DEVELOPMENT AND EVALUATION OF AN AUTOMATED PULSE IRRIGATION SYSTEM

By

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Dedication

This thesis is dedicated to my Mother, Father and Guide, who sacrificed much to bring me up to this level and to my lovely sisters, friends and their families for the devotion they made to make my life successful.

DECLARATION

I hereby declare that this thesis entitled **"DEVELOPMENT AND EVALUATION OF AN AUTOMATED PULSE IRRIGATION SYSTEM"** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associate ship, fellowship or other similar title of any other University or Society.

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SYMBOLS AND ABBREVIATIONS

Symbols		Abbreviations
<	:	Less than
>	:	Greater than
%	:	Percent
±	:	Plus or minus
×	:	Multiplication
÷	:	Division
≤	:	Less than or equal to
≥	:	Greater than or equal to
AC	:	Alternate current
cc	:	Cubic Centimetre
cm	:	Centimetre
cm^2	:	Square centimetre
cm^3	:	Cubic centimetre
db	:	Dry basis
DC	:	Direct current
ds/m	:	Deci Siemens per meter
DWA	:	Daily water availability
ET	:	Evapotranspiration
et al.	:	And others
etc.	:	et cetera
FC	:	Field capacity
Fig.	:	Figure
g	:	Gram
g/cc	:	Gram per cubic centimetre
GPRS	:	General packet mobile service
GPS	:	Global positioning system
GSM	:	Global system for mobile

ha day^{-1}	:	Hector per day
hp	:	Horse power
hr	:	Hour
I2C	:	Inter integrated circuit
ICT	:	Information and communication technologies
IoT	:	Internet and other things
IS	:	Indian standards
KAU	:	Kerala Agricultural University
KCAET	:	Kelappaji College of Agricultural Engineering and Technology
Kg	:	Kilogram
kg cm^{-2}	:	Kilogram per square centimetre
kPa	:	Kilopascal
L	:	Length
LCD	:	Liquid crystal display
LED	:	Light emitting diode
LL	:	Liquid limit
lph	:	Litre per hour
m	:	Meter
m^2	:	Square meter
m^3	:	Cubic meter
MAD	:	Maximum allowable depletion
MC	:	Moisture content
mm	:	Millimetre
MS	:	Mild steel
N	:	Newton
NSE	:	Nash-Sutcliffe model efficiency
PCB	:	Printed circuit board
pH	:	Potential of hydrogen

PI	:	Plasticity Index
PL	:	Plastic limit
PWP	:	Permanent wilting point
RMSE	:	Root mean square
Sl. No.	:	Serial Number
SMS	:	Short message service
SWCC	:	Soil water characteristic curve
USB	:	Universal serial bus
USDA	:	United States department of agriculture
V	:	Volts
W	:	Width
Wb	:	Wet basis
A	:	Alpha
θ	:	Theta
μ	:	Mu
π	:	Pi

CHAPTER I

INTRODUCTION

Water is a critical input into agriculture with a determining effect on the yield of the produce, as even the finest seeds on fertile lands fail to achieve the full yield potential under non-optimal water availability. India has only four percent of the world's fresh water resources while the primary source of livelihood for about 58 per cent of India's population - which is about 17% of the world's population - is Agriculture. India ranks 2nd in the world in farm output which contributes about 13.7 per cent of India's gross domestic product (GDP) and irrigation accounts for about 80 per cent of the water use. India has about 140 million ha of cultivable land 54% of which practices rainfed farming.

Diodorus following Megasthenes affirms about the ancient India before invasions that "famine has never visited India", which was because Indians at that time saved themselves from the vagaries of rain by working out the system of irrigation from very early times, The Harappans who perfected the system of town-planning as early as the 3rd millennium B.C, had a thorough knowledge of irrigation and Gordon Childe as well as Dr. Wheeler reiterates that Indus people grew crops by irrigation farming (New light on the most ancient East, London, 1952, p. 176, India and Pakistan, p 108). The earliest evidence of a channel and dockyard with embankment walls, built out of burnt bricks was unearthed at Lothal, dated c 1500 B.C. to 1000 B.C. In the Vedic period, RV VII. 49.2 refers to the artificial distribution of water by dug up canals and to the well having water and to its use for irrigation (RV VIII 87.4, X.68.1). The Yajur-veda mentions *sarasi* and *kulya* in the sense of 'dam' and 'canal' respectively. (Vedic Index, I, p. 173). Canals are frequently mentioned in the Sutra-works like *Kausika-sutra* and *Bodhayana Dh. Sutra.* The irrigation development in India continued through the British period till today, bringing more land under irrigation.

India is blessed with rich and vast diversity of natural resources. The precise and accurate use of these natural resources plays a vital role in increased agriculture production needed for the growing population. The mismanagement of water resources reduces production of agricultural commodities, which affects the economy of the country. Use of Integrated Water Management leads to reduction in poverty, and increased sustainability of agriculture and environment which lead to sustainable economic development. Agriculture production is also affected by inaccurate and uncontrolled irrigation, which causes water stress to plant and subsequent reduction in yield. National Water Policy (2002) envisages integrated development and management of water resources by utilising irrigation systems that apply water more uniformly and in controlled quantities as per the crop needs so as to avoid plant water stress and to prevent deep percolation loss beyond root zone due to the excessive water application. Water use efficiency decreases and leaching of nutrients increases due to over application of irrigation water. This also leads to groundwater pollution and nutrients deficiency in the root zone due to leaching.

Pressurized irrigation systems such as drip irrigation and sprinkler irrigation systems apply water more precisely. The micro irrigation systems have becoming widely popular in recent years for irrigating orchards and horticultural crops. It gives high value to nursery and horticultural crops and plays a vital role in increasing water use efficiency. In rainfed arid regions, the micro irrigation is beneficial due to the low application rate of water. The proper use of irrigation control and scheduling is very important for the efficient functioning of these irrigation systems.

Irrigation scheduling can be practiced using tensiometers. Tensiometers are devices that measure the soil water potential and gives the moisture content of soils. Nevertheless, the applicability of tensiometer is limited to a soil water potential up to 0.8 bar due to technical limitation of the device.

Researchers have been continuously striving to improve the methods used for irrigation scheduling. Technological strides brought the use of information and communication technologies in agricultural applications. The use of wireless sensors for the measurement of the soil water potential is gaining ground. The plant water stress could be obtained through these sensors and water requirement could be determined. Thus, irrigation scheduling using tensiometers was replaced with the sensor-based irrigation control system. This type of sensors is easy for irrigation scheduling compared to the tensiometers. Various sensors for moisture content, temperature and humidity were used to obtain parameters influencing the plant water requirement. The soil moisture content sensors used in these systems generally work on the principle of electrical conductance. The conductance of soil matrix when moisture is present in different levels will be different. The sensors are calibrated to show the moisture content corresponding to the conductance and so the current moisture content is displayed. These sensors can used with a micro controller to trigger the operation of solenoid valves controlling water supply. There are several microcontrollers such as Arduino UNO, Raspberry PI etc. which could be used for this purpose.

The particular command code for these operations can be written to the microcontroller memory for the automation. These sensors are able to continuously check the status of the moisture in the soil. The command code can be so programmed to trigger the start and stop of the irrigation application based on the sensed moisture value. Thus, the right quantity of water can be applied at the right time through automation.

The automation system reduces the labour cost and by applying the correct amount of water at the right time increases the water use efficiency. These automation technologies are usually adopted in large scale irrigation. For garden and horticultural crops, the automation was found successful with sufficient accuracy. The gardener can keep the system on and need not worry about the irrigation if he is away from the nursery or garden. Nevertheless, such automation systems have higher capital cost and due to such reasons, it has not become much popular. The automation system consists of the very sophisticated sensors, microcontrollers and valves. Since these automatic irrigation controllers are very expensive, for less payback period it can be afforded only in large scale cultivation of high value crops. According to previous research, reviews it has seen that this

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can be solved using low-cost soil moisture and other sensors along with open source microcontrollers like Arduinos as irrigation controllers.

Researchers found different yield values for different crops by using these automated irrigation systems. However, in general, the yield increased due to automation systems compared to normal traditional methods. When the irrigation is performed through trickle systems, the water is to be applied at the root zone of the crop at the right time. Nevertheless, several studies showed the flooding of root zone due to continuous water application. In trickle irrigation, the soil remains nearly saturated for a period of time between consecutive irrigation supplies, especially in heavy clay or vertisols that makes trickle irrigation undesirable to that soil. The macro pores and micro pores are completely flooded with the water. Thus, in less drainable soil, saturation condition in heavy soils makes the air/oxygen in pores to be replaced with water and causes deficiency of oxygen near the root zone.

Plant performance is affected by inadequate oxygen especially in heavy, compacted and saline soils. Inadequate aeration lead to deficiency of oxygen in crop root zone and thus reduces the root respiration and water and nutrients absorption of root, leading to reduction in the yield. This could change the hormone levels and enzyme activities of the plant (Bhattarai, *et al.*, 2005). The healthy growth of the crops are hindered by traditional irrigation methods due to the hypoxia stress on roots (Yuan, *et al.*, 2015). Traditional irrigation methods replace the air in the macro-pores of the soil with water and that results in lack of aeration in crop root zone thus reducing yield.

Respirations of the root, soil microbes and soil animals are sustained by air in the soil and that is compromised due to lack of oxygen in the root zone. A prolonged presence of excessive soil moisture or wetness produces stress which reduces the yield and it can cause build-up of metabolic poisons, nutrient deficiency and increased incidence of root diseases. Saturated soils will trap metabolites, ethylene and carbon dioxide in the root zone, concentrations of which can seriously affect the rate of growth and size of the plant. The solutions available to provide sufficient aeration in the crop root zone include irrigation of crops with aerated

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irrigation water and providing pulsed irrigation operation to reduce the higher rate of application of the trickle emitter.

The pulse irrigation is aimed at achieving a lower rate of application which permits proper aeration in the rootzone from a higher application rate irrigation emitter. Thus, the irrigation is done in ON and OFF phases/cycles, which may cause higher labour cost if the valves operated manually. Thus, the automation of pulse irrigation is essential for the proper and effective use of it.

The present research work is undertaken to study the pulse irrigation system with automation using moisture sensors and Arduino micro-controller and to evaluate the performance of this system with respect to the change in wetted bulb it forms. The system is aimed at automatically controlling the irrigation based on the matric potential developed in the crop root zone due to soil water and irrigating with different ON/OFF cycle pulses to achieve adequate aeration in the rootzone. The specific objectives are:

1. Development of an Automated Pulse Irrigation System using sensors and microcontroller.
2. Evaluation of the Performance of the Developed Automated system for Pulse Irrigation with respect to the change in wetted bulb under the emitter.

CHAPTER II

REVIEW OF LITERATURE

A review of previous research works related to pulse irrigation, importance of soil aeration, automation using different sensors and application of sensors in pulse drip system are presented in this chapter.

Irrigation is the application of water into the field through different methods and methods used for irrigation purposes includes different application efficiencies and field efficiencies. However, looking to a condition of water availability and conditions of farmers in India the Precise application of water gives better worth to farmers. Whereas Drip irrigation system has also became popular nowadays in India. But the according to Researchers Drip irrigation usually gives water at or near to the root zone of Plant but due to continuous watering the macro pores and micro pores are flooded with water and which regrets the oxygen to enter from plant root to plant and due to this lack of aeration the plant growth also affects. Whereas in other low application of water usually makes the problem of clogging of emitter. To overcome or to the solution of all this problems Pulse irrigation came into practice. Pulse irrigation applies water in the cycles of irrigation, which gives enough time to aerate the soil and helps in increase of plant growth.

Pulse irrigation also improves water use efficiency when it was used with mulching. Almedia, *et al.* (2015) observed that pulse irrigation saved 25 % of water in treatment without mulching and 50% when plastic mulching was used, contributing substantially to improve irrigation water efficiency. Zin El-Abedin (2006) also observed that Pulse drip irrigation increased grain yield by 11.8 % compared with continuous drip irrigation. While the total applied, water saved was 2.01 % for pulse drip irrigation than that of continuous drip.

Methods and Results of the experiments of Researchers were studied and the researches useful for the present study are described.

2.1 ROLE OF PULSE IRRIGATION IN MICRO IRRIGATION SYSTEM

Karmeli and Peri (1974) suggested Pulse irrigation as an irrigation technique achieving a relatively low application rate while using an irrigation device with a higher application rate. Pulse irrigation is composed of a series of irrigation time cycles where each cycle includes two phases, the operating phase followed by the resting or non-operative phase. As a function of the irrigation parameters and the number of cycles in the irrigation, the variables of the pulse pattern, the real irrigation time, the resting time and the total time of a single pulse were defined. A suggested method to determine the number of cycles in one pulse irrigation which in general would be in the range of 5-10 cycles.

Fraisse, *et al.* (1995) studied emphasization of conjunctive management of irrigation water and chemicals for both protection of groundwater quality and for optimizing production from limited water supplies. The small plot studies were done with the linear-move irrigation system machine installed at the Colorado State University Agricultural Research, Development and Education Center (ARDEC). Because of the many small plots under the machine it was necessary to control water and chemical applications both along the lateral line and in the direction of travel. Laboratory tests showed that as a means of obtaining a wide range of application rates to plot areas electrical solenoid valves can be pulsed, so long as pulse frequency is less than 1 min. It was concluded that under pulsed conditions water application was directly proportional to the fraction of time the valve was opened, and that was the viable technique for controlling applications to research plots.

However, the use of continuous irrigation gives the problems of clogging of emitters and loss due to deep percolations of water beyond crop root zone. If applied water is in the cycles of irrigation, it gives an advantage of reducing the clogging and loss due to deep percolation of water and increases aeration in soil. Jackson and Kay (1987) studied that by increasing the emitter size with pulses of irrigation the problem of clogging of emitters can be significantly reduced. An approach to reduce the clogging problem is to increase the size of the waterway in the emitters, this can lead to increased emitter discharge and changes in the soil wetting pattern which may adversely affect water availability to plants. Researchers gave evidence to suggest, however, that established soil wetting patterns can be maintained at the higher discharges if the flow is pulsed.

Al-Naeem (2008) experimented the effect of pulse irrigation using high flow rates. Study was conducted with line source on sandy loam soil packed in soil tank. Results showed that increase in pulsed flows up to six times to that of the equivalent continuous flow can be used with little change in soil wetting pattern. The deep percolation of water was reduced and the horizontal spread was increased twelve time to that of continuous flow when pulsed flow was used. Strong correlation was obtained between water application rates and horizontal and vertical advances and that could be expressed as power function. Experiment also gave result that the emitter sizes can increase upto 2.4 – 3.5 times and cross-sectional area of emitter upto 6.0 – 12.0 times than of a normal size to reduce trickle clogging problems. Through Empirical analysis of vertical and horizontal advances, it was seen that both the parameters can be expressed as Power Function.

Researches have been conducted to study and develop an irrigation strategies to save energy on farm and response was positive when it came to pulse irrigation. García-Prats and Guillem-Picó (2016) found that reductions in Emitter discharge, Energy consumption and Energy cost savings are not inherently related to each other. Pulsed irrigation showed an energy saving potential of 10.67, 6.43 and 6.99 % for power capacity, Energy consumption and Energy cost respectively.

Elmaloglou and Diamantopoulos (2009a) investigated the infiltration and redistribution of soil moisture under surface drip irrigation considering hysteresis of different textured soils (loamy sand and silt loam). The evaluation of soils was done in terms of wetting front advance patterns and deep percolation under the root zone with the effect of continuous versus intermittent application of 1, 2 and 4 l/h. The soil water retention characteristic curve, evaporation from the soil surface, and water extraction by roots in a cylindrical flow model incorporating hysteresis was used for this purpose. The results showed that, pulse irrigation slightly reduces the water losses under the root zone in both cases (with and without hysteresis) compared with continuous irrigation,. Also in both types of irrigation, at the total simulation time, hysteresis reduces significantly the water losses under the root zone. Finally, the greater effect of hysteresis was found at higher discharge rate (4 l/h) and consequently at higher water content of the soil surface.

Skaggs, *et al.* (2010) used numerical simulations and field trials to investigate the effects of application rate, pulsed water application, and antecedent water content on the spreading of water from drip emitters and the simulation results showed that minor increases in horizontal spreading were produced at end of application of water due to pulsing and lower application rates. Primarily due to longer irrigation times, the small increase, however not to flow phenomena also associated with pulsing or low application rates. After a period of 24 hours, the infiltrated water had redistributed which mostly results in disappearing of the small increases. Field trials were matched with the simulation findings, with no statistically significant difference in wetting being found among five water application treatments involving pulsed applications and varying application rates.

Nikolidakis, *et al.* (2015) sudied the integrated collabrated system for automation with the help of advanced novel routing protocol for Wireless Sensor Networks (WSNs) which named as ECHERP (Equalized Cluster Head Election Routing Protocol). The historical data and the change on the climate values are taken into consideration for the calculation of irrigation water requirement. In case the collected data changes and is above threshold value then most frequent data collection is proposed to minimize water requirement and in case if change is below threshold value then time interval to collect data increses to save the sensor energy which inreases sensor life. Resulted showed that lifetime improved up to 1825 minute and in case of a round of 110 seconds model provides energy efficiency using smaller quantites using ECHERP.

As an efficient means of irrigating small plots, home yards and greenhouses from limited water supplies, without requiring an external energy source realised substantial savings of water and energy, in Bulgaria (Georgiev and Conley, 1996).

2.2 EFFECT OF APPLICATION OF PULSE IRRIGATION WITH RESPECT TO CROP GROWTH

Researchers studied the crop growth with the application of Pulse Irrigation and results compared to the continuous irrigation. Results showed significant effect to crop growth when it was irrigated with Pulses.

Levin, *et al.* (1979) studied the soil moisture distribution in a high-yielding apple orchard. With different discharge rate, spacing between tricklers and frequency of application, soil moisture content was determined with three treatments. Results showed that when irrigated twice a week with 8 l/h tricklers the soil moisture and root system distribution covered a wider area than by irrigating daily or once a week with 4 1/h tricklers. Similar root distribution pattern was found in both irrigating daily and once a week but a narrower soil moisture distribution was found with irrigating daily. 17 % of the water applied was found water loss by drainage under the trickler. Pulse irrigation decresed this loss by supplying the water in pace of plant consumption.

Assouline, *et al.* (2006) conducted a case study and investigated the combined effects of pulsed irrigation and water salinity on the response of the soil–plant system. Bell pepper (Capsicum annuum L.) was cultivated as a test crop in a screen house and irrigating daily with drip at high frequency with saline and fresh water. Simultaneous meteorological, physiological, soil physical, plant and soil chemical, and yield data was monitored during the experiment. High water salinity affected most negatively physiological parameters. During the early stages of plant growth pulsed irrigation led to higher plant weight and leaf area and there was no consistent effect found on the overall season by irrigation frequency. Under pulsed irrigation salinity in the root zone was higher and an oveservation by leaf chloride content and tensiometer readings indicated that salts from top soil was more

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efficiently removed by once daily application. Under once daily irrigation with fresh water, yield, fruit weight, and irrigation water use efficiency (IWUE) were highest. In leaves and fruits, high-frequency irrigation led to higher Mn concentrations and increased concentrations of Cl, N, and P in leaves, confirming earlier conclusions under pulsed irrigation P mobilization and uptake was improved.

Abdelraouf, *et al.* (2012) experimented in two fields and studied the effect of short irrigation cycles on soil moisture distribution in root zone, fertilizers use efficiency and productivity of potato. The results indicated that, 3rd cycle under subsurface drip irrigation gives maximum productivity of potato, due to increased in soil moisture distribution and soil moisture content in the root zone after applying short irrigation cycles compared with continuous drip irrigation. Due to increasing number of pulses inside each irrigation cycle, it causes increase in water movement in horizontal direction than vertical direction hence, increasing in moisture content in root zone and wetted soil volume more than field capacity. Where increasing in wetted soil volume more than field capacity means increasing in volume of available water and nutrients in root zone. By increasing both moisture content in root zone and wetted soil volume more than field capacity in the root zone, these nutrients would be more available for plant.

El-Mogy, *et al.* (2012) evaluated the effects on yield and nutritional elements of green beans (Phaselous vulgaris L.) by pulse irrigation. Based on number of pulses irrigation system consists of four irrigation treatments. Results showed that yield was maximum when water was applied in 4 pulses and minimum when water was applied in one time. It was seen that by increasing the number of increasing number of pulses per each irrigation the vegetative growth of green bean plants were improved. The highest concentration and lowest concentration of all determined nutrient elements was obtained under high pulse irrigation and low pulse irrigation respectively.

Phogat, *et al.* (2012a) experimented the pulse and continuous irrigation to almonds through surface drip, and water applications and moisture distribution in the soil were also monitored throughout the season. To evaluate the impact on water balance and salinity distribution in the soil of pulsed application of irrigation, a finite element numerical model (HYDRUS 2D) was used. The modelled values of moisture content matched well with the weekly measured values with neutron probe at different soil depths (10 cm to 160 cm) with RMSE of mean values varying from 0.01 to 0.08 and 0.01 to 0.05 in pulsing (Ip) and continuous (Ic) treatments respectively. Result showed that simulated seasonal water uptake was slightly higher in pulsing than continuous irrigation, whereas the soil storage was slightly higher under continuous irrigation. The leaching fraction was varying upto 0.25 in both treatments and was higher during August and March – April because of the water requirement of irrigation. The salinity distribution was similar in both treatments and simulated average salinity of soil solution varied from 0.47 to 3.38 dS/m and 0.49 to 3.67 dS/m in I_p and I_c treatments respectively. Hence the modelling simulations revealed that pulsed irrigation at higher discharge rate produced similar water and salinity distribution in the soil as obtained in low discharge continuous irrigation.

Phogat, *et al.* (2012b) experimented and verified water and salinity distribution during the profile establishment stage of almond under both pulsed and continuous drip irrigation. Under both irrigation scenarios model simulated values of water content were compared with neutron probe measured values. Model closely predicted total salts in the root zone which was indicated by correlation with meaured values. Change in soil water salinity and soil water content were simulated by HYDRUS-2D in both wetting pattern and flow domain. Initially salinity was decreased in both pulsed and continous irrigations and soil profile as a function of irrigation was mathematical described best by power function under both irrigation systems. Higher leaching was found in pulsed irrigation than in continuous irrigation with same amount of water applied. On the basis of crop evapotranspiration (ETc) when irrigation was applied daily with a suitable leaching fraction pulsing influence on soil water content, salinity distribution, and drainage flux was completely vanished.

Eid, *et al.* (2013) experimented and studied the effect of pulse drip irrigation and mulching systems for saving water, increasing and improving yield of soybean. The factors that were considered were Pulse drip irrigation technology and mulching systems. The parameters to evaluate the effect were Soil moisture distribution in root zone, Growth characters of soybean plant, Yield of soybean, Irrigation water use efficiency of soybean, Oil content and oil yield, Protein content and protein yield and some Economical parameters. According to the economical view and the results of statistical ana- lysis for effect of pulse drip irrigation and mulching systems on yield, quality traits and Irrigation water use efficiency of soybean indicated that, with using Black Plastic Mulch and applying the irrigation requirements on 8 pulses/day is the best conditions because these conditions gave the highest value of yield, quality traits and Irrigation water use efficiency of soybean. Through pulse irrigation tecniques water movement in horizontal direction increeses than vertical direction and will result in improves soil moisture distribution and wetted soil volume in root zone. Traits of applying irrigation requirement on 12 pulses/day were decreased by increasing of pulses, this may be due to irrigation water was very small with every pulse at applying irrigation requirement on 12 pulses/day and in addition increasing the total time of time-off, this mean, unsufficient application for irrigation water to remove water stress in the root zone.

Phogat, *et al.* (2013) investigated the use of HYDRUS-2D simulations conducted on field for a full grown surface drip irrigated almond orchard over a season. Daily fluctuation of water was evaluated by model under full pulsed, sustained deficit pulsed and full continuous irrigation. Assessement of pulsing impact on water flux dynamics was also seen. In the sustained deficit pulsed treatment, 65% of calculated crop evapotranspiration (ETc) was replaced by applied water, compared to replacement of 100% ETc in the other two treatments. Efficiency of water uptake under sustained deficit pulsed was higher compared to full water application conditions (full pulsed and continuous irrigation). Non-productive water fluxes were largely contributed by higher irrigation amount under full pulsed and continuous irrigation. For all treatments during the growing seasons for yield reduction, the average modelled soil solution salinity of the profile remained below the threshold. Under pulsed and slow discharge continuous irrigation seasonal water uptake by almonds remained almost on par indicates that the pulsing did not provide any additional advantage, although it is an alternative to slow discharge continuous irrigation. Under sustained deficit irrigation, irrigation water productivity increased substantially, yield was increased by 8% and about 35% of irrigation water was saved compared to full irrigation. For almond cultivation region with severe water scarcity sustained deficit irrigation appears to be a promising deficit irrigation strategy and irrigating almonds above the sustained deficit irrigation may enhance unproductive water usage in the form of accelerated drainage, which may lead to potential danger of migration of nutrients and solutes to the groundwater, thereby posing a threat to the quality of groundwater and receiving surface water bodies.

Maller, *et al.* (2016) studied and verified that the effects of pulse irrigation on cucumber plants which were subjected to either water deficit or were sufficiently supplied with water and by considering the hypothesis that the water application during times when evapotranspiration demand is greater then that will promote benefits to the crop compared with the continuous irrigation in the early hours of the day. Designed used was completely random and treatments were distributed in 3 × 4 and 4 × 4 factors in the first and second respectively, while the replenishment of the irrigation depth relative to the crop evapotranspiration was the first factor and the number of pulses was the second factor. The first and second cycles there were total 48 and 64 plots respectively. For first and second cycles the application of treatments were started in the vegetative phase and in the reproductive phase respectively. It was concluded that smaller irrigation depths than the crop requires can be applied by pulses without resulting in a reduction in the vegetative growth in Japanese cucumber.

Several experiments have shown positive responses in some crops to high frequency drip irrigation (Freeman, *et al.*, 1976; Segal, *et al.*, 2000; Sharmasarkar, *et al.*, 2001).

2.3 SOIL MOISTURE CHARACTERISTIC CURVE

The soil water characteristic curve also known as moisture characteristic curve or water retention curve is the relationship between the volumetric water content and matric suction. Different wetting and drying curves could be distinguished for the hysteretic effect of water filling the pores of soil as well as draining from the pores. Greater the clay content, the greater the water content at any particular suction and more gradual the slope of the curve. Fredlund and Xing (1994) proposed a general equation for predicting soil moisture characteristic curve. General form of equation was based on assumption that the soil moisture characteristic is dependent on pore size distribution of the soil. Over the entire range of 0 to 106 kPa the equation provided a good fit for sand, silt and clay soils. Fredlund, *et al.* (1998) concluded that for estimating the unsaturated soil properties the soil water characteristic curve is of great value. Once a reasonable estimate of the soil-water characteristic curve is obtained, satisfactory predictions of the shear strength function can be made for the unsaturated soil (Fredlund, *et al.*, 1996). Where a simple soil – water characteristic equation was used in the prediction model for the shear strength function of unsaturated soils closed – form solutions were obtained for such cases. The degree of saturation corresponds to a particular suction could be defined in the soil and thus becomes measure of the pore size distribution of the soil.

To overcome the difficulty of statistical assessment and sensitivity analysis of soil moisture characteristic curve parameters de FN Gitirana Jr and Fredlund (2004) developed a new equation. To clearly defined soil properties traditional representation of these equations do not individually correspond. The new equation represented both bimodal and unimodal soil moiture characteristic curve. It was also defined by parameters that are independently related to shape features and that have physical meaning of the soil moisture characteristic curve. The treatment of soil moisture characteristic curve data became easier by the proposed equation and from the use of an equation whose parameters are mathematically independent, statistical analysis on a large amount of data will benefit.

Zhou and Jian-Lin (2005) investigated various factors influencing the soil moisture characteristic curve. They studied the effects of void ratio, initial water content, stress state and high suction in their work revealing that water content and stress state are more important than the other effects; but that the influences tend to decrease when suction increases.

2.4 EFFECT OF PULSE DRIP IRRIGATION ON SOIL WATER DISTRIBUTION

Researches showed that from the upper half of the plant root zone approimately 70% of water used by plants is removed. When soil – water tensions in this area kept below 5 atmospheres optimum crop yields resulted. Root penetration can be extremely limited into dry soil, a water table, bedrock, high salt concentration zones (Elwin, 1997).

Levin, *et al.* (1979) conluded for his resesarch that the pulse treatment can replace the advantageous low (1 liter/hour) discharge rate to a large extent avoiding the difficulties of blocking of outlets by maintaining a higher (2 liter/hour) discharge rate. Study was to compare results between laboratory and field experiments for prediction of soil mositure distribution from point source trickle and computerized simulation model. However, both computed and experimental data were in good agreement. Under point source trickle when continuous water was applied 26 % loss of total amount applied was found for 1 lph where as 2 lph pulsed flow resulted in only 12 % loss. The lateral distribution of water for continuous irrigation 80 % of the water in the wetted soil volume was distributed 45 and 43 cm horizontally where as in pulsed treatment distribution was to 29 and 40 cm after 12 to 24 hours respectively. With not significantly affecting the horizontal distribution pulsed treatments showed a clear advantage in reducing water loss under the root zone.

Mostaghimi and Mitchell (1983) conducted laboratory experiments to study the effect emitter dicharge rate of trickler on the distribution of soil moisture in silty-clay loam soil. A simulated model was used to predict soil moisture distribution pattern and was used to evaluate laboratory results. For both pulsed and continuous irrigation treatments soil moisture distribution was studied and results showed good agreement between predicted and measured values. As increasing the trickle discharge rate resulted in decrease in horizontal component where as increase in vertical component of wetted soil profile. The water loss below root zone was found significanty less in pulse irrigation compared to the continuous. Pulsed applications rates can replace continuous small discharge rates to reduce irrigation water runoff problems on heavy soils and with restricted infiltration allow the use of larger emitter orifices to decrease potential clogging of the trickle system.

