0	21.0

Appendix D6: Cont'd.

Rep. 5 (mm)				**Target (mm)**	**Base (mm)**
Row 1	2	3	Average		
0.0	0.0	0.0	0.0	**0.0**	**19.9**
0.0	0.0	0.0	0.0	**0.0**	**21.8**
0.0	0.0	0.0	0.0	**0.0**	**24.7**
0.0	0.0	0.0	0.0	**0.0**	**25.9**
0.0	0.0	0.0	0.0	**0.0**	**24.9**
0.0	0.0	0.0	0.0	**0.0**	**24.5**
0.0	0.0	0.0	0.0	**0.0**	**24.6**
0.0	0.0	0.0	0.0	**0.0**	**24.4**
0.0	0.0	0.0	0.0	**0.0**	**23.3**
0.0	0.0	0.0	0.0	**0.0**	**25.0**
1.5	2.5	2.0	2.0	**0.0**	**23.0**
5.0	5.0	4.0	4.7	**0.0**	**23.3**
4.5	4.0	4.0	4.2	**0.0**	**24.8**
5.0	5.0	5.0	5.0	**0.0**	**22.9**
8.5	8.5	7.0	8.0	**0.0**	**22.8**
10.0	10.5	8.0	9.5	**0.0**	**23.7**
10.0	10.0	10.0	10.0	**24.0**	**24.9**
13.0	15.5	13.5	14.0	**24.0**	**23.9**
15.5	15.0	14.5	15.0	**24.0**	**23.9**
15.0	14.0	14.0	14.3	**24.0**	**23.4**
20.0	22.5	21.5	21.3	**24.0**	**22.9**
23.0	23.5	23.0	23.2	**24.0**	**23.9**
23.0	23.0	24.0	23.3	**24.0**	**24.3**
24.0	23.5	25.0	24.2	**24.0**	**24.0**
26.0	25.5	27.0	26.2	**24.0**	**24.2**
26.5	26.5	25.5	26.2	**24.0**	**25.0**
24.5	26.0	25.5	25.3	**24.0**	**24.9**
25.5	26.0	26.5	26.0	**24.0**	**23.3**
26.5	26.5	26.5	26.5	**24.0**	**24.6**
25.0	24.5	25.0	24.8	**24.0**	**23.9**
27.0	26.0	27.0	26.7	**24.0**	**22.7**
24.0	24.0	26.0	24.7	**24.0**	**24.9**
23.0	23.0	23.5	23.2	**24.0**	**22.8**
23.0	23.0	24.5	23.5	**24.0**	**22.0**
26.0	25.0	26.5	25.8	**24.0**	**23.2**
24.0	23.5	24.5	24.0	**24.0**	**23.3**
23.5	23.0	23.5	23.3	**24.0**	**21.8**
25.5	26.0	27.0	26.2	**24.0**	**22.9**
25.0	24.0	26.0	25.0	**24.0**	**23.0**
19.0	20.5	21.0	20.2	**24.0**	**19.2**

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