Goodwin and Boland (2001) studied deficit irrigation scheduling for optimistic water use efficiency and indicated that on Israeli sandy loam soils, within the first 30 centimeters the main root zone had been found under pulse irrigated citrus, which results in uneven distribution of root zone temperatures as upper layer soil temperatures will increase more quickly in spring than in the lower parts of the soil.

Bouma, *et al.* (2003) showed that vapour pressure deficit about the trees was reduced by pulsing irrigation in a consistent trend. To reduce water stress within the tree pulsing irrigation regime is effective. Researches from USA and Israel provided evidence that productivity and water saving improvements were provided by Open Hydroponic principle of maintaining soil moisture as close as possible to field capacity. In sandy soils when soil moisture levels fall below field capacity trees begin to experience water stress. In order to replenish soil moisture supplies near the root more quickly than with lower soil moisture contents, higher movement rates of water or hydraulic conductivity of the soil is found at higher soil moisture contents.

Applying irrigation water in pulses rather than giving it at one time can save or prevent from losses by giving enough time to media to mositen and hence allowing it to absorb subsequent irrigation more readily and reducing the total amount of water required. Scott (2000) experimented four different areas irrigated for one hour each and hence four hours of total time, and result showed that a 25 % reduction in water usage was obtained along with the adequate wetted container media by irrigating each area sequentially for 15 minutes intervals and repeating this process twice. The system becomes easy when it is automated wih solenoid valves and thus labour cost is reduced, required to turn various zones on and off.

Due to narrow paths of water which gives small discharge, the problem of emitter's clogging in sandy soil for continous drip irrigation system was major and depth of wetting pattern was relatively higher than the width, thus causes deep percolation beyond root zone. The information on depths and widths of wetted zone of soil plays the greatest role in design and management of drip irrigation system and there is a lack of models to predict wetting pattern under pulse and intermittent flow regime, since the applicability of the available models were limited to continuous flow regime only. Ismail, *et al.* (2014) researched and developed a dimensional analysis model to estimate both depth and width of wetting pattern under different flow regimes. Semi – empirical approach and dimensional analysis method was used to develop a model for determining geometry of wetted root zone. Results which were predicted values were compared to those obtained through laboratory experiments conducted in same soil. After 1, 2, 3, 4 hours of water application maximum depths and widths of wetted zone were determined under different flow regimes. Model performance was found good on the basis of root mean square, mean error and model efficiency parameters and concluded that to predict wetting pattern under continuous, intermittent and pulse flow with line source of water application developed models can be used. Pulse flow results showed that the wetted diameter increased and wetted depth decreased as the operating on-time decreased for the same amount of applied water. Deep percolation was reduced and horizontal spread increased as the pulsed flow was

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increased from six to twelve times the continuous flow. This result showed the advantage of pulse flow, for reducing the deep percolation of water under the crop root zone, while obtaining a wide horizontal spread of wetting. This enabled use of a highly discharge emitter with the same amount of water.

Weeting Pattern is mostly influenced by soil hydraulic properties, trickle discharge rate and irrigation frequency as these factors are not adequelty incorporated in the design of trickle system. Elmaloglou and Diamantopoulos (2007) studied that factors influncing on wetting front advance and on the water losses by deep percolation under the root zone for surface trickle system. The evaporation from soil and water extraction by plants root were incorporated to introduce a cylindrical flow model. Results showed that, for pulse irrigation the vertical component of wetting front was greater than for continuous irrigation in both type of soil for which study was conducted with two discharge rates and for equal irrigation time duration.

Mulching also affects wetting pattern as researches have found significant difference of wetting front under mulch and non mulch condition with trickle irrigation system. Zhou, *et al.* (2017) found that under low frequency irrigation soil moisture was most affected by mulch coverage (full or half surface coverage) where as under high frequency irrigation soil moisture was most affected by lateral spacing (adjacent to or between crop rows).

2.5 EFFECT OF PULSE DRIP IRRIGATION ON CLOGGING RATIO OF EMITTERS

The emitters likely to clog depends on mostly cross-sectional area of flow channel amount of turbulence in the flow channel. A large cross section allows flow to pass freely without clogging and highly turbulent channel allows dirt particle in suspended form while passing through emitter. Yardeni (1989) found that Pulse irrigation itself can increase the resistance to blockage in trickle irrigation and that permits to avoid bulky and costly filters. Pulse irrigation ensures more uniform irrigation over whole cycle. Use of larger emitters in drip irrigation was an effective solution to avoid clogging. Al-Amoud and Saeed (1988) proposed that to maintain application rate, system should be operated in pulses rather than continuously. Jackson and Kay (1987) demonstrated that with small change in wetting pattern pulsed flow with three times the continuous flow can be used with reduced tendency to clog and allowing a significant increase in emitter sizes.

2.6 AUTOMATION OF DRIP IRRIGATION SYSTEM

Due to increase in labour cost and operating cost of irrigation the automation of irrigation systems through sensors came and effective and efficient irrigation became possible. World irrigation systems came into a new era of automation mostly drip irrigation systems and made quality as well as quantity production possible. Through the controlling of a valves, to optimize yields and increases water use efficiency a site specific wireless sensor based controlled irrigtion system is best solution. The advantage of using wireless sensors was that it reduces complications of wires and cables and also it can be easily setup. After the use of wireless sensors researchers also tried use of microcontrollers and many such technologies like ZigBee networking. Many researcheres conducted experiments to inspect the yield and water use efficiency with automation in drip irrigation as well as pulse irrigation. For Precision Agriculture different utilities to implement wireless sensors protocol terms such as infrared, GSM/GPRS WPANs (Wireless Personal Area Networks), Bluetooth, WLANs (Wireless Local Area Networks) were also used. The main aim for automation research was to develop and verify the low cost equipped and feedback type controller for specific management of irrigation systems and this such systems can be cost effective. Moreover, this research can reduce work man power which usually floods the field and it can prevent trees or plants from moisture stress. Coates, *et al.* (2013) conducted a work to study economical aspects and payback period of automated wireless valve control system. Result showed that valve control network was estimated to have a payback period of about 3.5 – 4.5 years.

Blonquist Jr, *et al.* (2006) studied and compared irrigation scheduling in turfgrass based on weather station ET estimates with those from a novel time domain transmission (TDT) soil moisture sensor. At the burial depth of the sensor and any drainage occurring below the turfgrass rooting depth to simulate volumetric soil water content (u) dynamics computer-based numerical model was applied. TDT sensor was directly connected to a custom irrigation controller or to interface a small display/control box with a conventional irrigation timer where irrigation scheduling is based on a threshold water content. The preprogrammed schedule allowed the sensor controlled irrigation schedule by allowing it to operate whenever the sensor estimated water content dropped below threshold water content. To estimates ET for comparison TDT sensor was installed under Kentucky bluegrass with a nearby weather station over a period of approx seven weeks. For prediction of water content in the soil profile the HYDRUS-2D numerical simulation model was used. Along with estimates of evaporation, precipitation, transpiration, irrigation and root water uptake data, the flow domain geometry and boundary conditions were included in model input requirements. Results showed that when irrigating with a sprinkler having a relative application depth of 0.80 at the position of the sensor TDT system applied approximately 16 % less water, relative to ET-based irrigation recommendations where as TDT system applied approximately 53% less water, relative to a fixed irrigation rate of 50 mm week^{-1}. when uncontrolled application events were ignored no detectable water drained below the estimated 30 cm rooting depth of turfgrass which was indicated in TDT sensor control. The sensor burial depth and threshold soil moisture content performance of the TDT system is dependent. Via consideration of soil moisture content at field capacity and permanent wilting point threshold soil moisture content value is eshtablished and is also soil-type dependent. The potential water savings with the TDT system is not only important to water conservation, but can save irrigators an estimated US $5.00 – 100.00 per month based on average water prices in the US and a 1000 m^2 irrigated turfgrass plot.

Hema, *et al.* (2012) proposed an conceptual design of automated irrigation system for palm trees and GPS, soil moisture, temperature and climate sensors were used. Using Penman Monticth water demand model site specific and real time irrigation water requirement was calculated. The overall cost was reduced by making a clusters of trees in honeycomb model which covers maximum ZigBee range. Compared to square spacing of trees honeycomb model covers more clusters of trees per wireless sensor node.

Uddin, *et al.* (2012) proposed a model with variable rate automatic microcontroller based irrigation system. The source of power to control the overall system solar power was used. Sensors were used for moisture content of soil and were placed all over field and sensing was continous with data transporting to farmer, giving information of water level or water content. With the help of watere level data the motor could be controlled by mobile or remote and could ON/OFF without visiting farm. When the water content goes above the threshold value the motor will automatically start and stop without confirmation of farmer to maintain the reliable water content.

Gao, *et al.* (2013) designed an irrigation system based on wireless sensors and fuzzy controls. Monitoring nodes are used to collect the soil moisture information with growth of different crops in different periods. The input variables for fuzzy controllers were the soil moisture content deviation and the rate of change of deviation. From wireless sensor network node the data is transmitted to monitoring center and output the information on irrigation water demands and accordingly controls the opening and closing time of the valve. Results show that the system has a stable and reliable data transmission. This achieves real-time monitoring of soil on crop growth and give a right amount of irrigation based on crops growth information.

Lea-Cox, *et al.* (2013) studied wireless sensor networks and implimented for nine commercial horticultural operation. Wireless sensor networks have advantage of controlling over a wide range of area without the need for any expensive equipment and also sums the value to exisiting irrigation system as they provide direct information of crop water requirement. Two approches were cosidered for implimentation of wireless sensor networks to monitor and control irrigation water applications. Set point control approach which was based on substrate moisture measurements and Model based control which applied speciesspecific irrigation in response to transpiration estimates. Result illustrated that to greatly reduce water use, with direct economic benefits to growers wireless sensor networks have been successfully implemented in horticultural operations.

Gutiérrez, *et al.* (2014) developed an automated irrigation system to optimize water use efficiency. Wireless soil moisture sensors were distributed in the root zone of plants and also transmits data to web application. Microcontroller was programmed to control quantity of water through an algorithm developed with threshold values of soil moisture content nd temperature. The automated system was tested for sage crop field for around 136 days and results showed that compared to traditional methods this method showed 90 % of water saving and three replication of this automated system was used successfully in other places for 18 months. Because of its energy independence and low cost this system can be useful in in water limited geographically isolated areas.

Rani and Kamalesh (2014) experimented master slave combination and used grove moisture sensor, water flow sensor and Arduino. The ZigBee protocol was used for communication. Nodes cotains wireless sensor networks and actuators for analyzing, monitoring and sensing. The grove moisture sensor updates amount moisture content of the soil. Soil moisture is being measured by the dielectric constant. When the dielectric constant is high the moisture content of the soil is also high and vice-versa. Depending on the moisture content in the soil water flow will be allowed.

Shirgure and Srivastava (2014) experimented time scheduled automatic irrigation system. The treatments consisted of automatic daily irrigation with 60 min, interval 3 times, 90 min with interval two times, automtic irrigation at alternate days with 120 min, three times and 180 min, interval two times with six replications in randomized block design. Results found that water use in October varied from 65.0-72.4 l/day/plant and during May-June it was 133.0 - 147.7 l/day/plant. The fruit yield was 30.91 tonnes/ ha with irrigation on alternate day 120 min three times, followed by irrigation scheduled with 90 min. interval two times daily (30.11 tonnes/ha). With automatic irrigation at alternate day with 120 min, three times

Fruit weight (154.7 g), TSS (10.22° Brix) and juice percent (40.77) was found higher. Besides enhancing the yield, fruit quality and water use efficiency in Nagpur mandarin, the automatic drip irrigation scheduling was found as better substitute for manual drip irrigation operation.

Avatade and Dhanure (2015) studied different technologies that can be used in the implementation of the automated irrigation system. Design of the automated irrigation system based on ARM microcontroller was made. To reduce water consumption designed was proposed for optimum use of water. Temperature sensor and soil moisture sensor were used to detect the moisture level in soil. The sensors status were continously monitored by remote PC through web controller. The motor can be controlled by web page with its IP address and can switch ON/OFF without visiting farm.

Grace, *et al.* (2015) proposed the automated irrigation system using GSM. The signals obtained from moisture sensors were used. With the help of GSM modem output signals of the sensors are coordinated by the microcontroller and transmitted to the user. The proposed system is low cost system with exchange of information is done via SMS. The appropriate level of water in the farm field contributes to the quality of grains and highly affects the incidence of pests and diseases on crops.

Ferrarezi, *et al.* (2015) designed and developed the low cost open source microcontroller to overcome the use of highly expensive dataloggers. Use of capacitance sensors with microcontrollers made irrigation system more effective for both agricultural and domestic applications. 'Panama Red' hibiscus *(Hibiscus acetosella*) in a peat:perlite substrate was used for experiment and system effectively monitored and controlled the available moisture content over a range of irrigation threshold. DC solenoid valves with latching 6–18 V and AC solenoid valves with 24 V can be used with microcontrollers. The irrigation controller required little maintenance over the course of a 41-day trial. The low cost of this irrigation controller makes it useful in many horticultural settings, including both research and production.

Koprda, *et al.* (2015) experimented android as operting system and used a low-cost micro controller Arduino for automation and since sysem consists of three parts control, regulatory and server part. Control part consists of a monitoring activities for decision making process. Regulatory part consists of an arduino uno which controls switching of solenoid valves. Arduino measures humidity and sends it to database and controls the valves based on decisions of control parts and it allows the automatic control of solenoid valves. Whole system can be controlled by used with the help of android mobile phone.

Mahesh, *et al.* (2015) experimented the automation system of irrigation based on GPRS module and wireless sensor networks. The water wireless sensor network consists of a high- performance embedded micro-controller and low-power technology. Hydrographic information such as water-level, gate position and rainfall are gathered by sensor node whereas sink node receives the real time data. Those data which are transmitted from the sink node through the GPRS network are stored and processd by information center. To irrigate larger areas of plants with less water spending and minor pressure automation always ensures the sufficient level of water in the paddy field avoiding the over-irrigation and under-irrigation. System provides definite amount of water to the plant under different amount of water requirements for different types of soil according to the type of crop and water resistance capacity in different seasons hence, large amount of water can be saved.

Arvindan and Keerthika (2016) studied the automated irigation system with android smart phone. The system design includes a soil moisture sensor which senses the moisture content of soil which is then compared to the threshold value determined through sampling of various soils and specific crops. The feedback is fed to arduino micro controller connected to smart phone. Through smart phone information regarding moisture content can be collected also it is programmed to act as remote control including the turning on/off motor. This remote-controlled management can be used to control the irrigation pumps along with the valve system for the water flow and direction of flow to be controlled. The water flow quantity can be controlled with the switching of the pump motors and the draining and letting the water out of the farm fieldsregulates the direction of the water flow. The real-time agriculture applications can be possible by by updating the above system.

Castro, *et al.* (2016) researched the design and implementation of a wireless sensor network for strawberry crops and to get soil moisture measurements from different zones. During the production stage of crop the field capacity and irrigation threshold both the prameters were calculated for entire crop and through both parameters the water requirements for crops were estimated. The ZigBee networking systems were used for communication between network nodes. Compared to the traditional irrigation system results showed more water use efficiency and improved strawberry quality.

Giri and Pippal (2016) studied how effectively the water resources could be utilized in the irrigation process using the Wireless Sensor Networks (WSN). By supplying water to the roots of the plants using the drip irrigation system and uses low water pressure. The future work that could be done is to supply water based on the soil moisture as well as based on specific crops and changes to temperature.

Kumar, *et al.* (2016) reserched and proposed a home made moisture sensor which uses block of thermo-col along with two long coppers wires which acted as a sensor. To increase the range of the sensing device multiple sensors were used. Arduino then receives the voltage proportional to the resistance. This system used two methods in which first method the amount of moisture content was obtained and the values were recorded. Zones of conductivity were defined by three LED's in which if the red LED glows, then it indicates that the soil is dry also referred as the dry zone. If the green LED glows on the PCB, it indicates that the moisture content is up to the level and does not require any more water. The third zone is the one in which the soil has more water content than the normal. In second method the same sample of soil was taken in a bottle of certain height and the moisture at different levels of the soil were being tested and three sensors were being inserted at three different depths. The output of the three sensors wass given as an analog input A0, A1, A2 to the Arduino board. The warning if the water level is too low or too high, LED's can be used as an indicator. When and how much water is required for the root of the crop that can be understand by the calculation of the moisture at different levels.

Manoj Guru, *et al.* (2017) conducted an experiment to develop a low cost wireless sensor network and an automatic irrigation system for the agricultural lands. Automation provides comfort, reduce energy, efficiency and saves time. Research was based on multi sensors which were combination of temperature sensor, humidity sensor, motion sensor, light sensor, vibrating sensor and UV sensor. Sensors value were directly sent to analytical device which analyzes the value and send back the signal through GSM to mobile and also it was used to detect the level of pesticides. This system can be impliment to field for the quantity and quality production by replacing continous drip irrigation with pulsed drip irrigation system.

Okasha (2017) designed a system to control the water pump for pulse irrigation system. The arduino uno was used to control the water pump and was working according to the programmed with 20 min on cycle and 20 min off cycle which can be changed according to crop and moisture content of soil. This helps in reducing the enegy and time for pulse irrigation to on and off the valve according to on/off cycle timings. Due to on/off valves automatically for pulse irrigation system it saves cost, time and energy. The use of soil moisture sensors, microcontrollers and solenoid valves makes the irrigation smarter and economic.

Numerous researchers have worked with automatic water sprinkling or irrigation system and many matrix were prepared to maintain the water level of soil. Different types of soil sensors were also used for different automated irrigation system. The sensing and transporting of data to user was controlled by different microcontrollers and design of control system was discussed. Bhawarkar, *et al.* (2014) and Rane, *et al.* (2014) proposed review paper of different technologies used for automation and different control sytems were discussed. The methods used for present research and the technical aspects were covered in next chapter.

CHAPTER III

MATERIALS AND METHODS

The main goal of any irrigation management system such as to control opening and closing of valves, automatic fertilizer application in the field etc. is to make a most efficient system by deciding the correct and proper use of water, fertilizer and energy. Thus, this system enables the application of right amount of water to plant at the right time and in right place. The system reduces the labour cost and it is more reliable compared to other systems. In other side, it is very sophisticated and applicable mostly to large-scale cultivation only. Hence, this study is mainly intended to make an irrigation control system according to the moisture content available in the soil. The system consists of low-cost Wireless Soil Moisture Sensor connected with Arduino UNO to control the irrigation system (based on the moisture available in soil) with opening and closing the solenoid valve. This chapter includes the study of soil characteristics of the study location and development of the automated Pulse drip irrigation system.

3.1 STUDY AREA

3.1.1 Location

The experiment was conducted at instructional farm of Kelappaji College of Agricultural Engineering & Technology, Tavanur, Malappuram district located at 10°51'05" N latitude and 75°59'14" E longitude with an altitude of 27 meter above mean sea level.

3.1.2 Climate

The climate of the study area is humid – tropical with an average rainfall of 3000 mm mainly from South – West and North – East monsoon and average pan evaporation is 6.8 mm/day. April to June remains hot month with the mean temperature varying between 28.9 °C to 36.2 °C and December to February remains cold month with mean monthly minimum temperature varying between 17.0 °C to 23.3 °C.

3.2 CHARACTERISTICS OF SOIL

Different physical soil characteristics such as soil texture, soil moisture content, bulk density, pH, electrical conductivity were measured using different apparatus available in the soil and water laboratory.

3.2.1 Moisture content

The present moisture content was measured by taking the three soil samples each at different depths of 10 cm, 20 cm, 30 cm, 40 cm and 50 cm. The gravimetric method was used to measure the moisture content. The core cutter was used to measure moisture content of undisturbed soil sample.

3.2.2 Bulk density and dry density

Bulk density at all above-mentioned depths were measured using core cutter as undisturbed samples. The corresponding moisture content were also measured to determine dry density.

3.2.3 E_c and pH

The E_c and pH of soil were measured through EC and pH meters respectively by making soil water extract. The pH and E_c meters were calibrated with standard solutions before taking measurements.

3.2.4 Soil texture analysis

The bulk quantity of soil was dried and then were mixed up homogeneously. These soils were then kept in sieve shaker apparatus for 10 min. The percentage of soil retained were measured and percentage finer was tabulated. Hydrometer analysis was also done to measure the percentage of fine particles such as silt and clay content. The hydrometer reading was taken and wet sieve analysis was performed, the percentage finer were tabulated afterwards. The Particle size distribution curve was prepared based on all the tabulated data. Through soil textural classification triangle, the texture of soil was obtained.

3.2.5 Liquid limit and plastic limit

The liquid limit of soil was measured through Casagrande method. Liquid limit is the moisture content at which the groove formed by a standard tool into the sample of soil taken in the standard cup, closes for 10 mm, on about 25 blows in standard procedure. Liquid limit is limiting moisture content at which cohesive soil passes from liquid state to plastic state (IIT KGP lab manual). Plastic limit of the soil is the moisture content at which soil begins to behave as a plastic material. At this water content, the soil will crumble when rolled into threads of 3.2 mm in diameter (The constructor Determination of PL of soil).

3.2.6 Saturated hydraulic conductivity

The saturated hydraulic conductivity of soil was measured through permeameter with falling head method. The undisturbed sample was placed in permeameter and the falling head method was performed. The permeability decreases with increase in bulk density.

3.2.7 Specific gravity

The specific gravity was measured through pycnometer method. The dried soil was taken into pycnometer and distilled water was poured into it. Then the weight was taken and again it was cleaned. It was again filled with distilled water and the weight was measured. The standard expression was used to determine specific gravity determine.

3.3 SOIL MOISTURE CHARACTERISTIC CURVE

The tension corresponding to Management Allowed Depletion (MAD) was obtained by plotting soil moisture characteristic curve. Maximum Allowed Depletion is the maximum amount of plant available water and it is also known as allowable soil water depletion. The portion of water used by plants prior to irrigation based on the plant and its management conditions is the allowable soil water depletion. Soil moisture characteristic curve represents the relationship between the soil suction and corresponding moisture content of soil. Tensiometric irrigation scheduling could be done by the soil moisture characteristic curves. These curves are hydraulic properties related to size and pores spaces that are strongly affected by soil texture and structure. The moisture characteristics curve was obtained by measuring different moisture content values at different suction values.

It was also known that soil water retention curve experiences hysteresis effect when it comes to wetting cycle from the drying cycle. The drying curve was obtained by using the pressure plate apparatus manufactured by Soil Moisture Equipment Cooperation (USA). The wetting cycle was measured through the capillary rise open tube method (Yang, *et al.*, 2004).

3.3.1 Wetting cycle

The soil retention curve for wetting cycle can be obtained by capillary rise open tube. The capillary rise tube was filled with the undisturbed soil. The tube was placed in the soil fully through hammer to get undisturbed soil samples. The tubes were then oven dried. These tubes were placed into the tray and water table was maintained in the tray. The tops of the tubes were covered with cloth to prevent evaporation. Water in the tray starts to move in to the soil through capillary actions as soon as it was placed into the tray. The capillary tube was reached to equilibrium within 2 weeks. Water table in tray was maintained to constant and after equilibrium water level was constant. Then soil samples were taken out from various levels.

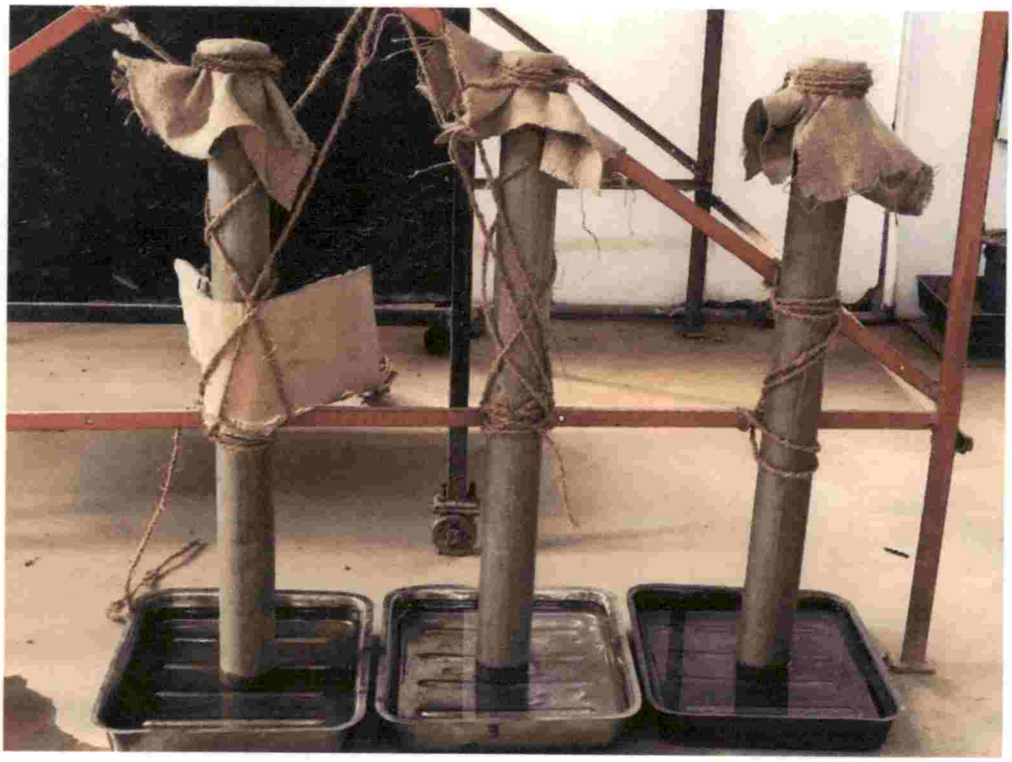

Plate 3.1 Capillary Rise Open Tube setup

The samples were oven dried to determine moisture content. The height of the soil specimen above the water level was assumed equal to capillary or negative pore-water pressure. This magnitude of negative pore-water pressure head is equal to the matric suction head at that point. Air pressure in this tube was at atmospheric pressure. The plot of water content versus matric suction gives the wetting Soil moisture characteristic curve of soil (Yang, *et al.*, 2004). These capillary tubes were kept until the equilibrium between soil capillary action or upward movement. The moisture content at different heights were measured and tabulated to prepare wetting cycle of SWCC.

3.3.2 Drying cycle

The soil retention curve for drying cycle can be obtained by simulating the required pressure in pressure plate apparatus and finding respective moisture content. Pressure plate apparatus was introduced in 1930's by L. A. Richards. The pressure plate apparatus was used to quantify the moisture retained in soil. The basic principle of this apparatus is to apply the different matric tensions to the saturated sample placed between the porous plates. For determining the moisture characteristic curve, this apparatus was used as a standard technique. The samples were first saturated and were placed on a porous ceramic plate inside the pressure chamber. The ceramic plate was maintained at atmospheric pressure while samples were pressurized and thus subsequent flow occurs through saturated ceramic plate from the samples. Once the soil samples reach equilibrium with the imposed pressure according to theory the flow ceases. The suction pressure used for obtaining the Soil moisture retention curve were 0, 0.1, 0.33, 1.0, 3.0, 5.0 & 15.0 bar. The moisture content of the samples after experiment were measured through gravimetric method. Then the measured moisture content at corresponding suction were plotted on graph. The soil water retention curve was drawn using that observed values. Since the curve undergoes through hysteresis effect, the drying as well as wetting curve were prepared.

Plate 3.2 Pressure Plate Apparatus

For characterizing the hydraulic and mechanical behaviour of unsaturated soils, the soil moisture characteristic curve, which relates water content or saturation to suction, is essential. The soil moisture characteristic curve is basically used for the determination of field capacity and permanent wilting point moisture values. According to theory, the field capacity is generally attained at 1/10 to 1/3 bar suction pressure whereas the permanent wilting point is attained at 15 bar pressure. Where lower suctions (< 5 bar) are to be applied, pressure plate extractor is generally used. Pressure membrane apparatus are used for higher matric suctions that have robust pressure cells, which can withstand higher air pressures up to 15 bars. The plants can easily extract water from soil up to a critical point from saturation or field capacity, which is known as readily available water. In this range, plants are neither waterlogged or water stressed. The critical point is called as nominated refill point for unrestricted growth. This point is generally obtained at 50 % of available water. Thus, the irrigation scheduling can be planned according to the values of field capacity and 50 % of available water content value. Through which the plant can easily extract the water and thus, there will not be any effect on plant growth.

3.3.3 Hysteresis effect of soil moisture characteristic curve

The soil water characteristic curve (SWCC) and the saturated hydraulic conductivity are the two most commonly used hydraulic functions for numerical models determining the groundwater flow. Hysteresis in the SWCC refers to the non-unique relationship between the soil's matric suction and its water content, whereby the soil can have two different water contents at the same matric suction value, depending on the preceding sequence of wetting and drying (Bashir, *et al.*, 2015). Various factors can be the reasons of such hysteresis effects. The different contact angles in the advancing and receding soil-air interface menisci, variable and irregular cross-sections of the pores, and the difference in entrapped air volume at different matric suction values are some of the factors causing hysteresis effect. The hysteresis effect showed that at any given pressure head the soil could have two different moisture contents, one from drying curve of SWCC and other from wetting curve. The hysteresis effect is also called as ink-bottle effect. Considering the ink-bottle effect as the imbibition and draining. As the suction increases, smaller and smaller pores are drained and the films of water around particles become thinner. If the water is fed to the soil, thus reducing the suction, larger pores refill but smaller pores resist adsorption.

3.4 VARIOUS MODELS OF SOIL WATER RETENTION CURVE

The traditional ways to determine the moisture retention curves involves many methods with and without considering the hysteresis effect. The precision methods are used for the determination of retention curves for various soils. Researchers developed many models through which the predictive models with respect to various soil types can be yielded. The models developed by different researchers are having different characteristics, some are accurate for particular soils whereas some are accurate for all type of soils. During the past several decades, a large number of computer models have been developed to simulate water flow and contaminant transport in saturated and unsaturated soils and fractured rock (Ghanbarian-Alavijeh, *et al.*, 2010). These models either can be based on soil texture or basic index soil properties. Some of the models that were used for the present study are described below:

3.4.1 Ghanbarian *et al.* 2010 model

This model uses the basic soil properties for prediction of Soil water retention curve. The parameters are estimated for the Fine Grained and Coarse-Grained soils differently. The input values taken are clay content, voids ratio and saturated hydraulic conductivity. However, the objective was to develop fractal methods for estimating the van Genuchten model parameters. The retention curve based on these parameters were obtained.

The van Genuchten model has following form (van Genuchten, 1980) :

$$S_e = \frac{1}{[1+(\alpha h)^n]^m} \qquad \ldots 3.1$$

Where, S_e is the effective saturation (fraction),

h is the matric potential (kPa),

α (kPa^{-1}), n and m ($m = 1-(1/n)$) are empirical parameters.

$$S_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \qquad \ldots 3.2$$

Where, θ is the volumetric water content ($cm^3\ cm^{-3}$) at matric potential-h (kPa),

θ_r is the residual water content(fraction, cc/cc),

θ_s is the saturated water content (fraction, cc/cc),

The above equations are used to predict the moisture content for a given value of matric suction. Where the value of α, n and m are found through following tables:

$$D = a_0 + \frac{1-e^{a_1 C_p}}{a_2(1+e^{a_1 C_p}) + a_3(1-e^{a_1 C_p})} \qquad \ldots 3.3$$

Where, D is the fractal dimension of Soil water retention curve,

C_p is the soil clay percentage,

a_0, a_1, a_2 and a_3 are constant coefficients equal to 2.35, 0.0822, −0.497 and 1.238, respectively.

Now, m and n are found by,

$$m = \frac{3-D}{4-D} \qquad \ldots 3.3a$$

$$m = 1 - {}^{1}/_{n} \qquad \ldots 3.3b$$

The value of α is determined from the table:

Table 3.1 Values of various van Genuchten parameters for different Soil types

Soil Type	θ_r	θ_s	n	α cm^{-1}	Ks cm/sec	θ_r	α kPa^{-1}	α kPa
Sand	0.045	0.43	2.68	0.145	8.25E-03	0.045	1.47	0.677
Loamy sand	0.057	0.41	2.28	0.124	4.05E-03	-	-	0.791
Sandy loam	0.065	0.41	1.89	0.075	1.22E-03	0.061	1.01	1.308
Sandy clay loam	0.1	0.39	1.48	0.059	3.64E-04	-	-	1.663
Loam	0.078	0.43	1.56	0.036	2.89E-04	-	-	2.725
Silt loam	0.067	0.45	1.41	0.02	1.25E-04	0.082	0.39	4.905
Clay loam	0.095	0.41	1.31	0.019	7.22E-05	-	-	5.163
Silt	0.034	0.46	1.37	0.016	6.94E-05	-	-	6.131
Clay	0.068	0.38	1.09	0.008	5.55E-05	-	-	12.263
Sandy clay	0.1	0.38	1.23	0.027	3.33E-05	-	-	3.633
Silty clay loam	0.089	0.43	1.23	0.01	1.94E-05	0.077	0.16	9.810
Silty clay	0.07	0.36	1.09	0.005	5.55E-06	0.070	0.00	19.620

(Source: Ghanbarian-Alavijeh, *et al.*, 2010*)*

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3.4.2 Benson *et al.* 2014 model

Empirical functional relationships based on the particle size distribution and other compositional factors are known as Pedo-transfer functions (PTFs). It is the most common method used to determine Soil moisture characteristic curve (van Genuchten, *et al.*, 1992). This model is only suitable for Coarse-grained soil only. The objective of model was to develop an intuitive, quick, quantitative and simple method to estimate n and α based on particle size distribution data which captures the conceptual relationship between n and α and the size and distribution of particles in sand. This model uses the van Genuchten equation form but determination of van Genuchten parameters are in different way:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[\frac{1}{1+(\alpha\,\psi)^n}\right]^{1-(1/n)}} \qquad \ldots 3.4$$

Where, θ is the volumetric water content (fraction, $cm^3\ cm^{-3}$),

θ_r is the residual water content (fraction, $cm^3\ cm^{-3}$),

θ_s is the saturated water content (fraction, $cm^3\ cm^{-3}$),

α (kPa^{-1}), n and m ($m = 1-(1/n)$) are empirical parameters,

ψ is the matric potential (kPa).

Here the θ_s is calculated through voids ratio and in that study, θ_r obtained by fitting above equation to the SWCC data ranged from 0.030 to 0.045, and averaged 0.040. The input of this model is the D_{10} and D_{60} from Particle size distribution curve and voids ratio. This model gives both drying as well as wetting curve data.

van Genuchten parameters for drying and wetting were found as below:

$$Drying\ \alpha = N_\alpha * \alpha_d \qquad \ldots 3.4.1$$

$$N_\alpha = 0.99\ C_u^{-0.54} \qquad \ldots 3.4.1a$$

$$\alpha_d = 1.354\ D_{60} \qquad \ldots 3.4.1b$$

$$C_u = \frac{D_{60}}{D_{10}} \qquad \ldots 3.4.1a_1$$

Where, C_u is uniformity coefficient and N_α is normalize α.

$$Wetting\ \alpha = N_\alpha * \alpha_d \qquad \ldots 3.4.2$$

$$N_\alpha = 0.99\ C_u^{-0.54} \qquad \ldots 3.4.2a$$

$$\alpha_d = 1.993\ D_{60} \qquad \ldots 3.4.2b$$

$$C_u = \frac{D_{60}}{D_{10}} \qquad \ldots 3.4.2a_1$$

Where, C_u is uniformity coefficient and N_α is normalize α.

Here n and m are found based on the uniformity coefficient,

(Source: Benson, et al., 2014)

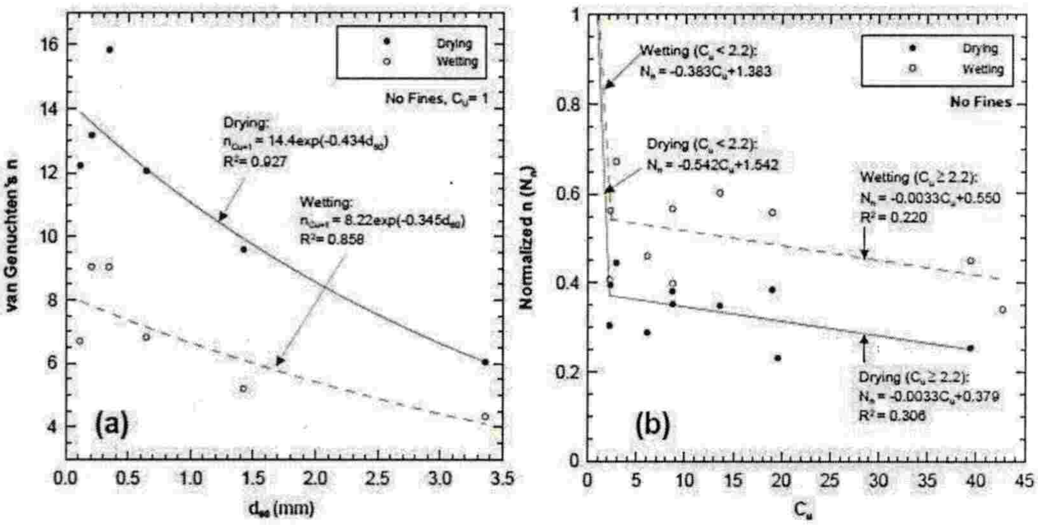

Plate 3.3 (a) Effect of D_{60} on n of clean and uniform sand (C_u=1) (b) Effect of breadth of particle sizes (in terms of C_u) on n of clean sand

3.4.3 Zapata *et al.* 2000 model

This model uses less data as input and the inputs are different for fine- and coarse-grained soils. The fine-grained soil requires only plastic limit and voids ratio data whereas coarse-grained soil requires D_{10} and voids ratio data. This model uses the same Fredlund and Xing model but the parameters are calculated differently.

The Soil moisture retention curve can be obtained by following equations:

$$\theta = C(\Psi)\left[\frac{\theta_s}{\left[\ln\left[exp(1)+\left(\frac{\Psi}{a}\right)^b\right]\right]^c}\right] \qquad ...3.5$$

$$C(\Psi) = \left[1 - \frac{\ln\left(1+\left(\frac{\Psi}{\Psi_r}\right)\right)}{\ln\left(1+\left(\frac{10^6}{\Psi_r}\right)\right)}\right] \qquad ...3.5a$$

Where, θ is the volumetric water content ($cm^3\ cm^{-3}$),

θ_s is the saturated water content ($cm^3\ cm^{-3}$),

a, b, c and Ψ_r are empirical parameters,

ψ is the matric potential (kPa),

$C(\psi)$ is correction factor which is a function of matric suction.

These empirical parameters are calculated differently based on fine grained and coarse-grained soils:

3.4.3.1 Fine grained soil parameters

When Plasticity Index *(wPI)* > 0,

$$a = 0.00364\ (wPI)^{3.35} + 4\ (wPI) + 11$$

$$\frac{b}{c} = -2.313\ (wPI)^{0.14} + 5$$

$$c = 0.0514\ (wPI)^{0.465} + 0.5$$

$$\frac{\Psi_r}{a} = 32.44\ e^{0.0186\ (wPI)} \qquad ...3.6$$

3.4.3.2 Coarse grained soil parameters

When Plasticity Index *(wPI)* = 0,

$$a = 0.8627\ (D_{60})^{-0.751}$$

$$\bar{b} = 7.5$$

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$$c = 0.1772\ \ln(D_{60}) + 0.7734$$

$$\frac{\Psi_r}{a} = \frac{1}{D_{60}+9.7\ e^{-4}} \qquad \ldots 3.7$$

Where, D_{60} = Grain diameter corresponding to 60 % of weight passing,

$\overline{b}$ = Average value of fitting parameter

3.4.4 Perera *et al.* 2005 model

This model is same as Zapata, *et al.*, 2000 model but the parameter calculations are different. Both Zapata, *et al.*, 2000 and Perera, *et al.*, 2005 model are used to determine the Fredlund and Xing models parameter. This models test results obtained were combined and compiled with an existing database of (Zapata, *et al.*, 2000). Each SWCC data set was fitted with Fredlund and Xing curve, which provided an S-shaped curve with four parameters, a_f, b_f, c_f, and h_{rf}. Using multiple regression analysis, equations were derived for these four parameters based on predictors derived from Grain Size Distribution and Plasticity Index (Perera, *et al.*, 2005).

The Soil moisture retention curve can be obtained by following equations:

$$\theta = C(\Psi)\left[\frac{\theta_s}{\left[\ln\left[exp(1)+\left(\frac{\Psi}{a_f}\right)^{b_f}\right]\right]^{c_f}}\right] \qquad \ldots 3.8$$

$$C(\Psi) = \left[1 - \frac{\ln\left(1+\left(\frac{\Psi}{\Psi_{rf}}\right)\right)}{\ln\left(1+\left(\frac{10^6}{\Psi_{rf}}\right)\right)}\right] \qquad \ldots 3.8a$$

Where, θ = The volumetric water content ($cm^3\ cm^{-3}$),

θ_s = The saturated water content ($cm^3\ cm^{-3}$),

a_f = Fitting parameter, which is primarily a function of the air entry value of the soil,

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b_f = Fitting parameter, which is primarily a function of the rate of water extraction from the soil, once the air entry value has been exceeded,

c_f = Fitting parameter, which is primarily a function of the residual water content,

Ψ_{rf} = Fitting parameter, which is primarily a function of the suction at which residual water content occurs,

Ψ = The matric potential (kPa).

These empirical parameters are calculated differently based on fine grained and coarse-grained soils:

3.4.4.1 Fine grained soil parameters

When Plasticity Index *(wPI)* > 0 or for Plastic soil,

$$a_f = 32.835\ \ln(wPI) + 32.438$$

$$b_f = 1.421\ (wPI)^{-0.3185}$$

$$c_f = -0.2154\ \ln(wPI) + 0.7145$$

$$\Psi_{rf} = 500 \qquad \ldots 3.9$$

3.4.4.2 Coarse grained soil parameters

When Plasticity Index *(wPI)* = 0 or for Non-Plastic soil,

$$a_f = 1.14\,a - 0.5 \qquad \ldots 3.10$$

Where,

$$a = -2.79 - 14.1\ \log(D_{20}) - 1.9 \cdot 10^{-6}\ P_{200}^{4.34} + 7\ \log(D_{30}) + 0.055\ D_{100}$$

$$D_{100} = 10^{\left[\frac{40}{m_1} + \log(D_{60})\right]}$$

$$m_1 = \frac{30}{[\log(D_{90}) - \log(D_{60})]} \qquad \ldots 3.10a$$

The value of a_f has been limited to 1.0

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$$b_f = 0.936\,b - 3.8$$

Where,

$$b = \left\{5.39 - 0.29\ \ln\left[P_{200}\left(\frac{D_{90}}{D_{10}}\right)\right] + 3\,D_0^{0.57} + 0.021\,P_{200}^{1.19}\right\}\,m_1^{0.1}$$

$$D_0 = 10^{\left[\frac{-30}{m_2} + \log(D_{30})\right]}$$

$$m_2 = \frac{20}{[\log(D_{30}) - \log(D_{10})]}$$

$$c_f = 0.26\,e^{0.758c} - 1.4\,D_{10} \qquad \ldots 3.11$$

Where,

$$c = \log m_2^{1.15} - \left(1 - \frac{1}{b_f}\right)$$

$$\Psi_{rf} = 100 \qquad \ldots 3.11a$$

The input values for non-plastic soils are D_{10}, D_{20}, D_{30}, D_{60}, D_{90}, silt content and voids ratio whereas for plastic soil only plasticity index and voids ratio data are needed. Some closed form models are also developed which uses the parameters determined by above models. van Genuchten (1980) and Gardner (1958) uses the parameter determined by Ghanbarian-Alavijeh, *et al.* (2010) model. Fredlund and Xing (1994) (1) and Fredlund and Xing (1994) (2)[3] models uses the parameter determined by Zapata, *et al.* (2000) and Perera, *et al.* (2005) models. The parameters obtained by Zapata, *et al.* (2000) and Perera, *et al.* (2005) models were averaged.

3.4.5 van Genuchten 1980 model

The simulation of fluid flow in unsaturated condition was became very popular and many models were based on derivation of closed form analytical expression of hydraulic conductivity models. Based on the information of soil water characteristic curve and saturated conductivity, Mualem, 1976 derived a model predicting hydraulic conductivity. Muallem's equation lead to a simple integral formula for unsaturated hydraulic conductivity that gave an opportunity to derive the closed form analytical expressions and providing suitable equations for Soil water retention curve. From soil water characteristic curve following equation was derived by (Mualem, 1976):

$$K_r = \theta^{1/2} \left[\int_0^{\theta} \frac{1}{\Psi(x)}\, dx \Big/ \int_0^{1} \frac{1}{\Psi(x)}\, dx \right]^2 \qquad \ldots 3.12$$

Where,

Ψ is pressure head given as a function of volumetric water content

$$\Theta = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} = \left[\frac{1}{1+(\alpha\, \Psi)^n}\right]^m \qquad \ldots 3.12a$$

Where, a, n and m are undetermined parameters

Burdine, 1953 model also gave similar results as above for Maulem, 1976 model. The equation given by (Burdine, 1953) :

$$K_r = \theta^2 \left[\int_0^{\theta} \frac{1}{\Psi^2(x)}\, dx \Big/ \int_0^{1} \frac{1}{\Psi^2(x)}\, dx \right] \qquad \ldots 3.13$$

The analysis is same as before. Primary tests indicate that Burdine based equations were in most in lesser agreement with experimental data than the Muallem based expressions. The prediction based on Muallem's theory that was basically by means of numerical approximations, were generally more accurate than those based on Burdine's various forms theory.

The soil moisture content as a function of pressure head is given by:

$$\Theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha\, \Psi)^n]^m} \qquad \ldots 3.14$$

As per the above equation four independent variables θ_s, θ_r, α and n are to be estimated from observed soil moisture characteristic data. Saturated water content θ_s and θ_r can be easily obtained by experiment in laboratory.

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3.4.6 Gardner 1958 model

Gardner proposed an equation for the permeability function. The equation simulates the Soil water retention curve and can be visualized by van Genuchten equation.

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha \, \Psi)^n]} \qquad ...3.15$$

Where,

θ is the volumetric water content ($cm^3 \, cm^{-3}$),

θ_r is the residual water content ($cm^3 \, cm^{-3}$),

θ_s is the saturated water content ($cm^3 \, cm^{-3}$),

α (kPa^{-1}) and n are empirical parameters.

3.4.7 Fredlund and Xing 1994 model

Equations proposed for the prediction of Soil moisture characteristic curve are often empirical in nature. Each equation is applied to particular group of soil type. To describe the general form of predictive Soil water retention curve over entire suction range, volumetric water content is referenced as zero moisture content. General form to approximate the soil retention curve is as follow:

$$\theta(\Psi) = \theta_s \int_{\Psi}^{\infty} f(h) \, dh \qquad ...3.16$$

Where, $f(h)$ is pore-size distribution as a function of suction

This equation generally given non-symmetrical S-shaped curve. By means of several equation's simulations and various integration techniques parameters were carried out and produces the non-symmetrical curve that is closer to the experimental data.

Volumetric water content and Soil moisture suction relationship can be given by:

$$\theta = \theta_s \left[\frac{1}{\ln[1+(\alpha \, \Psi)^n]}\right]^m \qquad ...3.17$$

According to above equation when suction is zero, θ becomes equal to θ_s and when suction goes, infinity θ becomes zero. Degree of saturation can also be used for curve fitting. Nevertheless, experimental data have shown that at zero moisture content the suction of soil reaches maximum value of approximately 10^6 kPa (Fredlund and Xing, 1994). The upper limit can be given to above equation as following:

$$\theta\,(\Psi, \alpha, n, m) = C(\Psi)\,\frac{\theta_s}{\{\ln[1+(\alpha\,\Psi)^n]\}^m} \qquad \text{...3.18}$$

$$C(\Psi) = 1 - \frac{\ln(1+\Psi/\Psi_r)}{\ln[1+(1{,}000{,}000/\Psi_r)]} \qquad \text{...3.18a}$$

Where,

Ψ_r is the suction corresponding to the residual water content θ_r.

Some applications require estimation of the residual moisture content. Following equation can be used to determine the residual moisture content θ_r.

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{\{\ln[e+(\alpha\,\Psi)^n]\}^m} \qquad \text{...3.19}$$

Through the best fit analysis of experimental data, the five parameters $\alpha, n, m, \theta_s, \theta_r$ can be systematically identified. However, θ_r, θ_s are treated as two additional parameters.

3.5 DESIGN CRITERIA OF PULSE IRRIGATION

The pulse drip irrigation is the irrigation in which the ON and OFF time of pulse cycle is repeated continuosly till the required depth of irrigation (D_i) has been applied. In each cycle, the irrigation application continued for the duration of t_{ON} and rest for the duration of t_{OFF}. The cycles of t_{cycle} duration will be repeated for the duration of irrigation time (T_c) for each of the shift.

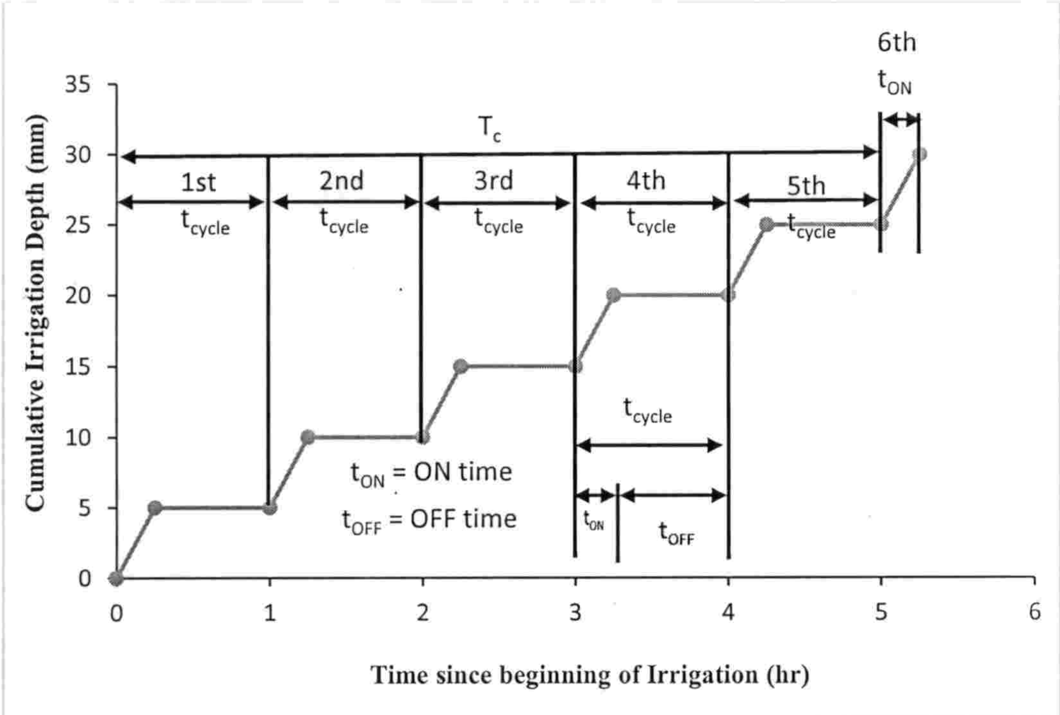

Fig. 3.1 Simplification of Pulse Irrigation

The design of pulse irrigation requires the infromation like water avaliability during the irrigation interval, daily water available, irrigation depth, irrigation interval, water pumping/conveyance/supply capacity, duration of the available power supply in a day and etc. The design of pulse irrigation will result the infromation namely area to be irrigated during the given irrigation interval, area to be irrigated in a day, area to be irrigated in a shift, number of solenoids valve/shifts, time components of pulse irrigation (ON time, OFF time, Cycle time, total time of irrigation in a shift), number of cycles in a irrigation.

The pulse drip irrigation can be degined on the basis of Total Available Water (TWA) in a given irrigation interval (IT), depth of irrigation (D_i) to be applied at given irrigation interval to the given cropped area (TA_c) by installing the drip system having total S_n solenoid valves.

Let considered the following parameters defined as below :

The field area that can be irrigated during the irrigation interval (IT) with D_i depth of irrigation can be determined as :

$$A_T = \frac{TWA}{D_i};\ \text{If}\ A_T \leq TA_c;\ A_T = \frac{TWA}{D_I};\ \text{otherwise}\ A_T = TA_c \qquad \ldots 3.20$$

If this area (A_T) to be irrigated during the irrigation interval (IT) is less than the available cropped area (TA_c), the A_T is taken as TA_c.

The daily water availability (DWA) can be dtermined as :

$$DWA = \frac{TWA}{IT} \qquad \ldots 3.21$$

Where,

DAW = Daily water availability (ha – mm/day)

TWA = Total available water in a given irrigation interval (ha – mm).

IT = Irrigation interval (Days).

If the depth of irrigation (Di) is required to be applied by pulse irrigation, the area that can be irrigated per day during the iririgation interval can be determined as :

$$A_d = \frac{DWA}{D_i};\ \text{If}\ A_d \leq \frac{TA_c}{IT},\ A_d = \frac{DWA}{D_i},\ \text{otherwise}\ A_d = \frac{TA_c}{IT} \qquad \ldots 3.22$$

Where,

D_i = Depth of irrigation to be given (mm) at an interval of IT days.

A_d = Area required to be irrigated (ha/day).

The water suply rate can be the constraint because of conveyance or pumping system capacity. Let Q is water supply rate (ha–mm/h) through pumping/conveyance system and I_{act} is actual rate of irrigation application (mm/h). The area that can be covered in each shift can be detrmined as :

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$$I_{act} = \frac{q}{(LL\ x\ DD)}$$

$A_s = \frac{Q}{I_{act}}$; If $A_s \leq A_d$, $A_s = \frac{Q}{I_{act}}$, otherwise, $A_s = \frac{DWA}{D_i}$ ...3.23

Where,

A_s = Area to be irrigated in a shift (ha).

Q = Water supply rate (ha-mm/h) through pumping system

I_{act} = Actual rate of irrigation application (mm/h).

Q = Dripper discharge (LPH)

LL= Lateral spacing (m)

DD = Dripper spacing (m)

The number of shift or solenoid valves can be estimated as :

$S_n = \frac{A_d}{A_s}$; (Take integer towards higher value) ...3.24

Where,

S_n = Number of solenoid valves/shifts required to cover daily irrigated area (A_d).

A_d = Total field area to be irrigated (ha/day)

A_s = Area served by one shift/solenoid valve (ha/solenoid valve)

Let the power supply available is for the duration of T hous in a day. The time of each pulse cycles can be estimated as :

$T_c = (n - 1)\ t_{cycle} + t_{ON}$ OR

$T_c = n\, t_{ON} + (n-1)\, t_{OFF}$ OR

$$T_c = n\, t_{cycle} - t_{OFF} \qquad \text{...3.25}$$

Where,

t_{ON} = Irrigation ON time in pulse cycle

t_{OFF} = Irrigation OFF (rest) time in pulse cycle.

T = Duration of hous in a day

The pulse irrigation can be time efficient system if the number of solenoid valves is matched with pulse ratio. It should be such that when 1st valve is open during the particular cycle, the rest $S_n - 1$ valves are closed. During the rest tiime of 1st valve after the particulr clycle, that pulse cycle should be completd by each of rest valves. These actions will be repeated for each of the pulse cycles. The relationship between the P and S_n can be establised as below.

The pulse ratio (P) is the ratio of irrigation ON – time to pulse cycle time, defined as below,

$$P = \frac{t_{ON}}{t_{cycle}} = \frac{t_{ON}}{t_{ON} + t_{OFF}} = \frac{1}{S_n}$$

$$S_n = \frac{t_{ON}+t_{OFF}}{t_{ON}} \qquad \text{...3.26}$$

The average application rate during the pulse irrigation can be estimated as

$$I_{ave} = \frac{D_i}{T_c} \qquad \text{...3.27}$$

Where,

T_c = Duration of pulse irrigation through n-pulse cycles (hr)

I_{ave} = Average application rate during the pulse cycle (mm/h)

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The ratio of average application rate and actual aplication rate can be determined as :

$$R = \frac{I_{ave}}{I_{act}} = \frac{\frac{D_i}{T_c}}{\frac{D_c}{n\,t_{ON}}} = \frac{n\,t_{ON}}{T_c} = \frac{n\,t_{ON}}{(n-1)\,t_{cycle} + t_{ON}} = \frac{n}{(n-1)\frac{1}{P}+1} = \frac{n\,P}{(n-1)+P} \quad \text{...3.28}$$

The rearrangement of the R, n and P terms in above eqn.

$$P = \frac{R(n-1)}{(n-R)} \quad \text{...3.29}$$

After incorporating the values of $P = t_{ON}/t_{cycle}$, $R = n\,t_{ON} / T_c$ and $T_c = (n-1)\ t_{cycle} + t_{ON}$ in above equation, it can be expressed as:

$$t_{ON} = \frac{R\,(n-1)\,T_C}{(n^2 - n)} = \frac{R\,T_C}{n}$$

$$t_{OFF} = \frac{n(1-R)\,T_C}{(n^2-n)} = \frac{(1-R)\ T_C}{(n-1)} \quad \text{...3.30}$$

Also verify that the duration of power supply meets the requiremnt in a day :

$$T = T_c + (S_n - 1)\,t_{ON}\ (T_c \leq T) \quad \text{...3.31}$$

The procedure for designing the pulse irrigation for the given water availability, irrigation interval, water supply capacity per day can be made through the following steps.

Step – 1 : Determine the cropped area that can be irrigated during the irrigation interval (IT) with D_i depth of irrigation. If this area (A_T) to be irrigated during the irrigation interval (IT) is more than the available cropped area (TA_c), the A_T is taken as TA_c.

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$A_T = \frac{TWA}{D_i}$; If $A_T \leq TA_c$; $A_T = A_T$; otherwise $A_T = TA_c$

Where, A_T = Area that can be irrigated during the irrigation interval (IT) with D_i depth of irrigation (ha), TWA = Total water availability during irrigatin interval (ha-mm), D_i = Depth of irrigation to be given (mm) at an interval of IT – days (mm).

Step – 2 : Find daily water availability (DWA).

$$\text{DWA} = \frac{\text{TWA}}{\text{IT}}$$

Where, DAW= Daily water availability (ha.mm/day), TWA = Total available water in a given irrigation interval (ha-mm), IT = Irrigation interval (Days).

Step – 3 : Find the area required to be irrigated in a day (ha/day).

$A_d = \frac{DWA}{D_i}$; If $A_d \leq TA_c$, $A_d = \frac{DWA}{D_i}$, otherwise $A_d = \frac{TA_c}{IT}$

Where, D_i =Depth of irrigation to be given (mm) at an interval of IT – days, A_d = area required to be irrigated (ha/day).

Step – 4 : Find the actual rate of irrigation application(mm/h).

$$I_{act} = \frac{q}{(LL\ x\ DD)}$$

Where, I_{act} = Actual rate of irrigation application (mm/h), q = Dripper discharge (lph), LL = lateral spacing (m), DD = Dripper spacing (m).

Step – 5 : Find the area to be irrigated in a shift (ha).

$A_s = \frac{Q}{I_{act}}$; If $A_s \leq A_d$, $A_s = \frac{Q}{I_{act}}$, otherwise, $A_s = \frac{DWA}{D_i}$

Where, Q = Water supply rate (ha-mm/h) through pumping system. A_s = Area to be irrigated in a shift (ha).

Step – 6 : Find the number of shift or solenoid valves. Take integer values of S_n towards the higher value.

$$S_n = \frac{A_d}{A_s};$$

Where, S_n = number of solenoid valves/shifts required to cover daily irrigated area (A_d).

Step – 7 : Find the pulsation ratio (P).

$$P = \frac{1}{S_n}$$

Step – 8 : Find the combination of R and n using chart as shwon in Appendix V for the values of P found in step – 7 such that the following relationships holds approximately and n can be preferbly between 8 to to 10 (Vishnu, *et al.*, unpublished data, 1992).

$$n = \frac{1}{R} + 1$$

Now, we have values of n, R and P.

Step – 9 : Redetermine the S_n towards the higher integer values.

$$S_n = \frac{n-R}{(nR-R)}$$

Step – 10 : Redetermine the R for the determined values of S_n in step-9.

$$R = \frac{n}{(n-1)S_n+1}$$

Step – 11 : Redetermine the I_{ave} for the determined values of R in step-10.

$$I_{ave} = I_{act}\,R$$

Step – 12 : Determine the T_c for the determined values of I_{ave} in step-11.

$$T_c = \frac{D_i}{I_{ave}}$$

Step – 13 : Determine the t_{ON} for the determined values of I_{act} and Di or based on n, Iact, and Di

$$t_{ON} = \frac{R(n-1)\,T_C}{(n^2-n)} \text{ OR } t_{ON} = \frac{(n-1)\,D_i}{(n^2-n)I_{act}} \text{ OR } t_{ON} = \frac{R\ T_C}{(n)} \text{ OR } t_{ON} = \frac{D_i}{n\,I_{act}}$$

Step – 14 : Determine the t_{OFF} for the determined values of of T_c, R, n, S_n, I_{act}, and D_i.

$$t_{OFF} = \frac{n\,T_C\ (1-R)}{(n^2-n)} \text{ OR } t_{OFF} = \frac{(S_n-1)\,D_i}{n\ x\ I_{act}}$$

Step – 15 : Determine the t_{OFF} for the determined values of I_{act} and D_i or based on n, I_{act}, and D_i

$$t_{cycle} = \frac{t_{ON}}{P}\ OR\ P = \frac{t_{ON}}{t_{ON}+t_{OFF}}$$

Step – 16 : Redetermine T_c

$T_c = (n - 1)\ t_{cycle} + t_{ON}$ OR $T_c = n\ t_{ON} + (n - 1)\ t_{OFF}$ OR $T_c = n\ t_{cycle} - t_{OFF}$

Step – 17 : Determine the duration of electricity requirement in a day.

$T = T_c + (S_n - 1)\ t_{ON}$ (T_c should be $\leq T$)

Where, T is the duration of electricity requirements in a day (hr).

3.6 COMPONENTS OF AUTOMATION SYSTEM

The low-cost wireless soil moisture sensor was resistive type sensor. The moisture present in soil and the resistance based on moisture differs. The sensor was measuring the resistive difference of soil and was calibrated based on the resistance values. The automation system designed was light weight, simple in operation and easy to handle. To use as automated irrigation system, the calibration and testing of sensors was properly performed.

The main components of automation system are:

1. Low cost Soil Moisture Sensor
2. Arduino UNO
3. Breadboard and Jumper Wires
4. Solenoid Valves
5. Main Line, Sub-main Lines, Laterals, Drippers
6. LCD I2C (16×2) Display
7. Electrical relay interface
8. Water Source and Pump
9. Battery
10. Pressure Gauge and Bypass assembly
11. Real Time Clock

The all above components were used for automation system and were arranged as shown in block diagram.

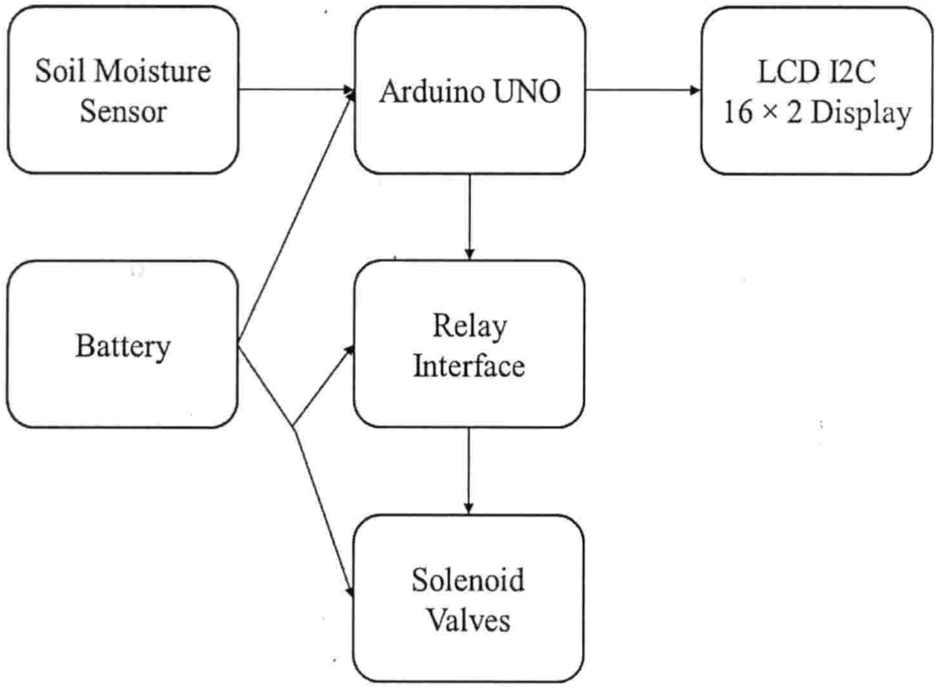

Fig. 3.2 Block Diagram of Automated Irrigation System

3.6.1 Soil moisture sensor

Generally, soil moisture measurement is done through gravimetric method. This method requires sampling, drying and weighing which makes slow measurements. However, some experiments need quick measurements such as automation based on different moisture levels. The quick measurements are performed through soil moisture sensors. These sensors measure the volumetric water content in soil indirectly by different properties of soil such as electrical resistance, dielectric constant, capacitance and conductance.

The present study was performed using resistance type moisture sensor. The sensor was bought online which was low cost and was having well enough accuracy. These sensors are calibrated before itself with the relation between the measured property and soil moisture and may vary depending on environmental factors such as soil type, temperature, or electric conductivity. The increase in moisture content of the soil gives the increase in electrical conductivity of the soil. The sensor used was as shown in Plate 3.4.

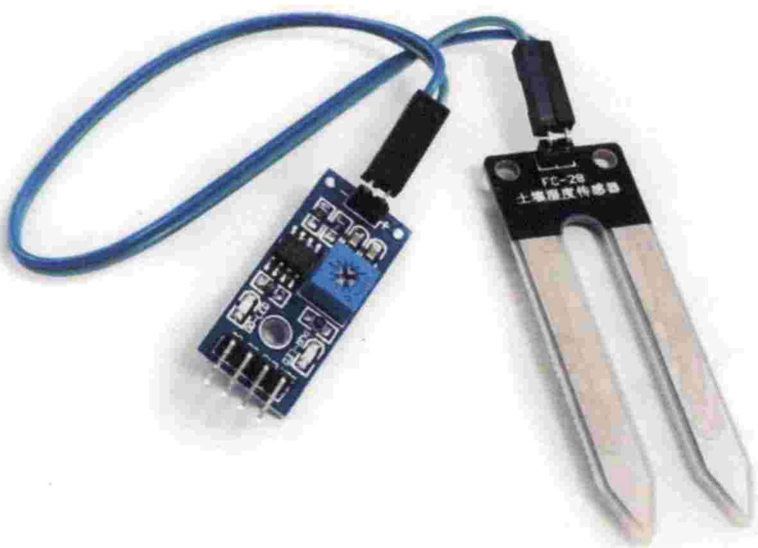

Plate 3.4 Resistive type Soil Moisture Sensor

3.6.1.1 Calibration and validation of soil moisture sensor

The calibration and validation of soil moisture sensor were done in the Soil and water Conservation Engineering laboratory. A low-cost wireless soil moisture sensor was purchased along with Arduino UNO online and for the accurate results, the output. The sensor was then allowed to show the values when fully submerged in water and fully opened in air. The code was written in the Arduino software to show the output values. The values found through this were noted and the code was written based on those values to make the calibration properly. The standard code gives the values of moisture content ranges from zero to 1023. The values corresponding to the moisture content when sensor was kept in air and when it was fully dipped in water were noted. Then the known moisture content samples were prepared and the values observed through sensor was noted. The samples were taken from that known moisture content soils to measure moisture at the time sensor reading were taken. The linear relationship equation was obtained through sensor readings and calculated readings and which was fabricated to code for the calibration of sensor and based on that code the Arduino command can be sent to sensor. The validation was performed after the calibration to check the calibration properly.

The validation of sensor was performed by checking the same known moisture content samples of soil. To ensure the calibration, the value indicated through sensor was noted down and the moisture content of particular sample was also verified. The known moisture samples were made on weight basis. The samples made were of 10 %, 20 %, 30 %, 40 % and 60 %. The sensor was kept in each known moisture content samples one by one and were checked accordingly. The values showed good familiarity with calibration and the validation was performed successfully.

3.6.2 Arduino UNO microcontroller

Arduino Uno is a microcontroller board developed by Arduino.cc, which is an open-source electronics platform. David Cuartielles and Massimo Banzi initiated Arduino project first on 2003, with a view to provide a cheap and flexible way to students and professional for controlling a number of devices in the real world. Arduino Uno has a USB interface and also 6 analogue input pins, 14 I/O digital ports. Designers are allowed to control and sense the external electronic devices in the real world by Arduino. Arduino board comes with all the required features and it can be easily connected to PC through USB. These boards can be used for Linux, Windows and MAC. Arduino Uno comes with an ability of interfacing with other Arduino boards, microcontrollers and computer. Arduino Uno is programmed using Arduino Software, which a cross-platform application called IDE is written in Java.

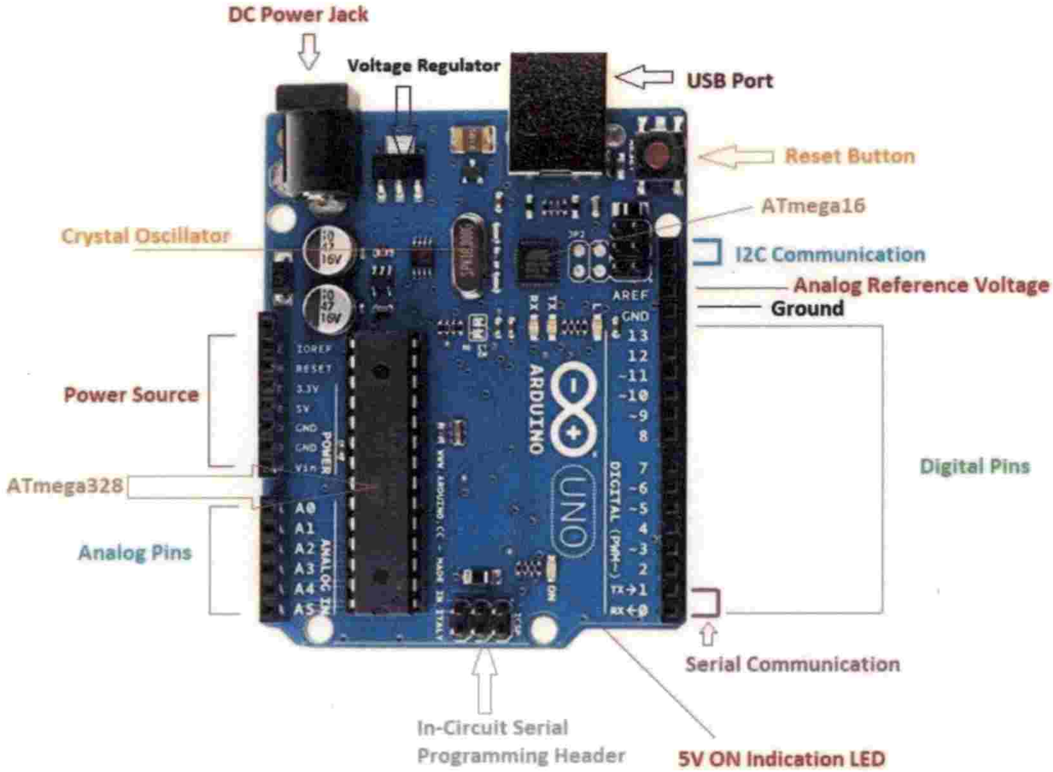

Plate 3.5 Arduino UNO microcontroller

Arduino have wide range of application in all fields. For scientific research majority of researchers are using Arduino boards for developing sensors and instruments. Embedded System, Security and Defence System, Digital Electronics and Robotics, Parking Lot Counter, Weighing Machines, Traffic Light Count Down Timer, Medical Instrument, Emergency Light for Railways, Home Automation, Industrial Automation, Irrigation Automation are some of the main applications of the board.

3.6.3 Breadboard and jumper wires

To connect soil moisture sensor to Arduino and LCD to Arduino, all the wires used were jumper wires. The wires come with male to male, male to female and female to female type. To connect many pins with Arduino, it is difficult to do soldering, so the better option opted was use of breadboard. A breadboard is a construction base for prototyping of electronics. The breadboard is solder-less type, which does not require any soldering. A variety of electronic systems may be prototyped by using breadboards, from small analogue and digital circuits to complete central processing units (CPUs). Breadboard and Jumper Wires are as shown in Plate 3.6. and Plate 3.7.

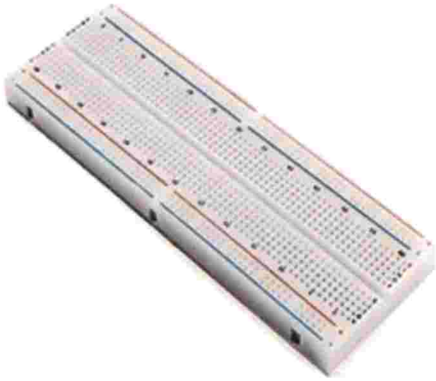

Plate 3.6 Breadboard

Plate 3.7 Jumper Wires

3.6.4 LCD I2C display

An LCD is a flat panel display, which uses the light modulating properties of liquid crystal. LCD serves a common weakness but also enrich the man-machine interaction. When LCDs are connected to a controller, multiple Inputs will be occupied of the controller, which has no so many outer ports. Therefore, LCD with an I2C bus was developed to solve the problem. For present research, LCD used was 16 × 2 with I2C bus within it and was used to display the moisture status of soil. Generally, it displays the characters like symbols, alphanumeric and coma. It is a dot matrix liquid crystal type display that is connected to the 4 or 8-bit microcontroller unit. The figure showed is LCD (16 × 2) I2C bus type in which all the connections are minimized with just 4 output pins.

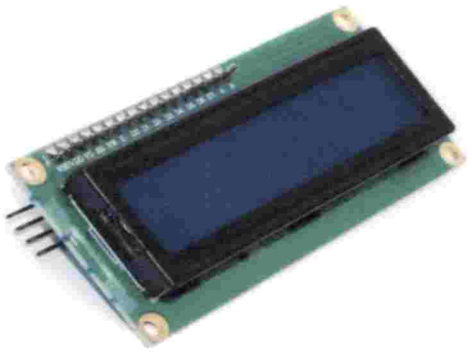

Plate 3.8 LCD I2C (16×2) type Display

3.6.5 Electrical relay interface

Some interfacing is required when a microcontroller is connected to an automatic system. It is very useful in controlling appliances and other mains powered devices using microcontrollers. Relay electronically opens and closes the circuit, which can be termed as switch. It has a wide range of applications. It can be used in home appliances, electronic circuits where there is a need of protection, robotics for controlling its motors from the proper motion and many more. The relay used for present research is as shown in Plate 3.9.

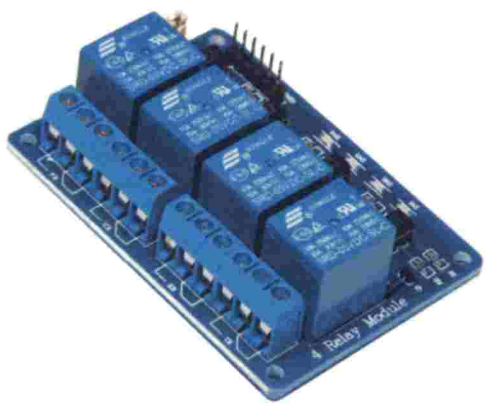

Plate 3.9 Relay module (5V)

3.6.6 Solenoid valves

Solenoid valves are the control units, which electrically operates the closing and opening of valves. Generally, opening and closing of valves are based on principle of magnetism. The electric current generates the magnetic field and thus operates a mechanism that regulates the valve opening and closing. The solenoid valves are initially shut but if it is operated, it will open and at the end when electric current is removed, it closes to its initial position. Three solenoid valves of 12 V were used for the present research as shown in Plate 3.10:

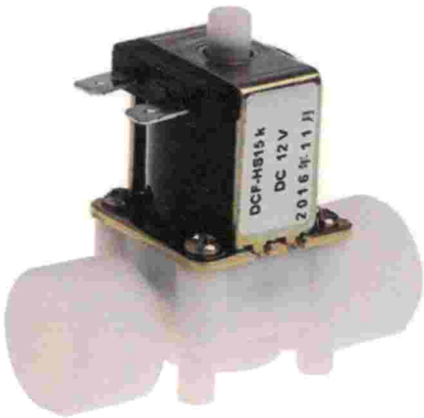

Plate 3.10 Solenoid Valve

3.6.7 Real time clock

The Real-Time Clock (RTC) is a computer clock (most often in the form of an integrated circuit) that keeps track of the current time. Although the term often refers to the devices in personal computers, servers and embedded systems, RTCs are present in almost any electronic device, which needs to keep accurate time. The time is not much accurate in Arduino so the device for accurate time was attached. The RTC is as shown in Plate 3.11.

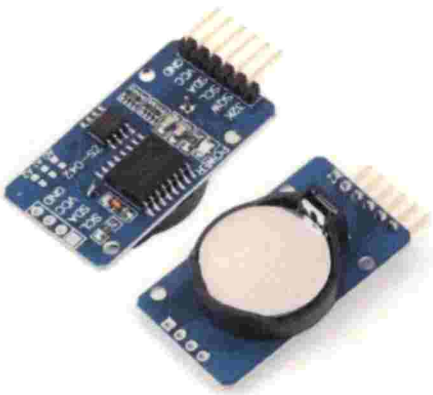

Plate 3.11 Real Time Clock

3.7 COEFFICIENT OF MANUFACTURING VARIATION

The coefficient of manufacturing variation is the measures of the variations from the nominal discharge of the drippers' discharge at nominal operating pressure of the system due to the manufacturing variations. It can be defined as the coefficient of discharge variations among the same rated discharge drippers due to manufacturing variations.

Total 3 samples, each of 10 drippers from each lot of 2 lph, 4 lph and 8 lph were randomly selected. The 16 mm lateral of 30 cm length was connected to sub main through grommet-take-off. The circular loop of 3 m lateral was made and connected both ends to 16 mm-Tee. The Tee was connected to the lateral fitted to sub main. Total 5 drippers of particular rated discharge were fitted on the lateral loop at uniform distance as shown in Plate 3.12. The pressure gauge was fitted to measure the pressure. The pressure of 1.2 kg/sq.cm. was maintained by regulating the lateral cock. The volume of water was collected from each of 5 drippers for the 15 minutes and dripper discharge was found. The similar experimentation work was adopted for each of 2 lph, 4 lph and 8 lph drippers.

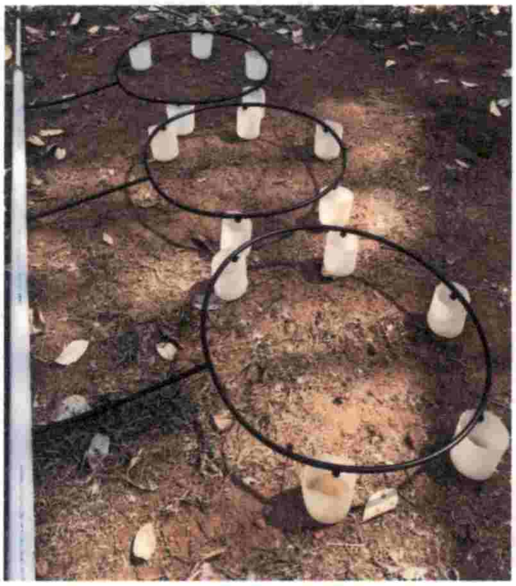

Plate 3.12 Setup for measurement of coefficient of manufacturing variation

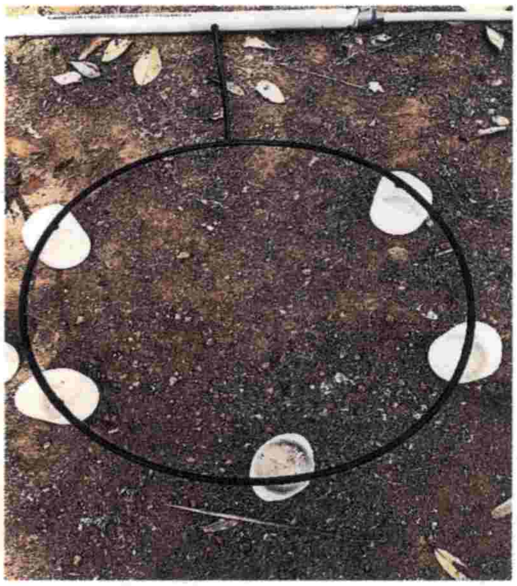

Plate 3.13 Measurement of coefficient of manufacturing variation for particular discharge

The coefficient of manufacturing variation (CV_m) for the each of 2 lph, 4 lph and 8 lph was estimated using the following expression.

$$CV_m = 100 \times \frac{\sqrt{\frac{\sum_{i=1}^{n}(q_i - q_{ave})^2}{(n-1)}}}{q_{ave}} \qquad \ldots 3.32$$

Where,

CV_m = The coefficient of manufacturing variation of the dripper discharge (%).

q_i = The discharge of the i^{th} dripper of the sample (lph).

q_{ave} = Average discharge of the n drippers (lph).

n = Total number of the drippers in the samples.

3.8 DESIGN OF AUTOMATED PULSE IRRIGATION SYSTEMS

The automation system was designed based on pulse cycles and moisture levels. The sensor was bound between two moisture levels. The plant can take available water between the FC and PWP. The easier to uptake is between FC and 50% of available water. So, to ensure the reduction of plants root stress the two moisture levels were taken into consideration. The sensor was bounded between the moisture content at FC and 50% of available moisture. The design was performed by assuming the plant for which the automation pulsation can be designed. The pulse irrigation has an advantage over continuous drip that it can be used with applying same quantity of water as continuous by using high discharge rate drippers for calculated time period. Also due to pulsation of irrigation, the plants root zone remains under aerating environment.

The design of pulse was based on following considerations:

Table 3.2 Design Consideration for Pulsations

System details	Unit	Value	Value	Value
Lateral to Lateral distance	m	1	1	1

Dripper to Dripper distance	m	0.5	0.5	0.5
Discharge	lph	2	4	8
Irrigation rate	mm/hr	4	8	16
Dripped Volume rate	lph	2	4	8
t_{ON} for 1 mm irrigation depth	min/mm	15	7.5	3.75
Irrigation depth	mm	4	4	4
t_{ON} for irrigation depth	min/ 4 mm	60	30	15

The consideration of pulsation is based on the pulse theory that same amount of water is given in pulse rather than continuous which casually effects the wetting front. The amount of water needed by plant can be calculated and the irrigation depth is to be found out. The next step irrigation depth is managed with different flow discharges. In the present research, the irrigation depth was assumed 4 mm and different flow discharges of 2, 4, 8 lph were taken into account. The amount of water that 2 lph discharges for 1 hr is same for 4 lph in 30 minutes and 8 lph for 15 minutes. Which means the same amount of water is given in all the three discharges. Now the pulse where designed based on the time required to discharge same amount of water. Present research has 2 lph for 1 hr so the t_{on} should be taken as 1 hr but with different t_{on} pulses. The 3 pulses were taken for present research so according to that, 20 min on cycle and 20 min off cycle for 2 lph. These cycles were performed, which gave total t_{on} as 1 hour. Same pulses were designed for 4 lph and 8 lph. The operating pressure for all the treatments was maintained constant at 1 kg/cm^2 through regulating by pass assembly.

The automation was also based on the moisture level so the position of sensor was more important. Researchers have found that the sensors should not be kept very near to the dripper as the soil near dripper may always be in saturation. Therefore, the experiments were performed for different discharges and the wetting distribution with moisture content were measured for continuous drip irrigation. The position was then decided for different discharge according to the results.

3.8.1 Arduino programming

The coding language is a basic need of any decision-making systems. The code language helps microcontroller to make decisions. The Arduino is having its own coding language. The code can be written in Arduino debug, which can be downloaded free from Arduino website, and easily it can be installed. The code is simple to learn and many codes are available on internet freely. The examples are also given in the Arduino debug to learn coding. The Arduino debug is as shown in Plate 3.14.

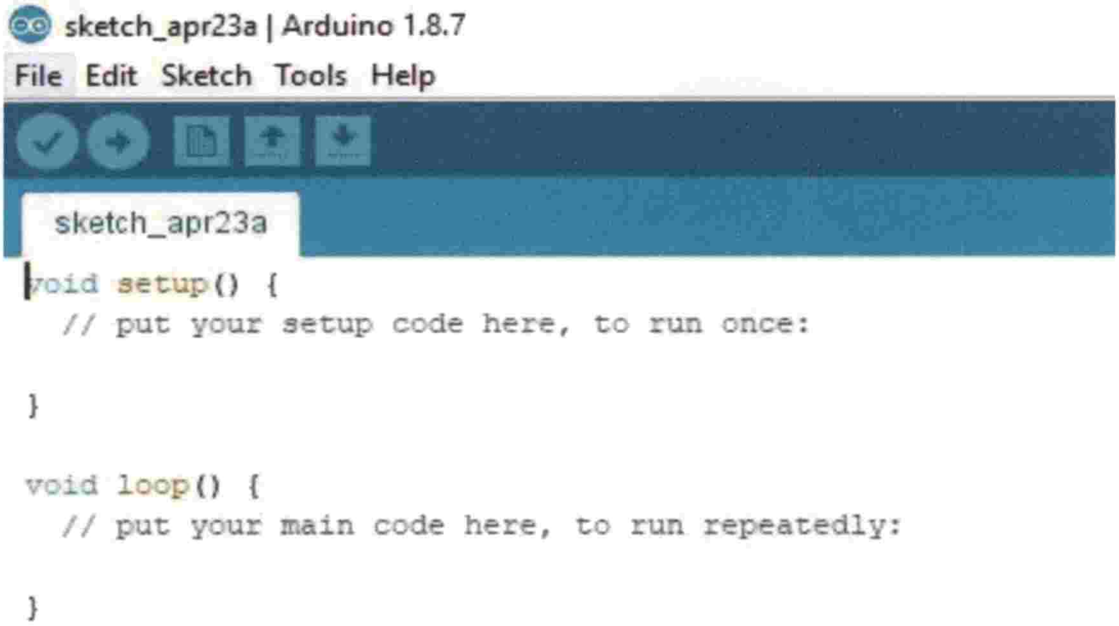

Plate 3.14 Arduino Debug for code compiling and uploading

The Arduino debug has a compiling facility so the error can be detected easily. The Arduino code can be set up in the screen as shown. The void setup makes the code run at one time. The void loop takes the code with continuous looping. Therefore, the code for present study was written in Arduino debug, which is shown in Appendix VII. The code for moisture measurements, showing the value to LCD screen and the real time clock for different time operation of solenoid valves were prepared and compiled through Arduino debug. This code was then uploaded to Arduino board and the automation was performed. The flowchart of the programming is as shown in Fig. 3.3.

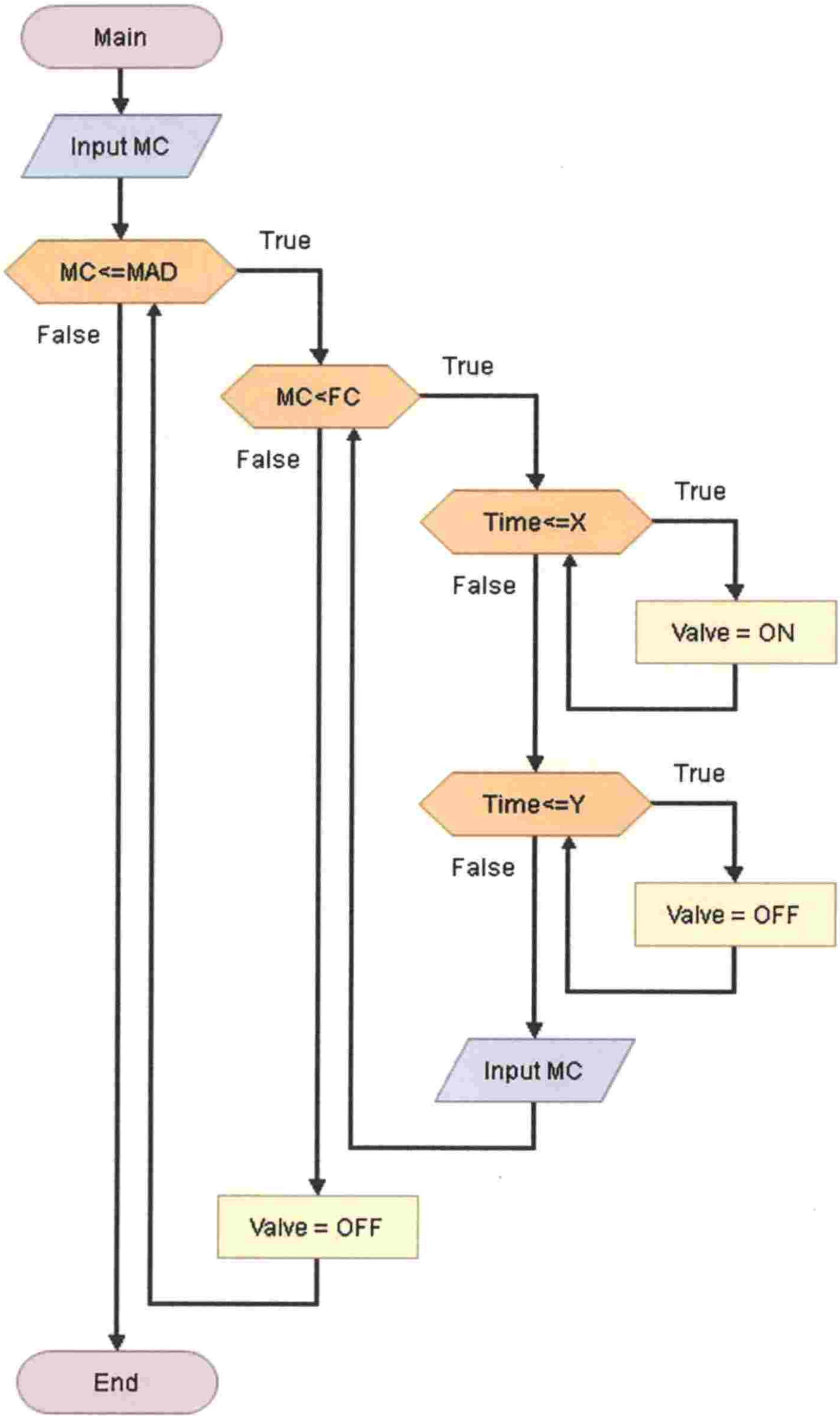

Fig. 3.3 Flow Chart of Automation System

3.9 EVALUATION OF AUTOMATED PULSATING SYSTEM

The system developed should be evaluated, thus the developed automated pulse irrigation system was evaluated. The irrigation system can be evaluated in many ways, one way is to grow crops and measure yield or you can measure the water distribution in soil. Thus, for present research, wetting front movement was measured at different discharges and the times. The system was evaluated with continuous irrigation as well as pulse irrigation for comparison.

3.9.1 Continuous drip irrigation system

The setup was installed at KCAET farm with separate tank as water source and a 0.5 hp Kirlosker pump with dischrge of 400 to 1800 lph. The electric connection were given to the field from nearby pump house.

Plate 3.15 Setup for Continuous Drip Irrigation System

As shown in Plate 3.15 the wetted bulb was obtained after continuous drip irrigation. The radial distance as well as vertical distance of wetted bulb was measured. The readings were taken for 2 lph, 4 lph and 8 lph dripper laterals after 1 hour, 2 hours and 3 hours of irrigation. The measure tap was used to measure the distance as shown in Plate 3.16 and 3.17. The pressure was maintained continuously by checking the pressure at the end of the lateral by pressure gauge as shown in Plate 3.18.

Plate 3.16 Wetted Diameter of Bulb

Plate 3.17 Wetted Depth of Bulb

Plate 3.18 Pressure Gauge

The wetting front gives the idea of the water flow pattern, which can be used to determine the dripper discharge and time for the given soil, plant and can be manipulated to reduce deep percolation losses. The horizontal distances were measured by measure tap and to measure depth, the soil profile was cut. The profile was cut in such a way that the half circle of wetting is removed and with front view, the pattern can be easily judged. For present research the wetting front were measured for 2 lph, 4 lph and 8 lph after 1, 2, 3 hours of continuous irrigation and the measurement were made for both with and without considering redistribution.

3.9.2 Pulse drip irrigation system

The same setup was installed at KCAET farm with separate tank as water source and a 0.5 hp Kirlosker pump with dischrge of 400 to 1800 lph. The electric connection were given to the field by nearby pump house. The pulse irrigation was performed in automation and the setup was as shown in Plate 3.19.

Plate 3.19 Setup for Automated Pulse Drip Irrigation System

Plate 3.200 Automation Components setup

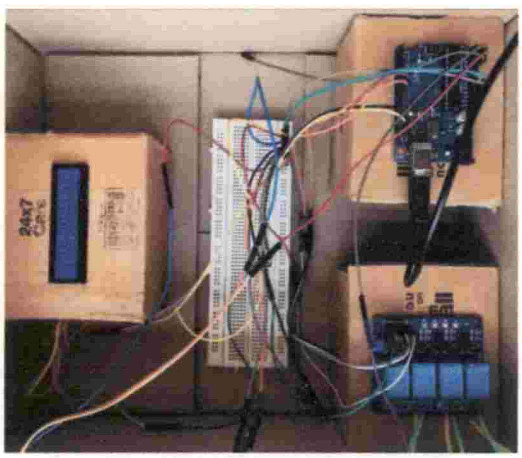

Plate 3.211 Inside view of Arduino connections

The Pulse irrigated wetting front were also measured in same way, after completion of whole pulse cycle. For pulse irrigation also 2 lph, 4 lph and 8 lph discharge were considered but the time of pulses were different.

Plate 3.22 Position of soil moisture sensor

The automation was based on moisture content so from the continuous data the sensor was kept at different positions from emitter as shown in Plate 3.22.

Plate 3.23 Solenoid Valves controlled by corresponding moisture sensors

Three sensors were used for 3 solenoid valve controls and each one was controlling based on that particular moisture content as shown in Plate 3.23. The wetting pattern was measured after completion of all the designed cycle and readings were compared with the continuous drip data. The moisture samples from the cut were taken for determination of moisture movement in the soil. Thus, the performance of developed irrigation system was measured and were also compared.

3.9.3 Aeration measurements

The aeration in the soil is mostly affecting the plant root zone growth. The aeration helps in root respiration which yields in planth growth. The aeration is measured as a term of air content of soil or oxygen concentration in particular soil mass. For present study the aeration was considered by measuring the air content of the soil. The air content in the soil can be obtained through following equation :

$$Saturation\ Percentage\ (S_e) = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \quad \ldots 3.33$$

$$Soil\ Aeration\ (a_c) = [1 - S_e] \quad \ldots 3.34$$

Where,

θ = Present Moisture Content ($cm^3\ cm^{-3}$),

θ_r = Residual Moisture Content ($cm^3\ cm^{-3}$),

θ_s = Saturated Moisture Content ($cm^3\ cm^{-3}$).

The all methodology used for present research was performed in field and laboratory as well, the results found and discussions based on that are presented in next chapter.

CHAPTER IV

RESULTS AND DISCUSSION

The present study was conducted with the objective of developing an automation system using Arduino Uno and soil moisture sensor that automatically controls the irrigation based on the matric potential developed in the crop root zone. This process details and results obtained in various laboratory and field experiments are discussed in this chapter.

4.1 CHRONICLE OF AUTOMATED IRRIGATION SYSTEM

The present world development into agriculture scenario is more important due to climate change and population increment. The world is developing towards information technologies that makes the agriculture smart. The information and communication technologies in agriculture can be opted for smart irrigation techniques and for other weed management and pesticides applications. The new techniques were not much familiar until some years after researchers started working on that. Smart irrigation technique was one of the challenging for researchers. The irrigation scheduling was making the labour cost to control it every time. To automate the whole system, the ICT application were opted. The systems were very much complicated and sophisticated which made small-scale farming less economic. Peoples with small farm were so much concerned about the small-scale automated irrigation researches. One of the researches was conducted to develop irrigation control valve through tensiometer (Peterson, *et al.*, 1993). However, tensiometers can be used for small potentials up to 0.8 bar only. So low cost soil moisture sensor was opted for potential measurements. The researchers also found that continuous watering through automated systems affects plant growth. Thus, the irrigation was opted with different pulses of on/off cycles. The different pulses given at high discharge gave good results. Hence, present study was aimed to develop wireless low-cost automated irrigation system with pulse irrigations system that can be simpler in mechanism and easily opted.

4.2 CHARACTERISTICS OF SOIL

The design of automated pulse irrigation system was initiated with determination of various characteristics of the soil in which the system is to be installed. Various characteristics of the soil used for this study were tabulated in Table 4.1.

Table 4.1 Basic Soil Properties

Sr. No.	Soil Properties		Units	Values
1	Texture of the soil	Sand	%	56.09
		Silt	%	36.58
		Clay	%	7.33
2	Specific Gravity		-	2.47
3	pH (1:2.5)		-	5.5
4	EC		ds/m	1.19
5	Field Capacity*		%	18.55
6	Saturation Percentage*		%	31.18
7	Wilting Point*		%	8.64
8	Hydraulic Conductivity		cm/s	3.21×10^{-4}
9	Porosity		v/v	0.435
10	Bulk Density		g/cc	1.528
11	Dry Density		g/cc	1.395
12	Plastic Limit*		%	25.15
13	Liquid Limit*		%	31.96
14	Moisture Content*	10 cm	%	7.085
		20 cm	%	8.294
		30 cm	%	8.959
		40 cm	%	10.761
		50 cm	%	12.355

* Dry weight basis (db, %)

4.3 SOIL TEXTURE ANALYSIS

Soil texture was performed with dry as well as wet sieve analysis. The percentage fines were determined and Grain size distribution curve was obtained. The percentage of sand, silt and clay was found from Grain size distribution curve as per proposed USDA classification. The proportion of clay, silt and sand particles in the experimental field soil were observed as 7.32 %, 36.59 % and 56.10 % respectively. The textural triangle was used to determine the soil texture type and was found as sandy loam soil.

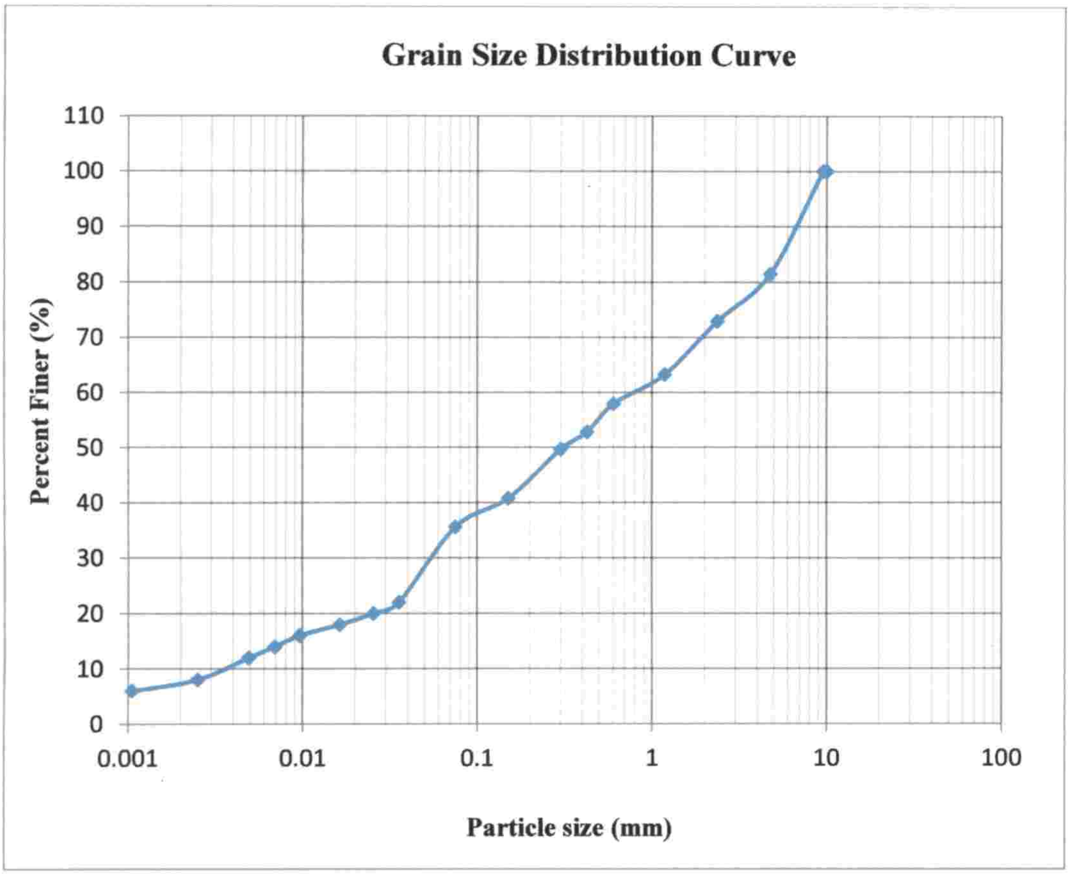

Fig. 4.1 Grain Size Distribution Curve

4.4 SOIL WATER RETENTION CURVE

The simulations of water flow through unsaturated soils necessitate an understanding of soils hydraulic properties. Among these unsaturated soil properties, the most important one is the water retention characteristic curve, which narrates the moisture retention under different tension and demonstrate hysteresis effects (Aubertin, *et al.*, 2003). Soil water moisture characteristics are needed to assess the easiness of available water to plants, unsaturated flow and solute transport (Gupta and Larson, 1979). The soil moisture characteristics behave differently during drying and wetting phases i.e. desorption and desorption processes. The disparities in behaviour of soil water retention at various suctions during desorption and sorption process is due to hysteresis effect. In the present investigation, desorption was carried out using the pressure plate apparatus (ASTM, 1997d; Fredlund and Rahardjo, 1993a). However, the assessment of the hysteresis effect requires the Soil water retention characteristics during the sorption process also. The soil water characteristics of the wetting process was observed using a capillary rise open tube method (Lambe and Whitman, 2008; Fredlund and Rahardjo, 1993b). For wetting curve, there is no accurate method other than the method of capillary rise open tube method, which is more proper (Fredlund and Rahardjo, 1993b).

The observed data on soil moisture retention during the desorption (Table 4.2) and sorption (Table 4.4) are depicted graphically in Fig. 4.2 and 4.3 respectively. The observed SWCC during both the processes are compared graphically in Fig. 4.4. The predicted data was then obtained through Sigma Plot software, which was used to fit the van Genuchten model parameters. The predicted data on soil moisture retention characteristics during the desorption and sorption are presented in Table 4.3 and Table 4.5 respectively. The strikingly hysteresis effects of soil water retention at various suctions can be seen in Fig. 4.4.

The Fig. 4.2 and 4.3 show that the observed data are closely hugged with the predicted data curve. Thus, the developed curve can be used to predict the soil moisture at various suctions accurately.

Table 4.2 Observed soil water retention characteristics and aeration during desorption process

Observation No.	Suction (kPa) Ψ	Moisture Content ($cm^3\ cm^{-3}$) θ	Soil Aeration ($1 - S_e$)
1	1500	0.1205	0.8901
2	500	0.1352	0.8485
3	300	0.1490	0.8095
4	100	0.1897	0.6943
5	33	0.2588	0.4986
6	10	0.3151	0.3393

Table 4.3 Predicted Soil water retention characteristics during desorption process using curve

Suction (kPa) Ψ	Moisture Content ($cm^3\ cm^{-3}$) θ
0.001	0.4350
0.01	0.4349
0.1	0.4338
1	0.4142
10	0.3050
50	0.2218
100	0.1951
150	0.1818
200	0.1733
500	0.1507
550	0.1487

96

1000	0.1374
1500	0.1308
5000	0.1155
7000	0.1122
7500	0.1115
8000	0.1109
8500	0.1104
9000	0.1099
9500	0.1094
10000	0.1090
100000	0.0951

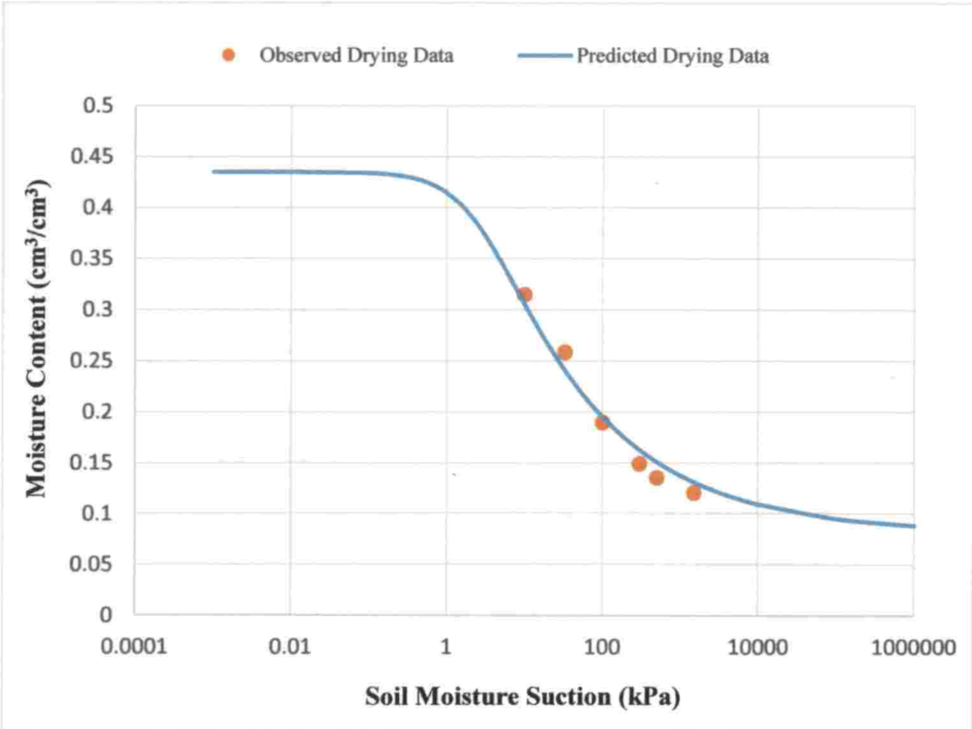

Fig. 4.2 Observed and Predicted Soil Water Retention characteristics during desorption process

Table 4.4 Observed soil water retention characteristics and aeration during sorption process

Observation No.	Suction (kPa) Ψ	Moisture Content (cm^3 cm^{-3}) θ	Soil Aeration ($1 - S_e$)
1	0.01	0.4201	0.0299
2	0.1	0.4130	0.0503
3	0.2	0.3240	0.3044
4	0.4	0.2649	0.4735
5	0.6	0.2429	0.5361
6	0.8	0.2230	0.5930
7	0.98	0.1961	0.6699
8	1.96	0.1790	0.7188
9	2.94	0.1539	0.7905
10	3.92	0.1459	0.8132
11	4.9	0.1360	0.8416
12	6.47	0.1320	0.8530

Table 4.5 Predicted Soil water retention characteristics during sorption process using curve

Suction (kPa) Ψ	Moisture Content (cm^3 cm^{-3}) θ
0.001	0.4305
0.01	0.4288
0.1	0.3917
1	0.2374

10	0.1390
50	0.1095
100	0.1019
150	0.0984
200	0.0963
500	0.0911
550	0.0907
1000	0.0884
1500	0.0871
5000	0.0844
7000	0.0839
7500	0.0838
8000	0.0837
8500	0.0836
9000	0.0835
9500	0.0835
10000	0.0834
100000	0.0816

99

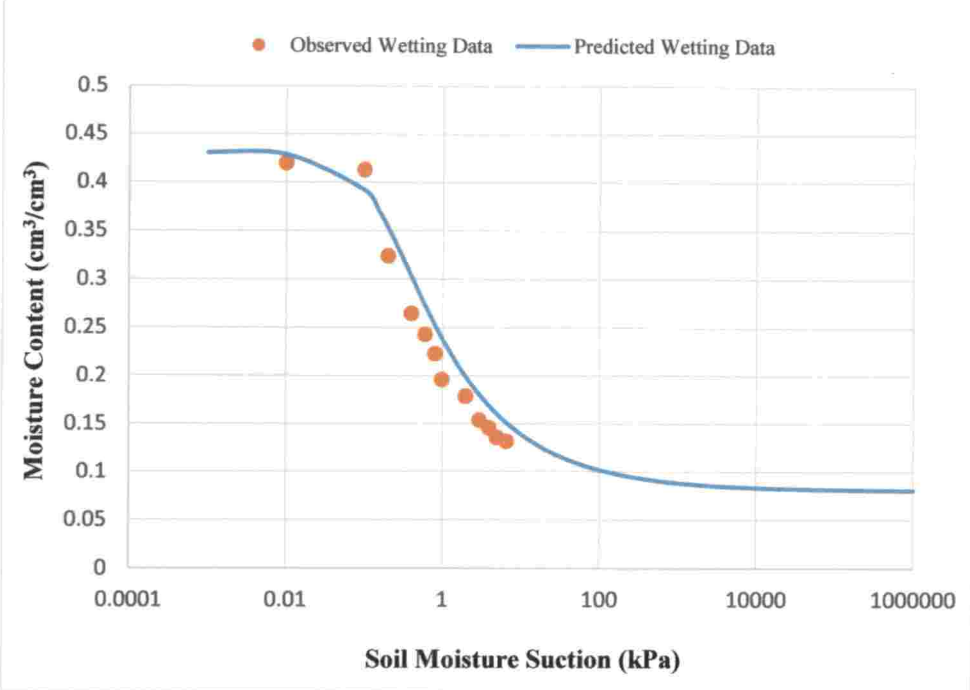

Fig. 4.3 Observed and Predicted Soil Water Retention characteristics during sorption process

4.5 HYSTERESIS EFFECT IN SOIL WATER RETENTION CURVE

The soil water retention characteristics during the wetting and drying phase is depicted graphically in Fig. 4.4. The hysteresis effect was found while comparing the drying and wetting retention curves as shown in Fig. 4.4. It can be seen that during wetting and drying process, the soil moisture at 1 kPa was observed as 0.25 and 0.41 cm^3cm^{-3} while at 100 kPa, it was as 0.1 and 0.19 cm^3cm^{-3} respectively. It indicated that the soil moisture during drying and wetting phase differed considerably between 0.01 kPa to 10000 kPa. The Fig 4.4 shows that soil moisture content is less for a wetting phase, as compared to that of during a drying phase for the particular suction. This is known as hysteresis effect. This is due to the tricky nature of the liquid-phase structure in an unsaturated soil medium, which yields the hysteresis effects as reported by Dane and Wierenga (1975). The Soil water retention curve between suction and moisture content is not sole for different soil types as it depends on various soil hydraulic properties. In the present study, the hysteresis between wetting and drying was found smaller as compared to found by

Yang, *et al.* (2004) because of more courser nature of the experimental field soil. As reported by Yang, *et al.* (2004) a coarse-grained soil has a smaller air-entry value, residual matric suction, and water-entry value and less total hysteresis than a fine-grained soil. The residual matric suction and water-entry value tend to approach the same value when the effective grain size D_{10} of the soil is small (3 to 6 mm). The soil water characteristics curve of the experimental field soil has somewhat flatter slope because of lower uniformity of soil. However, for the uniform soils have usually steeper slopes and less total hysteresis than those of less uniform soils. Soils with a low dry density have a lower air-entry value and residual matric suction than soils with a high dry density (Yang, *et al.*, 2004).

As reported by O'Kane, *et al.* (2004), the hysteresis effect can be attributed to four main causes like (a) "Ink Bottle" effect due to distinct pore size distribution, (b) Diverse three-dimensional connectivity of different pores during drying or wetting progression, (c) Dissimilarity of contact angle between the solid and liquid and (d) Air entrapment differently during drying and wetting. Since recently, these hysteresis occurrences remain neglected while applying for real field uses. Consequently, the results from laboratory and field tests can usually differ substantively and part of these variances can be ascribed to hysteresis effects (Maqsoud, *et al.*, 2012).

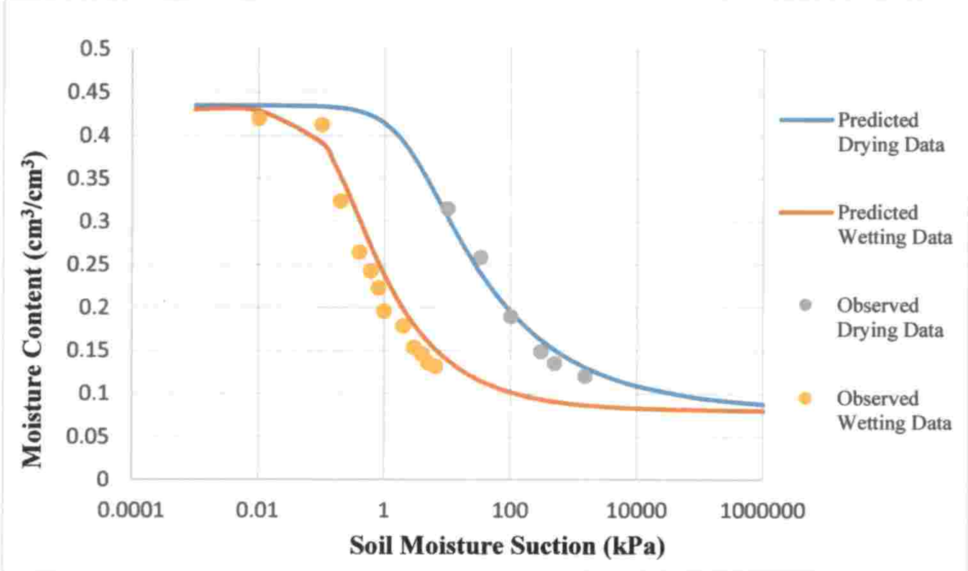

Fig. 4.4 Hysteresis effect in Soil Water Retention characteristics

4.6 MODELLING THE SOIL WATER RETENTION CHARACTERISTICS

The observed data on Soil water retention characteristic during the drying and wetting process were used to develop the various models and predict the soil moisture content beyond the practical range of the measurement in either field or the laboratories. Different models were used to predict the soil water retention curves. These models are mostly based on basic soil index properties. It is normally time-consuming to measure the Soil Water Retention characteristics. The required time depends on factors such as type of soil, size of soil specimen, applied air pressure, and type of ceramic disk (Topp, *et al.*, 1993). It is related to the pore-size distribution of the soil, which is in turn related to the grain-size distribution and porosity (Holtz, *et al.*, 1981). It is possible to relate D10 of a soil to its parameters of air entry values and residual soil suction. The slope of the retention curve is also consistent with the slope of the grain-size distribution curve of the soil. A steep slope on the grain-size distribution curve results in a steep slope on the SWCC. This observation indicates that the drying SWCC of the soil is closely related to the grain size distribution of the soil (Yang, *et al.*, 2004).

4.6.1 van Genuchten (1980) model

Different models input requirements are different, some models require sand, silt and clay percentage where some takes input as Liquid limit and Plastic limit additionally. The parameters of van Genuchten model for the coarse grained soil of the experimental field were determined using soil properties as per the approach reported by Ghanbarian-Alavijeh, *et al.* (2010).

4.6.1.1 Desorption process

The clay percent, void ratio and hydraulic conductivity of the soil as 7.33%, 0.7699 and 0.000325 cm/s were used to determine the a, n and m model parameters. The Table 4.6 shows that the van Genuchten model parameters namely residual moisture content (θ_r), saturated moisture content (θ_s), empirical coefficients a, n and m were found as 0.08167 cm^3cm^{-3}, 0.435 cm^3cm^{-3}, 2.55913 kPa, 1.309555 and 0.236382 respectively. The developed van Genuchten (1980) model was used to predict the soil moisture characteritics curve for the entire range of the soil moisture suction.

Table 4.6 Input and Output values for the van Genuchten model parameters of desorption process

Inputs for Coarse Grained Soil		
Input	Values	Unit
C_p (Clay Content)	7.33	%
e (Voids Ratio)	0.7699	–
K_s (Sat. Hydraulic Cond.)	0.000321	cm/sec
Outputs for Coarse Grained Soil		
Output	Values	Unit
θ_r	0.081667	cm^3/cm^3
θ_s	0.434996	cm^3/cm^3
a	2.55913	kPa
n	1.309555	–
m = 1 – 1/n	0.236382	–

The model parameters obtained were given to van Genuchten equation and for particular suction value, moisture content was determined and predicted values were obtained. To check whether the model was giving accurate results, the model efficiency was measured. The equation to measure Nash-Sutcliffe model efficiency (NSE) is as follow:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{Observed} - Y_i^{Simulated}\right)^2}{\sum_{i=1}^{n} \left(Y_i^{Observed} - Y^{Mean}\right)^2} \right]$$

Where,

$Y_i^{Observed}$ = i^{th} observation to be evaluated,

$Y_i^{Simulated}$ = i^{th} simulated observation to be evaluated,

Y^{Mean} = Mean of observed data to be evaluated,

n = Total number of observations.

Table 4.7 Nash-Sutcliffe model efficiency (NSE) of van Genuchten model for desorption process

Nash-Sutcliffe model Efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
1500	0.000106166	0.011782475
500	0.000239693	0.008805757
300	0.000182327	0.006408816
100	2.89957E-05	0.001549895
33	0.000336274	0.000887208
10	0.000101248	0.007406886
0.01	3.43679E-09	0.042419769
Total	0.000994707	0.079260806
NSE	0.9875	–

The Nash-Sutcliffe model Efficiency (NSE) of 0.9875 was found to describe the soil moisture characteristics by the van Genuchten model for the desorption process. It indicated that the model can be used to simulate the soil moisture characteristics accurately for the soils of the experimental field instead of performing the cost, time and labour intensive method of measuring it either in field or the laboratories (Klute, 1986). The similar results were also found by Vereecken, *et al.* (1989) stating that the soil moisture characteristics can be estimated with reasonable accuracy from soil properties like grain size distribution and dry density. The observed data of soil textural analysis can give a superior estimation of the model parameters simulating the shape of the soil water retention curve (a, n and m). They also highlighted that for the van Genuchten model gives a good description over the entire range of the suction and the method is pliable enough to model the SWC to the larger range of soil textures.

4.6.1.2 Sorption process

The observed data on the soil water retention at various sanction acquired through the capillary rise open tube method were used to obtain the model parameters through the SIGMAPLOT software. The model parameters were obtained through Sigma Plot software (Table 4.8). In can be seen in Table 4.8 that the van Genuchten model parameters of the sorption processes namely residual moisture content (θ_r), saturated moisture content (θ_s), empirical coefficients a, n and m were found as 0.08057022 cm^3cm^{-3}, 0.430576768 cm^3cm^{-3}, 0.1685 kPa, 1.438 and 0.304589708 respectively.

Table 4.8 van Genuchten model parameters for the sorption process

Outputs for Coarse Grained Soil		
Output	Values	Unit
θ_r	0.08057022	cm^3/cm^3
θ_s	0.430576768	cm^3/cm^3
a	0.1685	kPa
n	1.438	–
m = 1 – 1/n	0.304589708	–

The van Genuchten model equipped with obtained parameters was used to predict the moisture retention at various tension levels, which were applied during the experiment using capillary tube method. The agreement between the observed and simulated data was assessed though Nash-Sutcliffe model efficiency (NSE). The Nash-Sutcliffe model efficiency (NSE) of 0.92 (Table 4.9) with was found to describe the soil moisture characteristics by the developed van Genuchten model of the sorption process. It proves that the model can be used to describe the soil moisture characteristics accurately during the sorption processes of the soils of the experimental field, which can be the best alternative of performing the labour and time intensive method of measuring it through capillary rise tube method (Yang, *et al.*, 2004). The capillary tubes of soil may be required to wet for 64 days that can be considered adequate for the soil tubes to reach equilibrium as reported by Yang, *et al.* (2004).

Table 4.9 van Genuchten model efficiency for sorption curve

Nash-Sutcliffe model efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
0.01	7.50198E-05	0.033926
0.1	0.000453976	0.031357
0.2	0.000833196	0.007765
0.4	0.001412843	0.000838
0.6	0.000863029	4.96E-05
0.8	0.000847146	0.000166
0.98	0.001814024	0.001583
1.96	0.000400909	0.00324
2.94	0.000687155	0.006724
3.92	0.00050765	0.008092
4.9	0.000594037	0.009983

6.47	0.000371097	0.010794
Total	0.008860081	0.114519
NSE	0.9226	–

The simulated data of sorption process using developed van Genuchten model for the entire range of soil moisture tension were plotted. Through the drying and wetting data following graph was prepared.

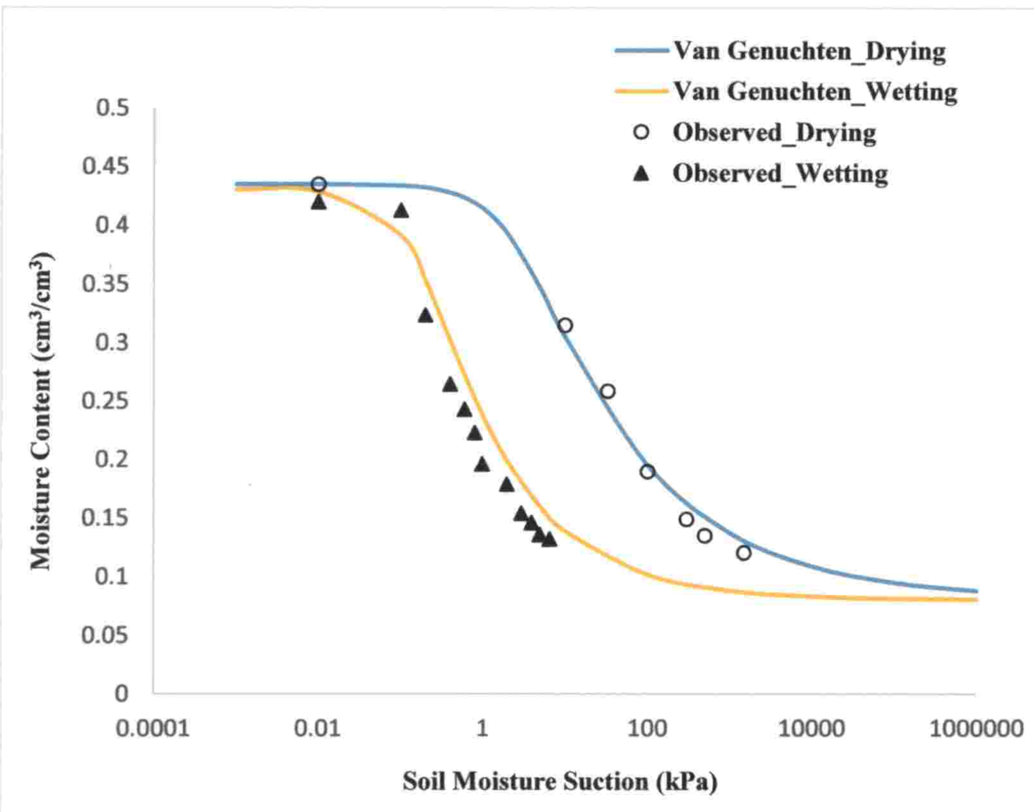

Fig. 4.5 Comparison of observed and simulated moisture content during drying and wetting by van Genuchten, *et al.* (1980) model

The Nash-Sutcliffe model efficiency (NSE) gives how accurately the model gives the predicted data. The Nash-Sutcliffe model efficiency (NSE) of the van Genuchten model to describe the soil moisture characteristics for the drying and wetting phase were found as 0.9875 and 0.9226 with goodness of fit as $R^2 = 0.99$ and $R^2 = 0.95$ respectively.

Nash-Sutcliffe model Efficiency (NSE) of the van Genuchten model during the drying and wetting phase indicated that it could be used accurately to simulate the soil moisture characteristics. Matlan, *et al.* (2014), also reported the similar findings. However, to assess how closely the simulated and observed data are hugged, the observed and simulated data were plotted as shown in Fig. 4.6. It can be seen that the observed data and simulated data are closely fitted around the line during the wetting and drying process indicating the model's predictability is acceptable.

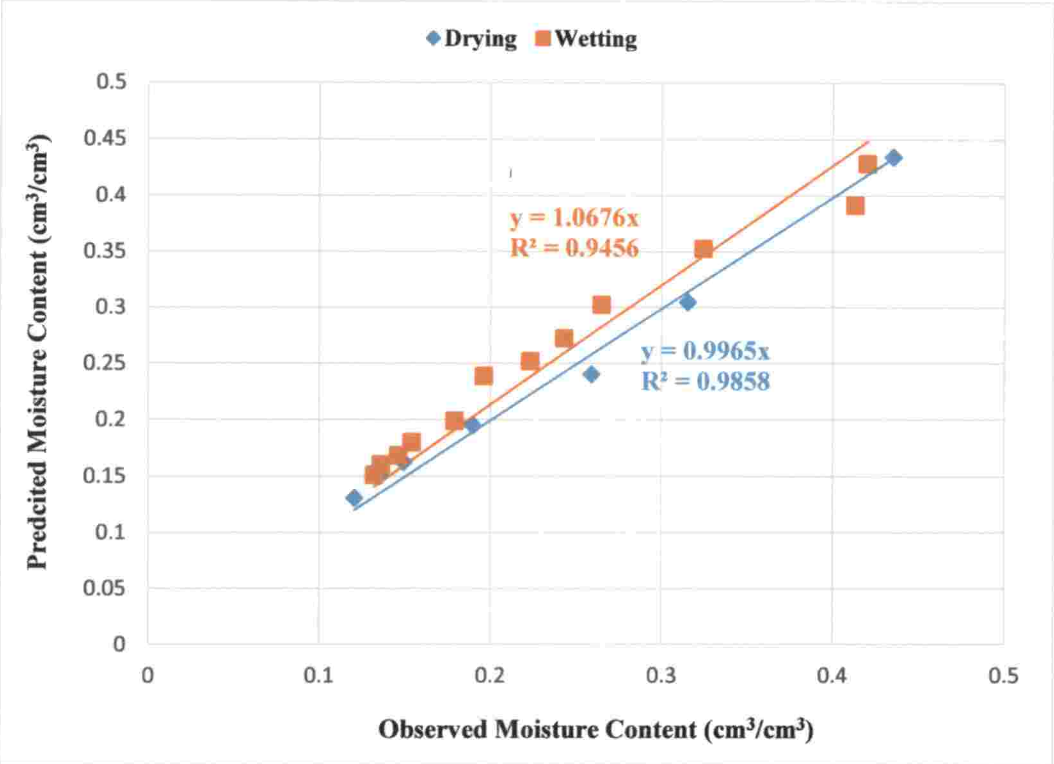

Fig. 4.6 Closeness of observed and simulated moisture content during drying and wetting by van Genuchten, *et al.* (1980) model

The above graph says how close predicted data are from observed data. The goodness of the fit for desorption and sorption processes were found as 0.9858 and 0.9456 respectively. The R^2 value is more in drying, which states that the predicted data are closer to the observed data for desorption than the sorption process.

4.6.2 Gardner (1958) model

Gardner (1958) model parameters for the coarse grained soil of the experimental field are taken same as van Genuchten (1980) model. The Gardner (1958) model differs from van Genuchten (1980) in context to only m parameter. In van Genuchten (1980) model, the m is taken as 1-1/n while in Gardner (1958) model it is taken as 1. Other model parameters are taken same. The Gardner model was one of the first equations to model the soil moisture retention characteristics. This model is effective in the sense that it can be used effciently to detrimne the soil moisture retention characteritics from limited data points. The Gardner model is simple having form with only few parameters, thus in turn, making it more suitable for the wide range of applications (Matlan, *et al.*, 2014).

4.6.2.1 Desorption process

The Gardner (1958) model parameters of desorption process considered for the present study are presented in Table 4.10. They are same as considerd in the van Genuchten (1980) model except values of m parameter which is considered here as 1 in place of 0.236382. The developed Gardner (1958) model was used to predict the soil moisture characteritics curve for the entire range of the soil moisture suction.

Table 4.10 Gardner (1958) model parameters of desorption process

Inputs for Coarse Grained Soil		
Input	Values	Unit
θ_r	0.081667	cm^3/cm^3
θ_s	0.434996	cm^3/cm^3
a	2.55913	kPa
n	1.309555	–

Observed and Simulated moisture content by Gardner (1958) model for the desorption process		
Soil Suction	Observed Values	Predicted Values
1500	0.1205	0.0818
500	0.1352	0.0820
300	0.1490	0.0824
100	0.1897	0.0846
33	0.2588	0.0937
10	0.3151	0.1324
0.01	0.434984163	0.434748388
Mean	0.228321965	–

The performance of the Gardner (1958) was tested by Nash-Sutcliffe model efficiency (NSE) and goodness of fit (R^2) between observed and simulated data by the model. The calculations to measure Nash-Sutcliffe model efficiency (NSE) is detailed in Table 4.11.

It can be seen in the table 4.11 that Nash-Sutcliffe model efficiency (NSE) of Gardner (1958) model for desorption process is negative indicating that this model does not fit to the observed data of the soil moisture characteristics of the soils of the experimental field. The reason behind this is the Gardner model simulated values differs significantly at saturation and near saturated moisture conditions as can be seen in Table-4.10. Matlan, *et al.* (2014), also reported the similar results.

Table 4.11 Nash-Sutcliffe model efficiency (NSE) of Gardner (1958) model for desorption process

Nash-Sutcliffe model efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
1500	0.001500644	0.011628031
500	0.002827805	0.008672309
300	0.004438971	0.006295045
100	0.011049537	0.001494205
33	0.027277659	0.000930237
10	0.033363024	0.007530253
0.01	2.25472E-05	0.04067403
Total	0.080480188	0.07722411
NSE	– 0.042164003	–

4.6.2.2 Sorption process

The model parameters were obtained through Sigma Plot software. The software was used to fit the equation based on observed data and the model parameters obtained are presented in Table 4.12. In can be seen in Table 4.12 that the Gardner (1958) model parameters of the sorption processes namely residual moisture content (θ_r), saturated moisture content (θ_s), empirical coefficients a, and n were found as 0.08057 cm^3cm^{-3}, 0.430576768 cm^3cm^{-3}, 0.1502 kPa and 1.8842 respectively.

Table 4.12 Gardner (1958) model parameters for the sorption process

Inputs for Coarse Grained Soil		
Input	Values	Unit
θ_r	0.08057	cm^3/cm^3
θ_s	0.430576768	cm^3/cm^3
a	0.1502	kPa
n	1.8842	–
Observed and Simulated moisture content by Gardner (1958) model for the sorption process		
Soil Suction	Observed Values	Predicted Values
0.01	0.4201	0.4285
0.1	0.4130	0.3195
0.2	0.3240	0.2095
0.4	0.2649	0.1283
0.6	0.2429	0.1046
0.8	0.2230	0.0949
0.98	0.1961	0.0905
1.96	0.1790	0.0833
2.94	0.1539	0.0819
3.92	0.1459	0.0813
4.9	0.1360	0.0811
6.47	0.1320	0.0809
Mean	0.2359	–

The model's parameters obtained were fitted to Gardner model and the soil moisture characteristics were simulated for the range of suction were used for the experiment. To check whether the model was giving accurate results, the model efficiency was determined. The model efficiency gives how efficient model gives the predicted data. It can be seen in the Table 4.13 that Nash-Sutcliffe model efficiency (NSE) of Gardner (1958) model for sorption process is 0.026895117 indicating that this model does not fit to the observed data of the soil moisture characteristics of the soils of the experimental field during the sorption process. Nevertheless, to assess how close predicted and observed data are, the observed and simulated data are plotted in Fig. 4.8. It can be seen in Fig 4.8 that that the observed data and simulated data differs significantly. The reason behind this is the Gardner model simulated values differs significantly at near saturated moisture conditions as can be seen in Table 4.12, Fig. 4.7 and Fig 4.8. The similar results were also as reported by (Matlan, *et al.*, 2014).

Table 4.13 Nash-Sutcliffe model efficiency (NSE) of Gardner model for sorption process

Nash-Sutcliffe model efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
0.01	7.00051E-05	0.033926423
0.1	0.00873203	0.031356621
0.2	0.013122165	0.007765036
0.4	0.018644057	0.000837751
0.6	0.019152761	4.95631E-05
0.8	0.016405549	0.00016625
0.98	0.0111566	0.001582997
1.96	0.009152761	0.00324015
2.94	0.005191518	0.00672426

3.92	0.00417728	0.008092478
4.9	0.003017578	0.009982811
6.47	0.002616409	0.010794364
Total	0.111438712	0.114518706
NSE	0.026895117	–

The observed and simulated data on soil moisture content at various suction during desorption and sorption process are compared graphically in Fig. 4.7 and Fig 4.8. Also, it can be in the Fig 4.7 and Fig 4.8 that Gardner (1958) model is not able to describe the soil moisture retention behaviour either for the desorption or sorption process of the soils of the experimental field.

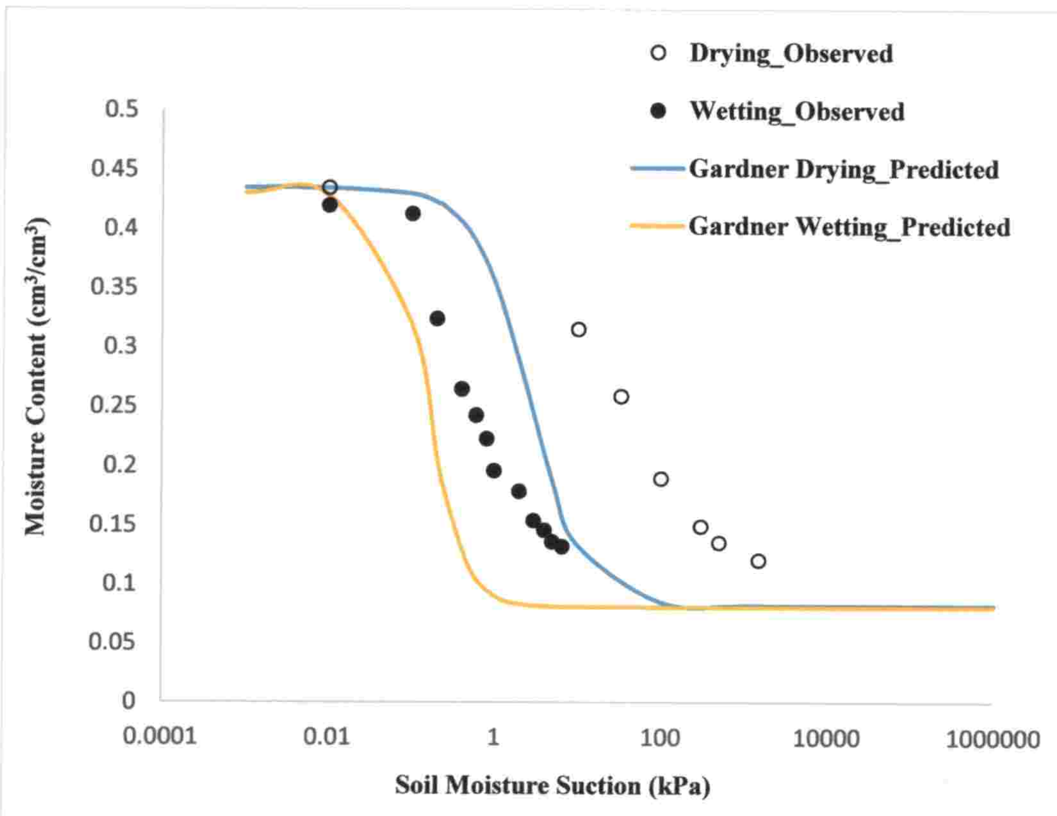

Fig. 4.7 Comparison of observed and simulated moisture content during drying and wetting by Gardner (1958) model

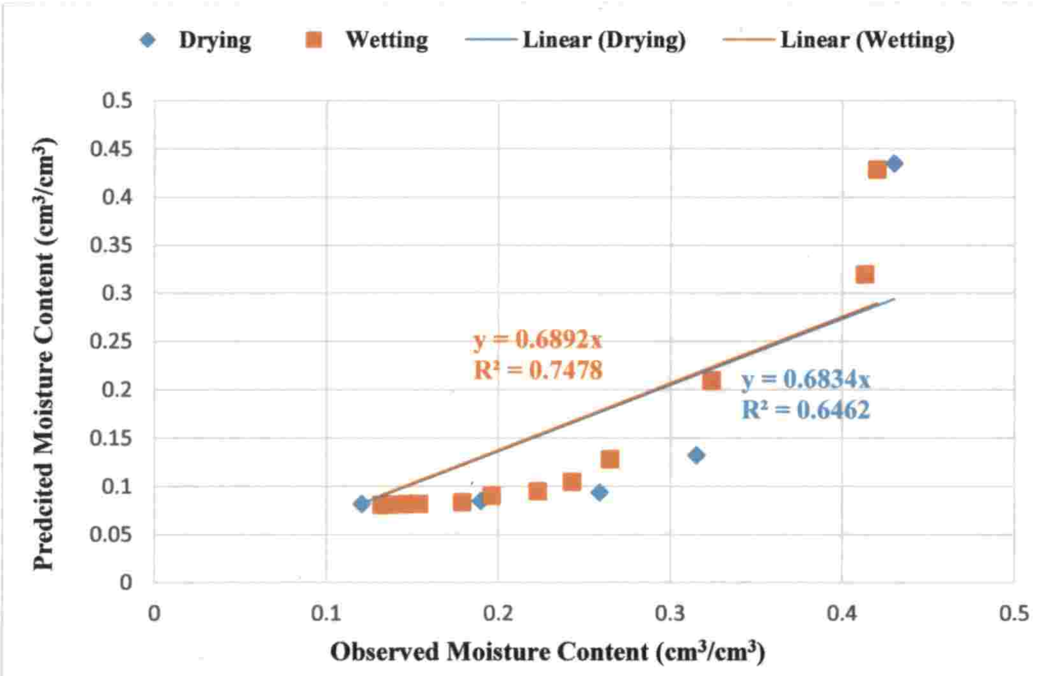

Fig. 4.8 Closeness of observed and simulated moisture content during drying and wetting by Gardner (1958) model

4.6.3 Fredlund and Xing (1994) model (1)

The Fredlund and Xing (1994) model is proposed assuming that the shape of the soil moisture retention behavour during desorption depends on the pore size distribution in the soil porous media. The research results reported by Fredlund and Rahardjo (1993b) has shown that there is an association among the soil moisture retention behaviors of a given soil and the unsaturated soil properties. The Fredlund and Xing (1994) model (1) form is an analogous to cumulative frequency distribution function. The model provides a good fit for sand, silt, and clay soils over the entire suction range from 0 to 106 kPa.

4.6.3.1 Desorption process

Fredlund and Xing (1994) model (1) parameters for the Coarse Grained soil of the experimental field were detrmined based on the soil propertes as per the Zapata, *et al.* (2000) and Perera, *et al.* (2005) model. The paticle size analysis was made through sieve shaker and hydrometer and the soil particle distribution curve was prepared. The input values of soil texture like D_{10}, D_{12}, D_{30}, D_{60} and D_{90}, as well as soil properties namely silt content and void ratio of the soil were found respectively as 0.0015 mm, 0.0163 mm, 0.031 mm, 0.48 mm, 3.1 mm, 36.58 % and 0.7699. The Table 4.14 shows that the Fredlund and Xing (1994) model (1) parameters namely residual moisture content (θ_r), saturated moisture content (θ_s), empirical coefficients a, n and m were found as 0.081666667 cm^3cm^{-3}, 0.434996327 cm^3cm^{-3}, 4.03 kPa, 4.33 and 0.66 respectively. The developed Fredlund and Xing (1994) model (1) was used to predict the soil moisture characteritics curve for the range of the soil moisture suction at which the soil moisture retention was determined during the experiment.

Table 4.14 Input and Output values of the sorption process for the Fredlund and Xing (1994) model (1)

Inputs values of soil properties for determining the Parameters of Fredlund and Xing 1994 model (1) for coarse-grained soil required for Zapata, *et al.* (2000) and Perera, *et al.* (2005) model.		
Input	Values	Unit
D_{10}	0.0015	mm
D_{20}	0.0163	mm
D_{30}	0.031	mm
D_{60}	0.48	mm
D_{90}	3.1	mm
e	0.7699	–
P200 (Silt content)	36.58	%

Parameters of Fredlund and Xing (1994) model (1) for coarse grained soil based on soil properties as per the Zapata, *et al.* (2000) and Perera, *et al.* (2005) model.		
Output	Values	Unit
θ_r	0.081666667	cm^3/cm^3
θ_s	0.434996327	cm^3/cm^3
a	4.03	kPa
n	4.33	–
m	0.66	–

The model's parameters obtained were furnished to Fredlund and Xing (1994) model (1) and the developed model was used to simulate the soil moisture characteristics for the suction values used for the experiment using pressure plate apparatus.

Observed and Simulated moisture content by Fredlund and Xing (1994) model (1) for the desorption process		
Soil Suction	Observed Values	Predicted Values
1500	0.120488616	0.123199561
500	0.13519673	0.129226135
300	0.148980644	0.132875162
100	0.189667017	0.143850772
33	0.258821756	0.163900386
10	0.315098993	0.223493261
0.01	0.434996327	0.434996327
Mean	0.229035726	–

The developed Fredlund and Xing (1994) model (1) performance were assessed through determination of Nash-Sutcliffe model efficiency (NSE) as detailed in Table 4.15. The Nash-Sutcliffe model efficiency (NSE) of 0.750151563 was found to describe the soil moisture characteristics by the Fredlund and Xing (1994) model (1) for the desorption process. It indicated that the model can be used to simulate the soil moisture characteristics accurately for the soils of the experimental field instead of performing the cost, time and labour intensive method of measuring it either in field or the laboratories (Klute, 1986). The results reported by Fredlund and Xing (1994) also supported stating that the model provided a good fit for sand, silt, and clay soils over the entire suction range from 0 to 106 kPa.

Table 4.15 Nash-Sutcliffe model efficiency (NSE) of Fredlund and Xing (1994) model (1) for desorption process

Nash-Sutcliffe model efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
1500	7.34922E-06	0.011782475
500	3.5648E-05	0.008805757
300	0.000259387	0.006408816
100	0.002099128	0.001549895
33	0.009010066	0.000887208
10	0.00839161	0.007406886
0.01	2.01827E-25	0.042419769
Total	0.019803189	0.079260806
NSE	0.750151563	–

4.6.3.2 Sorption process

The observed data on the soil water retention at various suction attained through the capillary rise open tube method were used to obtain the model parameters through the SIGMAPLOT software. The model parameters were obtained through Sigma Plot software (Table 4.16). In can be seen in Table 4.16 that the Fredlund and Xing (1994) model (1) parameters of the sorption processes namely residual moisture content (θ_r), saturated moisture content (θ_s), empirical coefficients a, n and m were found as 0.04085 cm^3cm^{-3}, 0.4279 cm^3cm^{-3}, 0.1628 kPa, 1.606 and 6.36E-01 respectively.

Table 4.16 Fredlund and Xing (1994) model (1) parameters of sorption process

Outputs for Coarse Grained Soil		
Output	Values	Unit
θ_r	0.04085	cm^3/cm^3
θ_s	0.4279	cm^3/cm^3
a	0.1628	kPa
n	1.606	–
m	6.36E-01	–
Observed and Simulated moisture content by Fredlund and Xing (1994) model (1) for the sorption process		
Soil Suction	Observed Values	Predicted Values
0.01	0.420099446	0.426880718
0.1	0.412986187	0.39394235
0.2	0.324027621	0.351499928
0.4	0.264852106	0.294920015
0.6	0.242948283	0.263717852
0.8	0.223014382	0.244439357
0.98	0.196121278	0.232414754

1.96	0.178985859	0.200101931
2.94	0.15390659	0.186142659
3.92	0.145949979	0.177852971
4.9	0.13599416	0.172167658
6.47	0.13201225	0.165846439
Mean	0.235908178	–

The model's parameters obtained were fitted to Fredlund and Xing (1994) model (1) and simulation was performed to describe the soil moisture characteristics for the suction range used during the experiment of open capillary rise tube method. The model performance was assessed by determining the Nash-Sutcliffe model efficiency (NSE) using the observed and simulated soil moisture characteristics. The Nash-Sutcliffe model efficiency (NSE) of 0.919 (Table 4.17) was found to describe the soil moisture characteristics by the developed Fredlund and Xing (1994) model (1) of the sorption process. It can lead to conclude that the developed model can be used to describe the soil moisture characteristics accurately during the sorption processes of the soils of the experimental field, which can be the best alternative of performing the labour and time intensive method of measuring it through capillary rise tube method (Yang, *et al.*, 2004).

Table 4.17 Nash-Sutcliffe model efficiency (NSE) of Fredlund and Xing (1994) model (1) for sorption process

Nash-Sutcliffe model efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
0.01	4.59857E-05	0.033926423
0.1	0.000362668	0.031356621
0.2	0.000754728	0.007765036

0.4	0.000904079	0.000837751
0.6	0.000431375	4.95631E-05
0.8	0.00045903	0.00016625
0.98	0.001317216	0.001582997
1.96	0.000445889	0.00324015
2.94	0.001039164	0.00672426
3.92	0.001017801	0.008092478
4.9	0.001308522	0.009982811
6.47	0.001144752	0.010794364
Total	0.009231209	0.114518706
NSE	0.919391255	–

The soil moisture characteristics of desorption and sorption processes were also simulated beyond the suction range which is not practically applicable and compared as depicted in Fig. 4.9. It can be seen the Fig. 4.9 that the observed data are in close agreement with the curve by developed model.

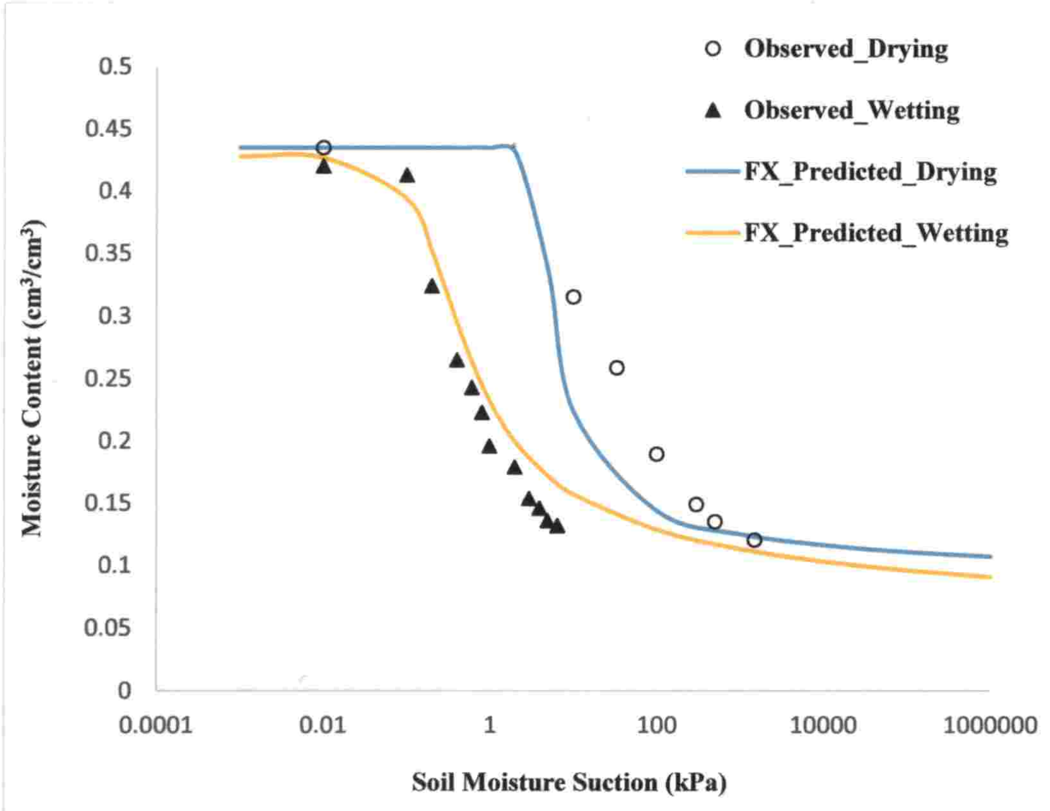

Fig. 4.9 Comparison of observed and simulated moisture content during drying and wetting by Fredlund and Xing, 1994 (1) model

The Fig 4.10 shows the comparison of observed and simulated data on soil moisture retention for desorption and sorption processes. It can be seen that the observed and simulated data during the sorption process are having higher agreement as compared to that of the desorption process. It can lead to conclude that Fredlund and Xing, 1994 (1) is better suited to describe the soil moisture characteristics of the sorption process ($R^2 = 0.93$, NSE = 0.92) as compared to that of desorption process ($R^2 = 0.86$, NSE = 0.75).

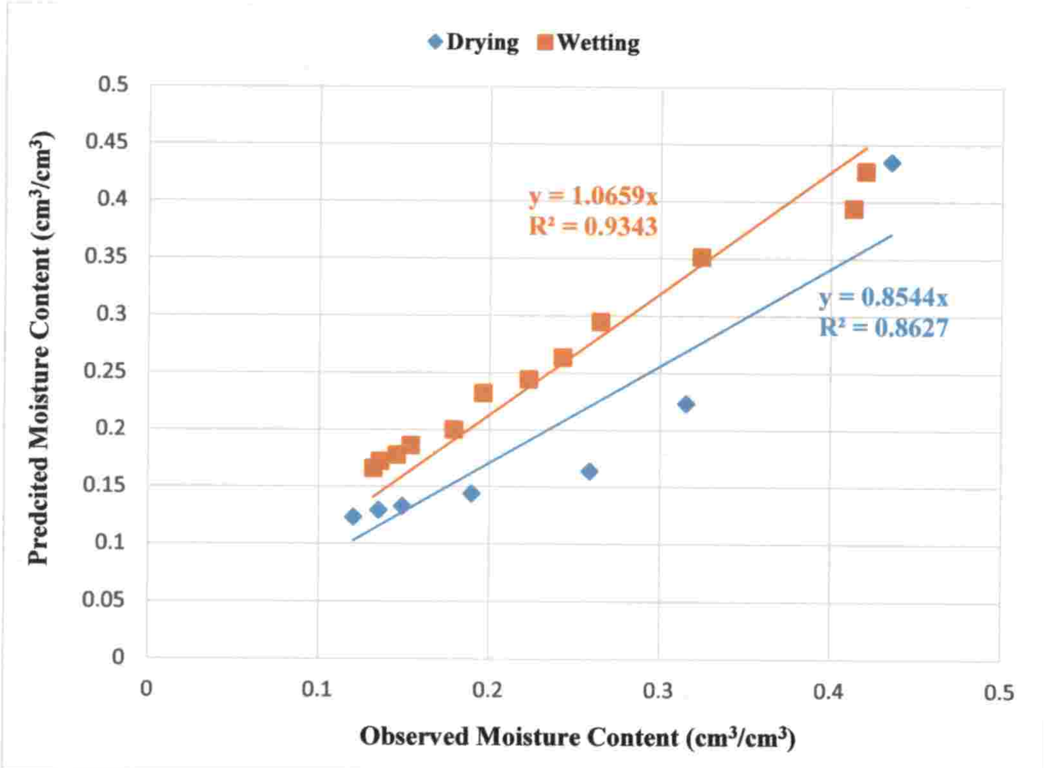

Fig. 4.10 Closeness of observed and simulated moisture content during drying and wetting by Fredlund and Xing (1994) (1) model

4.6.4 Fredlund and Xing (1994) model (2)

Fredlund and Xing (1994) model (2) parameters for Coarse Grained soil are taken same as Fredlund and Xing (1994) model (1) parameters which were determined using the soil particle distribution, void ratio and silt content as per the Zapata, *et al.* (2000) and Perera, *et al.* (2005) model.

4.6.4.1 Desorption process

The developed Fredlund and Xing (1994) model (1) was used to predict the soil moisture characteritics curve for the range of the soil moisture suction at which the soil moisture retention was determined during the experiment. The only difference is Fredlund and Xing (1994) model (1) and Fredlund and Xing (1994) model (2) is inclusion of parameter $C(\Psi)$ in latter from, which is the function of particular residual suction (Ψr) which help to obatian the reducing the soil moisture retention with suction beyond the residual sunction (Ψr). This can be better suited to fine grained soils (Fredlund and Rahardjo, 1993b). Model parameters for

Fredlund and Xing (1994) model (2) as shown in Table 4.18, requires to determine $C(\Psi)$ which consist of Ψ_r. It is the suction corresponding to residual moisture content. For present study Ψ_r was taken as 100 kPa.

Table 4.18 Parameters of Fredlund and Xing (1994) model (2) for Coarse Grained Soil based on soil properties as per the Zapata, *et al.* (2000) and Perera, *et al.* (2005) model.

Parameters of Fredlund and Xing (1994) model (2)		
Input	Values	Unit
θ_s	0.434996327	cm^3/cm^3
a	4.03	kPa
n	4.33	–
m	0.66	–
Observed and Simulated moisture content by Fredlund and Xing (1994) model (2) model for the desorption process		
Soil Suction	Observed Values	Predicted Values
1500	0.1205	0.0357
500	0.1352	0.0472
300	0.1490	0.0536
100	0.1897	0.0708
33	0.2588	0.0981
10	0.3151	0.1728
0.01	0.4350	0.4350
Mean	0.2290	–

The model's parameters obtained were furnished to Fredlund and Xing (1994) model (2) and the developed model was used to simulate the soil moisture characteristics for the suction values used for the experiment using pressure plate apparatus. The developed Fredlund and Xing (1994) model (2) performance were assessed through determination of Nash-Sutcliffe model efficiency (NSE) as detailed in Table 4.19. The Nash-Sutcliffe model efficiency (NSE) of negative values was found for the Fredlund and Xing (1994) model (2) for the desorption process. It indicated that the model could not be fitted to the soil moisture characteristics for the soils of the experimental field. The results reported by Fredlund and Xing (1994) also supported stating that the Fredlund and Xing (1994) model (2) is less suitable for the course-grained soils.

Table 4.19 Fredlund and Xing (2)[3] model efficiency for desorption process

Nash-Sutcliffe model efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
1500	0.007182276	0.01178246
500	0.007750179	0.008805745
300	0.009105958	0.006408805
100	0.014130421	0.00154989
33	0.025829524	0.000887212
10	0.020248787	0.007406897
0.01	1.80654E-11	0.042419603
Total	0.084247146	0.079260612
NSE	– 0.062913145	–

4.6.4.2 Sorption process

The observed data on the soil water retention at various suction attained through the capillary rise open tube method were used to obtain the Fredlund and

Xing (1994) model (2) parameters through the SIGMAPLOT software. The model parameters were obtained through Sigma Plot software (Table 4.20). In can be seen in Table 4.20 that the Fredlund and Xing (1994) model (2) parameters of the sorption processes namely residual moisture content (θ_r), saturated moisture content (θ_s), empirical coefficients a, and n were found as 0.04085 cm^3 cm^{-3}, 0.4279 cm^3 cm^{-3}, 0.1406 kPa, and 1.99 respectively.

Table 4.20 Fredlund and Xing (1994) model (2) parameters of sorption process

Inputs for Coarse Grained Soil		
Input	Values	Unit
θ_r	0.04085	cm^3/cm^3
θ_s	0.4279	cm^3/cm^3
a	0.1406	kPa
n	1.99	–
m	0.8657	–
Observed and Simulated moisture content by Fredlund and Xing (1994) model (2) model for the sorption process		
Soil Suction	Observed Values	Predicted Values
0.01	0.4201	0.4272
0.1	0.4130	0.3731
0.2	0.3240	0.2919
0.4	0.2649	0.2024
0.6	0.2429	0.1639
0.8	0.2230	0.1430
0.98	0.1961	0.1310

1.96	0.1790	0.1015
2.94	0.1539	0.0897
3.92	0.1459	0.0829
4.9	0.1360	0.0783
6.47	0.1320	0.0733
Mean	0.2359	–

The model's parameters obtained were furnished to Fredlund and Xing (1994) model (2) and the developed model was used to simulate the Soil moisture characteristics. The developed Fredlund and Xing (1994) model (2) was used to predict the Soil moisture characteristics curve for the range of the soil moisture suction at which the soil moisture retention was determined during the experiment using open capillary rise tube method. The developed Fredlund and Xing (1994) model (2) performance were assessed through determination of Nash-Sutcliffe model efficiency (NSE) as detailed in Table 4.21. The Nash-Sutcliffe model efficiency (NSE) of 0.61 was found to describe the soil moisture characteristics by the Fredlund and Xing (1994) model (2) for the sorption process. It indicated that the model can be used to simulate the soil moisture characteristics at somewhat lower accurately for the soils of the experimental field instead of performing the time and labour intensive method of measuring it either in field or the laboratories (Klute, 1986). The results reported by Fredlund and Xing (1994) also supported stating that the model (2) is less efficient for the coarse grain soils for the desorption as well as sorption processes as compared to that of Fredlund and Xing (1994) model (1).

Table 4.21 Fredlund and Xing (2)^3 model efficiency for sorption process

Nash-Sutcliffe model efficiency (NSE)		
Suction	$\left(Y_i^{Observed} - Y_i^{Simulated}\right)^2$	$\left(Y_i^{Observed} - Y^{Mean}\right)^2$
0.01	5.02685E-05	0.033926423
0.1	0.001587113	0.031356621
0.2	0.001029687	0.007765036
0.4	0.003896003	0.000837751
0.6	0.00625588	4.95631E-05
0.8	0.0063945	0.00016625
0.98	0.004238138	0.001582997
1.96	0.006004662	0.00324015
2.94	0.00412213	0.00672426
3.92	0.003975227	0.008092478
4.9	0.003327939	0.009982811
6.47	0.003452857	0.010794364
Total	0.044334405	0.114518706
NSE	0.612863199	–

The soil moisture characteristics of desorption and sorption processes were also simulated beyond the suction range which is not practically applicable and compared as depicted in Fig. 4.11. It can be seen the Fig. 4.11 and 4.12 that the observed data are not in close agreement with the curve by developed model.

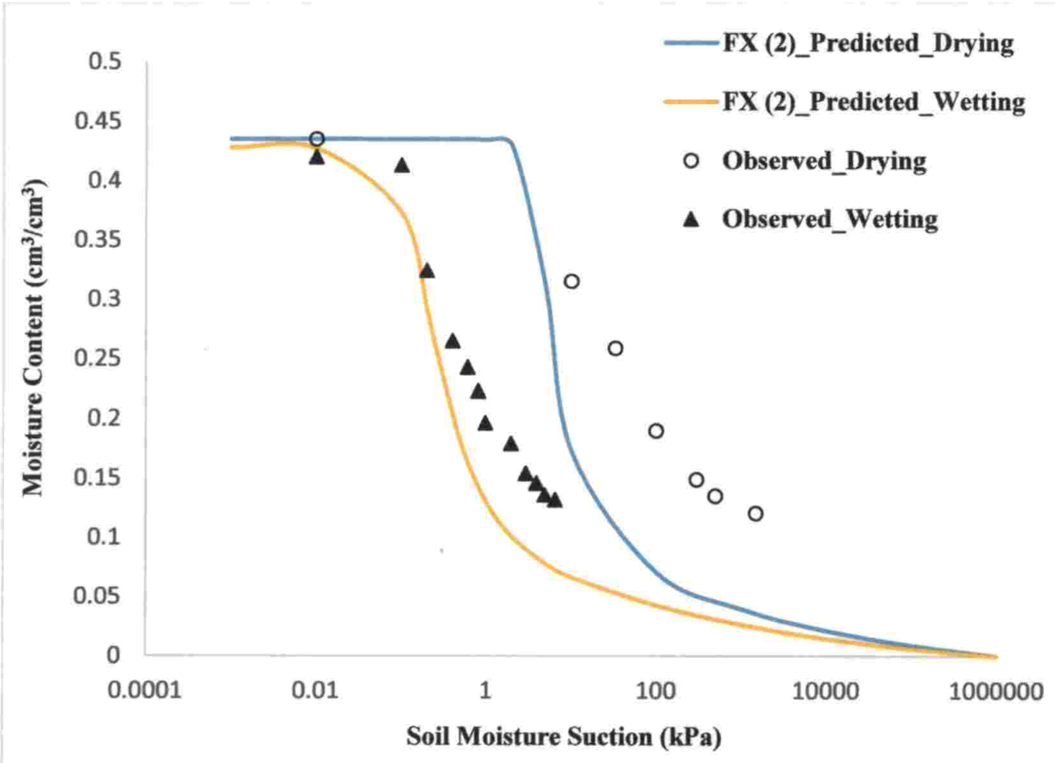

Fig. 4.11 Comparison of observed and simulated moisture content during drying and wetting by Fredlund and Xing, 1994 (2) model

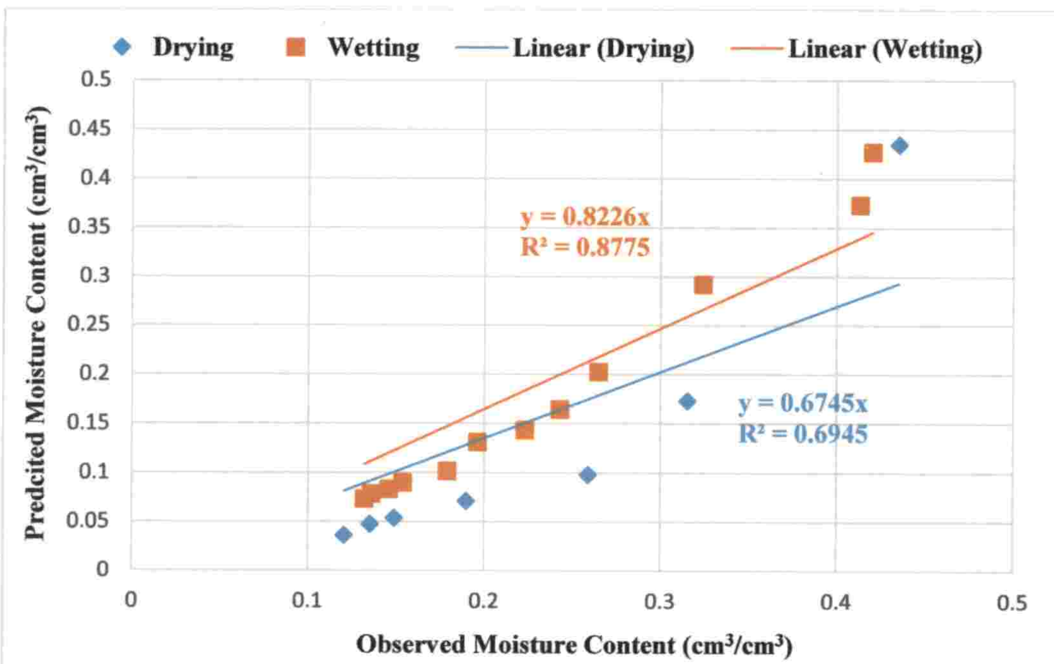

Fig. 4.12 Closeness of observed and simulated moisture content during drying and wetting by Fredlund and Xing, 1994 (2) model

4.7 COEFFICIENT OF MANUFACTURING VARIATION

The measured discharge of 2 lph drippers were found varied from 1.956 lph to 2.024 lph with standard deviations of 0.0198. Similarly, 4 and 8 lph rated dripper discharge had variations of 3.94 to 4.064 lph and 7.656 to 8.188 lph respectively having standard deviations of 0.0494 and 0.1984. The lowest coefficient of manufacturing variation was found as 0.99 % for 2 lph drippers followed by 1.23 % and 2.48 % respectively for the 4 and 8 lph rated drippers. The coefficient of manufacturing variations of 2, 4 and 8 lph discharge rated drippers fall under category of "excellent" because of lower than 5 % as per the ASAE standards (Goyal, 2016). The results found by Özekici and Sneed (1995) showed that 11 out of the 17 drippers had flow rates within 10 % to those claimed by the manufacturers.

The coefficient of manufacturing variation was found increased with increase in dripper discharge. The reason may be that the possibilities of water passage variations among the same discharge rated dripper can be higher due to the larger passage in higher rated discharge as compared to that of lower rated drippers during the manufacturing processes. However, the contradictory result was reported by Kyada and Munjapara (2013) stating that the coefficient of manufacturing variations for 2 lph, 4 lph, 8 lph, 14 lph and 20 lph drippers were 7.95 %, 4.95 %, 2.85 %, 0.89 % and 0.86 %, respectively. The reason might be the different manufacturers for the different rated drippers, which they tested. In fact, the report by Sharma (2013) highlighted that manufacturing coefficient of variation for drippers of 2, 4 and 8 lph capacity as 16.5 %, 17.1 % and 10.1 % respectively indicating no definite trend of coefficient of manufacturing variation with dripper capacity.

4.8 EVALUATION OF CONTINUOUS DRIP IRRIGATION SYSTEM

The research was conducted in KCAET farm itself and the soil was sandy loam type in texture. The water source was a separate tank of 500-liter capacity in which water was filled from conveyance pipe running nearby and an electric motor pump of 0.5 hp was used to run the pressurized drip irrigation system.

4.8.1 Wetting front movement under continuous drip irrigation

The hrizontal and vertical dimentions of the wetting bulb were measured for all the three laterals having different discharge drippers at different timings. The readings were noted and a graph was prepared. The readings were taken through measuring tap. The wetting front measured for 2 lph, 4 lph and 8 lph are shown below.

4.8.1.1 Wetting front movement under 2 lph continuous drip irrigation

The horizontal and vertical spreading of wetting front was measured from emitter for 2-lph discharge at various time intervals are as shown in Fig. 4.13. The Fig. 4.13 shows the wetting front movement in horizontal and vertical direction under 2-lph dripper at various times after irrigation start. The horizontal advancement rate was found lower as compared to later times. The advancement rate was decreasing with time due to increased wetted surface area of wetting bub. The horizontal expansion of the wetted bulb on ground surface at 1 hr, 2 hr and 3 hr were observed as 14.9 cm, 21.3 cm and 28.1 cm while at similar time the vertical depth of the wetted was found as 19.4 cm, 26.3 cm and 31.4 cm respectively. The results are in similar lines as reported by Shein, *et al.* (1988), Subbaiah and Mashru (2013).

The results in similar trends for Clayey loam soil were also found by Kyada and Munjapara (2013), stating that using the Drip irrigation with 2 lph drippers could produce wetted bulb having surface radius of 21 cm, 27 cm, 36 cm, 41 cm and 51 cm respectively. Depth of 36 cm, 41 cm, 47 cm, 52 cm and 55 cm, respectively after continuous irrigations of 1 hr, 2 hr, 3 hr, 4 hr and 5 hr durations.

The final wetting front after the redistribution of soil water inside the wetted was also measured after 24 hours as shown in Fig. 4.14. After redistribution soil water at 24 hr, the horizontal and vertical dimensions of the wetted bulb was increased to 29.38 cm and 33.76 cm respectively. After redistribution of soil water of the wetted bulb, the vertical expansion was found higher than the horizontal expansion due to dominancy of gravity forces as compared to matric forces of the soils which is in line with outcomes reported by Elmaloglou and Diamantopoulos (2007), Diamantopoulos and Elmaloglou (2012).

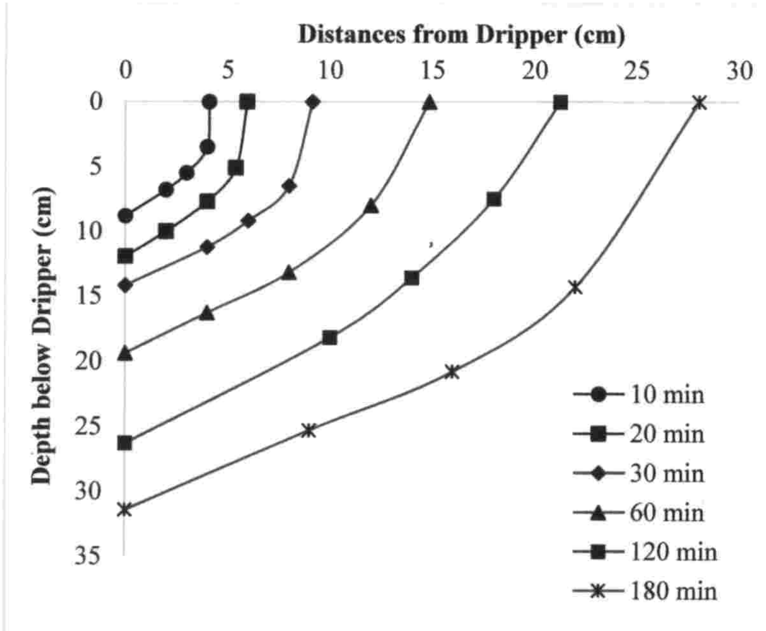

Fig. 4.13 Wetting front movement at various times under continuous drip irrigation using 2 LPH dripper

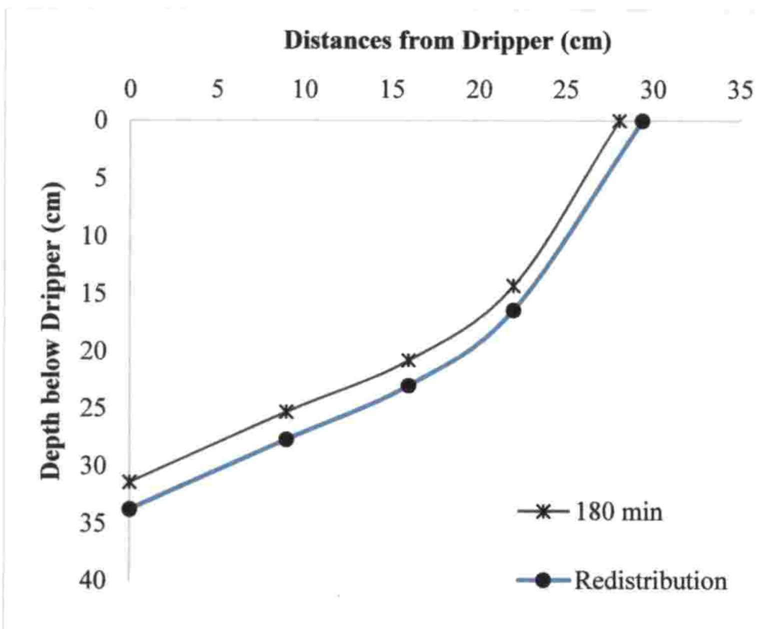

Fig. 4.14 Wetting front movement after redistribution under continuous drip irrigation using 2 LPH dripper

4.8.1.2 Wetting front movement under 4 lph continuous drip irrigation

The Fig. 4.15 shows the wetting front movement in horizontal and vertical direction under 4-lph dripper at various times after irrigation start. The horizontal advancement rate was found lower as compared to later times. The advancement rate was decreasing with time due to increased wetted surface area of wetting bub. The horizontal expansion of the wetted bulb on ground surface at 1 hr, 2 hr and 3 hr were observed as 25.8 cm, 37.0 cm and 48.4 cm while at similar times the vertical depth of the wetted was found as 21.7 cm, 29.9 cm and 36 cm respectively. The results are in similar lines as reported by Gontia (1990), Catzflis and Mortononi (1993).

However, the outcomes reported for clay loam soils by Kyada and Munjapara (2013) were somewhat different stating that the Drip irrigation adopting 4 lph drippers could formed the wetted bulb at the end of 1 hr, 2 hr, 3 hr, 4 hr and 5 hr duration. That was having the surface diameter of 50 cm, 68 cm, 86 cm, 102 cm and 114 cm and depth of 43 cm, 49 cm, 52 cm, 55 cm and 57 cm, respectively below dripper.

The final wetting front after the redistribution of soil water inside the wetted was also measured after 24 hours as shown in Fig. 4.16. After redistribution soil water at 24 hr, the horizontal and vertical dimensions of the wetted bulb was increased to 50.6 cm and 38.8 cm respectively. After redistribution of soil water of the wetted bulb, the vertical expansion was found higher than the horizontal expansion due to dominancy of gravity forces as compared to matric forces of the soils. The same phenomena were affected the results reported by Elmaloglou and Diamantopoulos (2008) and Elmaloglou and Diamantopoulos (2010).

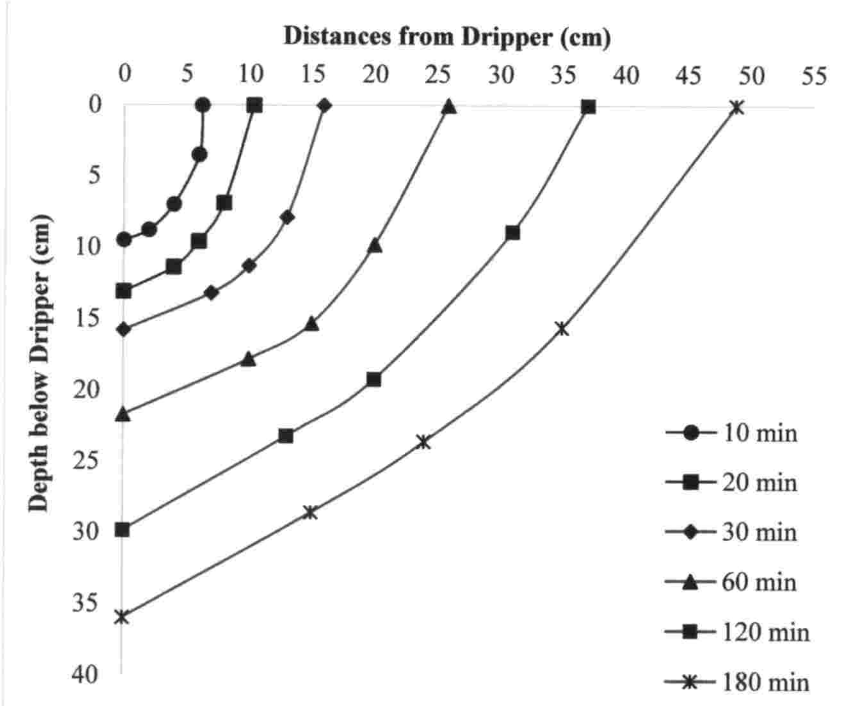

Fig. 4.15 Wetting front movement at various times under continuous drip irrigation using 4 LPH dripper

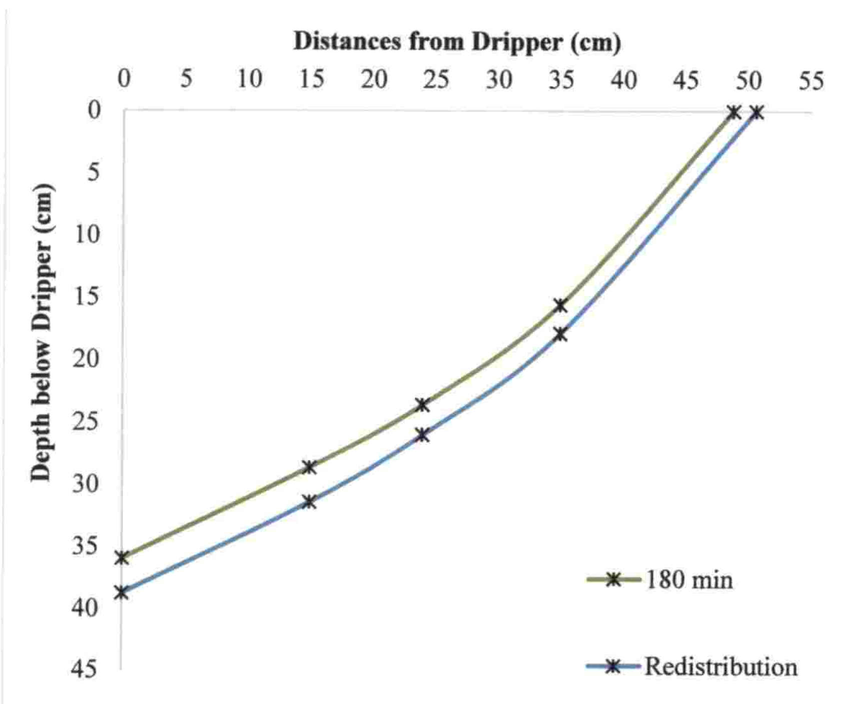

Fig. 4.16 Wetting front movement after redistribution under continuous drip irrigation using 4 LPH dripper

4.8.1.3 Wetting front movement under 8 lph continuous drip irrigation

The Fig. 4.17 shows the wetting front movement in horizontal and vertical direction under 8-lph dripper at various times after irrigation start. The horizontal advancement rate was found lower as compared to later times. The advancement rate was decreasing with time due to increased wetted surface area of wetting bub. The horizontal expansion of the wetted bulb on ground surface at 1 hr, 2 hr and 3 hr were observed as 41.6 cm, 55.2 cm and 72.9 cm while at similar times the vertical depth of the wetted was found as 24.3 cm, 33.8 cm and 41.1 cm respectively. The results are in more or less similar lines as reported by Singh, *et al.* (1990), Hammami, *et al.* (1994), Maheswarappa *et al.* (1997), Battam et. al. (2002).

The field experiment results as reported by Kyada and Munjapara (2013) slightly deviated due to different texture of the soil. Stating that by operating the drip irrigation adopting 8 lph drippers for the durations of 1 hr, 2 hr, 3 hr, 4 hr and 5 hr could able to wet the soil bulbs having surface diameter of 48 cm, 68 cm, 88 cm, 108 cm and 138 cm respectively. Also, depth of 45 cm, 55 cm, 62 cm, 66 cm and 69 cm below dripper respectively.

The final wetting front after the redistribution of soil water inside the wetted was also measured after 24 hours as shown in Fig. 4.18. After redistribution soil water at 24 hr, the horizontal and vertical dimensions of the wetted bulb was increased to 75.4 cm and 44.61 cm respectively. After redistribution of soil water of the wetted bulb, the vertical expansion was found higher than the horizontal expansion due to dominancy of gravity forces as compared to matric forces of the soils. The reasons of the same has been also reflected in the outcomes reported by Elmaloglou and Diamantopoulos (2007), and Diamantopoulos and Elmaloglou (2012).

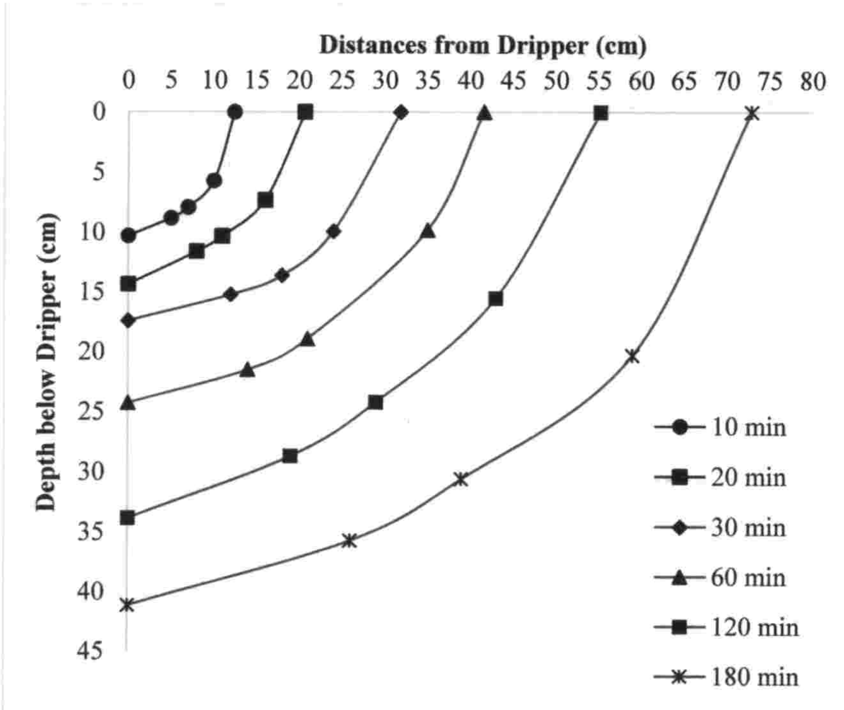

Fig. 4.17 Wetting front movement at various times under continuous drip irrigation using 8 LPH dripper

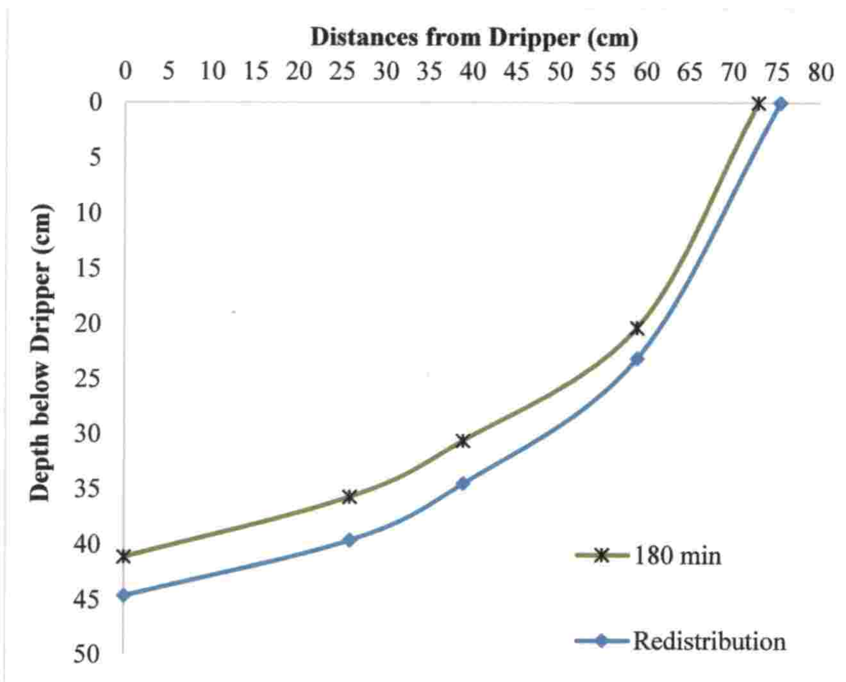

Fig. 4.18 Wetting front movement after redistribution under continuous drip irrigation using 8 LPH dripper

4.8.1.4 Effects of dripper discharge rate on wetted bulb size

The wetting movement for 8 lph discharge is quite different than the 2 lph and 4 lph, as the rate of flow is more so the water volume delivered in given time is more which makes the movement of water front more radially and vertically. Discharge of 8 lph gives the highest radial and vertical water movement for equal time of irrigation. The distribution of moisture may be more for 8 lph discharge.

The horizontal dimension of the wetted bulb at surface under 4 lph could be increased by 1.74 times as compared to 2 lph while it was increased by 1.49 times under 8 lph as compared to 4 lph. The vertical depth of the wetted bulb was increased by 1.14 times by doubling the dripper discharge from 2 lph to 4 lph and 4 lph to 8 lph. The size of the wetted bulb was found increased after 24 hr due to redistributions of the soil water. The horizontal dimensions of the wetted bulb of the 2 lph, 4 lph and 8 lph was increased by 4.74 %, 3.69 % and 3.43 % due to redistributions of the soil water after 24 hours while the vertical depth of the wetted bulb was extended by 7.38 %, 7.79 % and 8.51 % respectively. The percentage increase due to redistribution of soil water after 24 hr in vertical depth was found higher as compared to horizontal dimension for all dripper rates of 2 lph, 4 lph and 8 lph due to more stimulus effects of gravity forces as compared to matric and capillary forces particularly in sandy textured soils.

The results were also supported by Elmaloglou and Diamantopoulos (2007), reporting that the increase in vertical depth was higher than the increase in the horizontal dimensions of the wetted bulb due to redistributions of soil water. After the field studies and modelling through volume balance by Subbaiah and Mashru (2013) have also found that the diameter of the formed wetted soil bulb at surface increased with the increase in time and discharge rate. At any time, the diameter of the wetted surface at top was directly proportional to square root of discharge rate of the dripper. The depth of wetted bulb was found be less influenced by the discharge rate up to the lower than the infiltration abilities of the soil and if a resistive soil layer happens in the penetrating water. After redistributions of the soil water in the bulb, the effects of the discharge on the wetted depth becomes the practically negligible as also supported by Elmaloglou and Diamantopoulos (2007) based on the model studies for sandy soil group of texture. The slight deviation of the present investigation may be due to different initial soil conditions as reported by Shein, *et al.* (1988), Elmaloglou and Diamantopoulos (2008) and Elmaloglou and Diamantopoulos (2009b) stating that the shape and size of the wetted bulb depended on the initial moisture content of the soil.

4.8.2 Soil moisture distribution under continuous drip irrigation

The distributions of moisture below soil surface depend on hydraulic properties of the soil and dripper discharge. The moisture distribution after 3 hours was measured by gravimetric method for all 3 dripper discharge rates and found as depicted in Fig. 4.19, 4.20 and 4.21 respectively for 2 lph, 4 lph and 8 lph respectively.

4.8.2.1 Soil moisture distribution under 2 lph continous drip irrigation

The Fig. 4.19 shows that the soil wetted bulb-having depth of 6 cm below 2-lph dripper and width of 14 cm at surface had moisture content at least 27 % at end of 3 h continues irrigation. The moisture content more than 22 % was found in the wetted bulb of the horizontal width of 32 cm and depth of 17 cm. The wetted bulb having width of 44 cm and depth of 23 cm contained the moisture content above field capacity i.e. 18 %. The contour of moisture content of 15 % has horizontal width of 57 cm at surface and depth of 30 cm. The results revealed that the water front moves more in downward direction than horizontal expansion under 2 lph dipper.

The results through model studies by Elmaloglou and Diamantopoulos (2007) for sandy loam soil and field as well as model simulation by Subbaiah and Mashru (2013) for the clay loam soil were in close agreement to the present investigation outcomes. Also, the results stated by Catzflis and Mortononi (1993), Battam, et. Al. (2002), Rosa, *et al.* (2004), Thabet and Zayani (2008) supported the results of the present investigation.

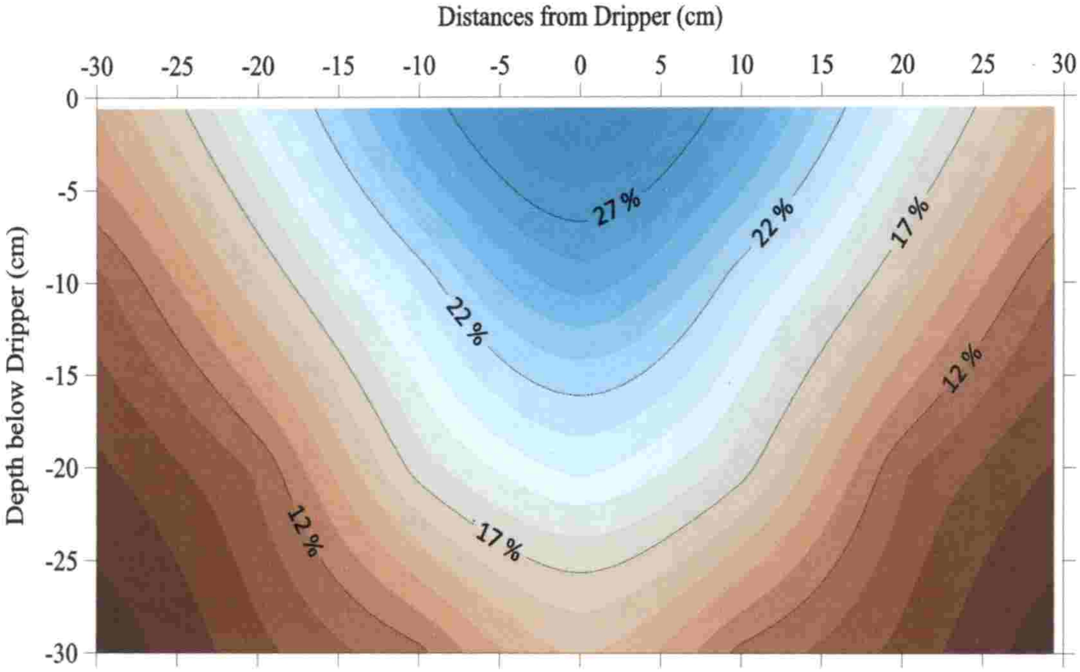

Fig. 4.19 Soil moisture Distribution below dripper for 2 LPH discharge after 3 hours of continuous irrigation

4.8.2.2 Soil moisture distribution under 4 lph continous drip irrigation

The soil-wetted bulb having horizontal width of 22 cm at surface and depth of 11cm below dripper contains moisture content minimum of 27 % as can be seen in Fig. 4.20 for 4 lph dripper indicating insufficient aeration during the irrigation time. The soil moisture content more than 22 % was found in the soil of the wetted bulb of 19 cm depth below dripper and 46 cm width at soil surface. The soil bulb having horizontal diameter of 60 cm and 82 cm at top and depth of 28 cm and 34 cm below dripper could be wetted with minimum moisture content of 18 % and 15 % respectively using 4 lph dripper for 3 h irrigation time. The horizontal and vertical expansion was found more for 4 lph dripper as compared to that of 2 lph dripper.

The outcomes of the model studies reported by Elmaloglou and Diamantopoulos (2010) and Diamantopoulos and Elmaloglou (2012) for the sandy loam soil is in close agreements with outcomes.

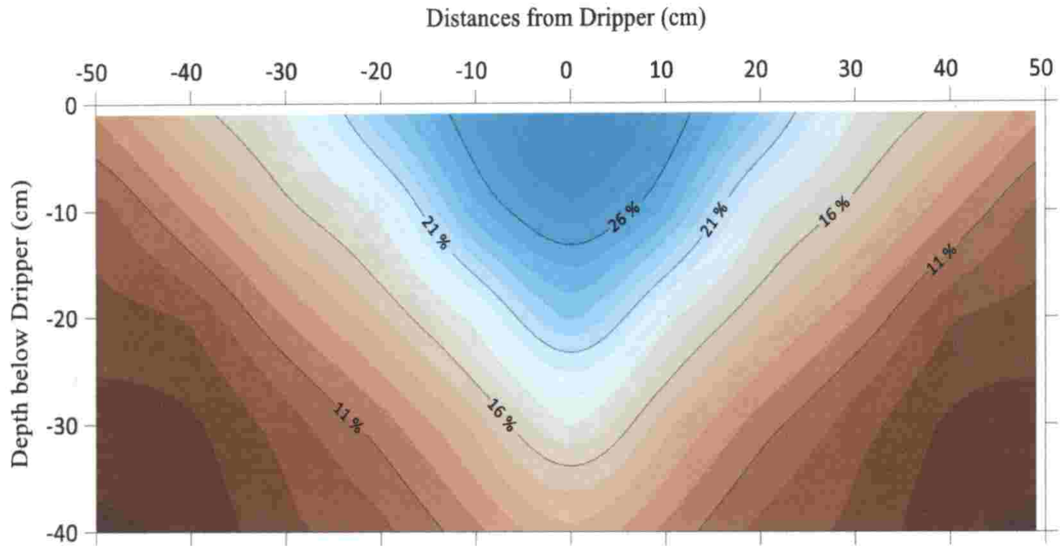

Fig. 4.20 Soil moisture Distribution below dripper for 4 LPH discharge after 3 hours of continuous irrigation

4.8.2.3 Soil moisture distribution under 8 lph continous drip irrigation

The soil-wetted bulb having horizontal width of 27 cm at surface and depth of 11cm below dripper contains moisture content minimum of 27 % as can be seen in Fig. 4.21 for 8 lph dripper indicating insufficient aeration during the irrigation time. The soil moisture content more than 22 % was found in the soil of the wetted bulb of 25 cm depth below dripper and 50 cm width at soil surface. The soil bulb having horizontal diameter of 76 cm and 98 cm at soil surface and depth of 30 cm and 40 cm below dripper could be wetted with minimum moisture content of 18 % and 15 % respectively using 4 lph dripper for 3 h irrigation time. The horizontal and vertical expansion was found more for 4 lph dripper as compared to that of 2 lph dripper.

The similar results were also reported by Gontia (1990) stating that the moisture distribution after irrigation were found higher under higher discharge rate as compared to lower discharge drippers in sandy loamy soil. Singh, *et al.* (1990) have also supported the results by stating that effects of discharge was more on horizontal as compared to vertical dimensions in fallow lands. The results reported by Catzflis and Mortononi (1993) also suggested that the drip irrigation design influenced by dripper discharge rate, water supply time and dripper spacing, soil, climate and crops.

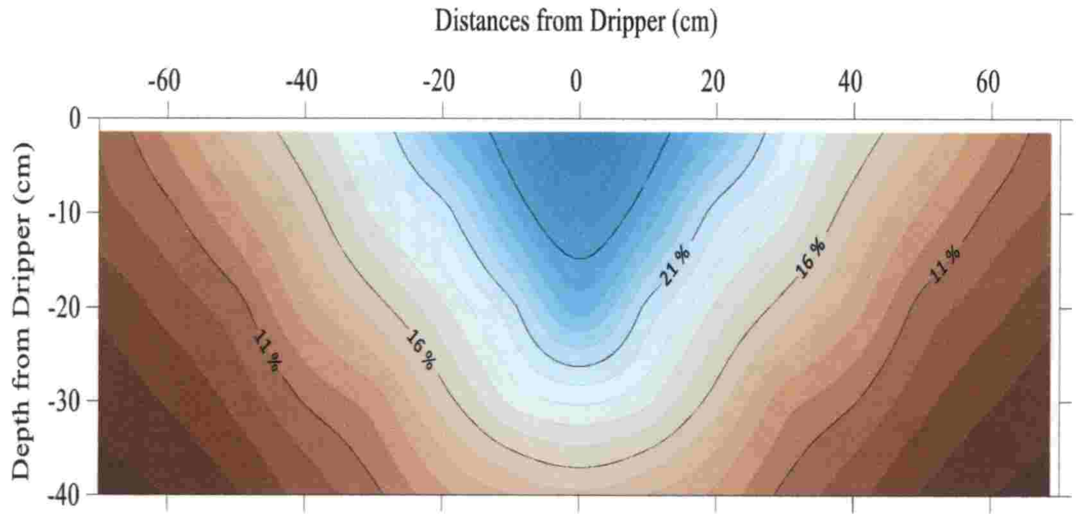

Fig. 4.21 Soil moisture Distribution below dripper for 8 LPH discharge after 3 hours of continuous irrigation

4.8.3 Soil aeration distribution under continuous drip irrigation

The soil aerations in the root zone during irrigation time depend on hydraulic properties of the soil and dripper discharge. The soil moisture distributions after drip irrigation duration of 3 h for the 2 lph, 4 lph and 8 lph drippers were measured and the soil aeration was determined adopting the procedure described in Section 3.8.3 of Chapter III. The soil aerations existed after 3 hours of irrigation were determined for all 3 dripper discharge rates and found as depicted in Fig. 4.22, 4.23 and 4.24 respectively for 2 lph, 4 lph and 8 lph. The soil aeration distribution under continuous drip irrigation adopting 2 lph, 4 lph and 8 lph dripper discharges were not found uniform.

The Fig 4.22, Fig. 4.23 and Fig. 4.24 reflected that soil bulbs having width of 25 cm, 30 cm and 36 cm at surface and depth of 10 cm, 15 cm and 18 cm below dripper had contained soil aeration below 25 % after continuous irrigation of 3 h durations adopting 2 lph, 4 lph and 8 lph drippers respectively. The soil aeration around 25 % is not enough for unrestricted respiration processes of the most of the crops except rice. The soil aeration of at least 50 % remained in the soil beyond the wetted soil bulb having width of 45 cm, 60 cm and 70 cm at soil surface and depth of 23 cm, 28 cm and 30 cm after 3 h continuous drip irrigation adopting the 2 lph, 4 lph and 8 lph drippers respectively. There were more than 75 % aeration after 3 h continuous drip irrigations using 2 lph, 4 lph and 8 lph drippers in the soil mass beyond the soil bulb having width of 66 cm, 100 cm and 120 cm at surface and depth of 35 cm, 45 cm and 50 cm respectively.

The Fig 4.22, Fig. 4.23 and Fig. 4.24 showed that the lower discharge dripper gave better soil aeration as compared to that of higher at the end of continues drip irrigation of 3 h. In fact, after redistributions of soil water in 24 h, the differences in the soil aeration might be negligible and might not be the effects of dripper discharge on soil aeration. The results reported by Elmaloglou and Diamantopoulos (2007), Elmaloglou and Diamantopoulos (2008) and Diamantopoulos and Elmaloglou (2012) through the model studies for the loamy sand soil were also found in close agreements with the results found in the present field experiment for the sandy loam soil.

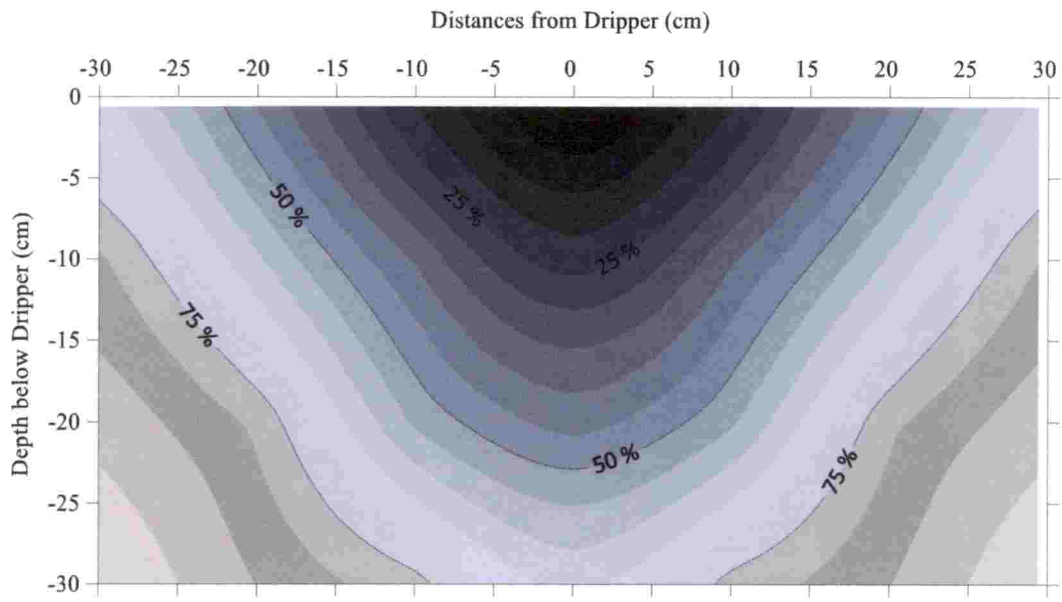

Fig. 4.22 Aeration percentage below dripper for 2 LPH discharge after 3 hours of continuous irrigation

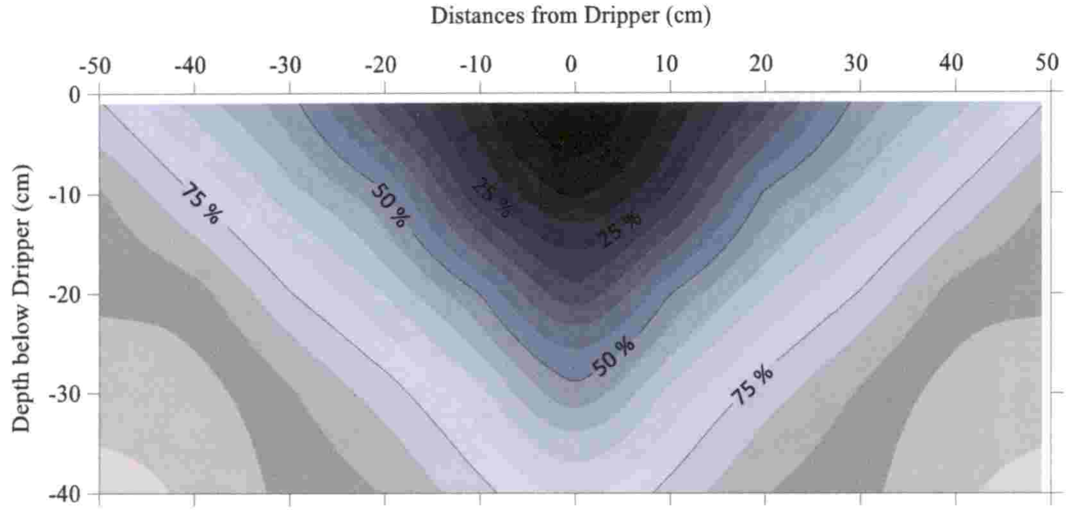

Fig. 4.23 Aeration percentage below dripper for 4 LPH discharge after 3 hours of continuous irrigation

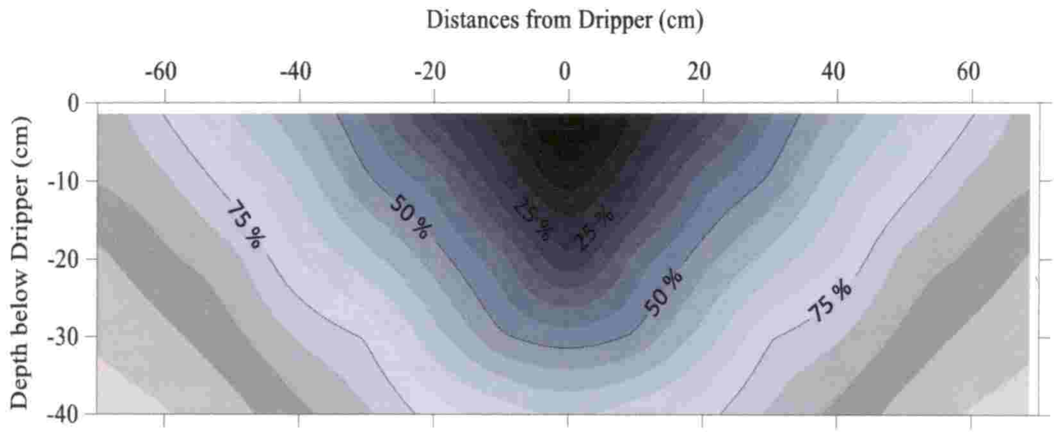

Fig. 4.24 Aeration percentage below dripper for 8 LPH discharge after 3 hours of continuous irrigation

4.9 PULSE DRIP IRRIGATION DESIGN

The water shortage and increased awareness in India about importnace of drip irrigation helped to get momentum for wide scale adoption of drip irrigation. The issues of drip irrigation desgin for the continous water application are emmitter clogging due to finer water path in drippers which leads to lower discharge and matching the shapes of wetted bulb with root zone particularly in sandy groups of soils. The dripping water on sandy loam soil resuls to higher vertical depth and lower horizonatl sperading which causes wastage of water underneath the root zone.

This losses can be eliminated through high discharge drip irrigation in sandy loam soil. However, the high discharge can increse both the vertical and horizonal diemnstions of the wetted bulb (Ismail, *et al.*, 2014). The solution to this problem is using high discharge dripper but operting in series of cycles of pulses.

The size and shapes of the wetted bulb that matches with root zone at various growth stages requires the infromation on dripper discharge, on and off times of pulse cycle and number of cycles for each soil texture. This types of infromation based on experimnal evidence for the sandy loam soils of the study area is yet not available.

The pulse irrigation has many considerations to design. The irrigation depth, no of valves, no of cycles and discharge of emmiter are the design parameters for the pulse irrigation. The system details, irrigation depth, dripper discharge, actaul irrigation rate, number of the pulses and pulse cycle times given in Table 3.2 which were considered for the present investigaons. The operational parameters of pulse irrigation design were decided accordingly for continous as well as pulsed irrigation as depicted in Table 4.22.

Table 4.22 Details of the considered parameters of pulse drip irrigation

<table>
<tr><th rowspan="2">Treatments</th><th rowspan="2">Discharge</th><th rowspan="2">No. of Pulse cycles</th><th colspan="2">Duration*</th><th colspan="2">Pulse cycle – 1</th><th colspan="2">Pulse cycle – 2</th><th colspan="2">Pulse cycle – 3</th></tr>
<tr><th>t_{ON}</th><th>t_{OFF}</th><th>t_{ON}</th><th>t_{OFF}</th><th>t_{ON}</th><th>t_{OFF}</th><th>t_{ON}</th><th>t_{OFF}</th></tr>
<tr><td>T1</td><td>2 lph continuous</td><td>1</td><td>60</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td>T2</td><td>4 lph continuous</td><td>1</td><td>30</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td>T3</td><td>8 lph continuous</td><td>1</td><td>15</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td>T4</td><td>2 lph in pulse</td><td>3</td><td>60</td><td>60</td><td>20</td><td>20</td><td>20</td><td>20</td><td>20</td><td>20</td></tr>
<tr><td>T5</td><td>4 lph in pulse</td><td>3</td><td>30</td><td>90</td><td>10</td><td>30</td><td>10</td><td>30</td><td>10</td><td>30</td></tr>
<tr><td>T6</td><td>8 lph in pulse</td><td>3</td><td>15</td><td>105</td><td>5</td><td>35</td><td>5</td><td>35</td><td>5</td><td>35</td></tr>
</table>

*Irrigation depth is 4mm

As shown in above Table 4.22, the same amount of water (2 litre for 4 mm irrigation depth) is applied but the timing are different for different discharges. So, pulse irrigation have an advantege of using high discharge rates and by giving it for small time period to reduce the deep percolation losses.

4.10 AUTOMATED PULSE DRIP IRRIGATION SYSTEM

The pulse irrigation system evaluation was performed by determining the wetting pattern of the emmiters under different discharge rates and at different pulses and also to compare it with continuous irrigaion. The first most important was to decide the position of the sensor for moisture measurement. Threfore, the determination of the wetting front movement for continuous irrigation was made first and the sensor locations were decided after studies on the wetting front movement under cotinous drip irrigation for 2 lph, 4 lph and 8 lph drippers.

The hardware like low cost soil moisture sensor, Arduino UNO, Breadboard and Jumper Wires, Solenoid Valves, LCD I2C (2×16) Display, Electrical relay interface, Battery, Real Time Clock were used to develop controller for the automated pulse drip irrigation.

The computer programmings were made for the display showing sensor number, sensors's soil moisture content reading (% db w/w), solenoid valve number and ON/OFF status. The calibration eqautions of the sensors from analog to digital signal was also enforced through required codings. The calibration equations are presented in Appendix VI. The coding were also inserted for the various ON/OFF times paparemers of the designed pulse irrigations as per Table 4.22 for the various 2 lph, 4 lph and 8 lph drippers.

4.11 EVALUATION OF PULSED DRIP IRRIGATION SYSTEM

The hrizontal and vertical dimentions of the wetting bulb were measured for all the three laterals having different pulse discharges. The readings were noted and a graph was prepared. The readings were taken through measuring tap. The wetting front measured for 2 lph, 4 lph and 8 lph are shown.

4.11.1 Wetting front movement under pulsed drip irrigation

The horizonatl as well as vertical diemnsions of the wetted bulbs were measured for all the three laterals having different rates of discharge namely 2 lph, 4 lph and 8 lph after different pulse cycles. The observations were recodered and analysed. The observations were taken through measuring tap. The wetting front movement after various pulse cycles were found as depicted in Fig. 4.25, Fig. 4.27 and Fig. 4.29 respectively for 2 lph, 4 lph and 8 lph. The wetted soil bulbs after soil water redistribution in 24 h were found larger as comaperd that of after 3rd pulse cycle of 2 lph, 4 lph and 8 lph pulse drip irrigation as can be seen in Fig. 4.26, Fig. 4.28 and Fig. 4.30 resepctively.

4.11.1.1 Wetting front movement under 2 lph pulse drip irrigation

The Fig. 4.25 depicts that the horizonatl expansions of the wetted soil bulb at soil surface under 2 lph dripper after 1st, 2nd and 3rd pulse cylces was 12.4 cm, 19.8 cm and 25.8 cm respectively. The horizontal expansion rate of wetted bulb was found decerasing during the later pulses as comapred to former ones. The depth of wetted bulb below 2 lph dripper at soil surface was recorded as 12.0 cm, 16.4 cm and 19.8 cm respectively. The vertical expansion of the wetted bulb was found lower during succeeding pulse cylces as comaperd to preceedings as the infiltration rate during latter pulse cylces would be lower as comapred to that of formers.

The Fig. 4.26 depicts the soil wetted bulb size at the end of 3rd pulse cycle and after redistributions of soil water after 24 h under 2 lph pulse drip irrigation. The horizontal width at soil surface and vertical depth below 2 lph dripper at soil surface were found increased from 25.8 cm to 27.0 cm and 19.8 cm to 21.3 cm respectively. The increase in the width was found lower as compared to vertical depth. This may be due to more influence of gravity forces as compared to soil matric forces. The results are close to that of reported by Hammami, *et al.* (1994), Dhanapal, *et al.* (1995), Maheswarappa, *et al.* (1997).

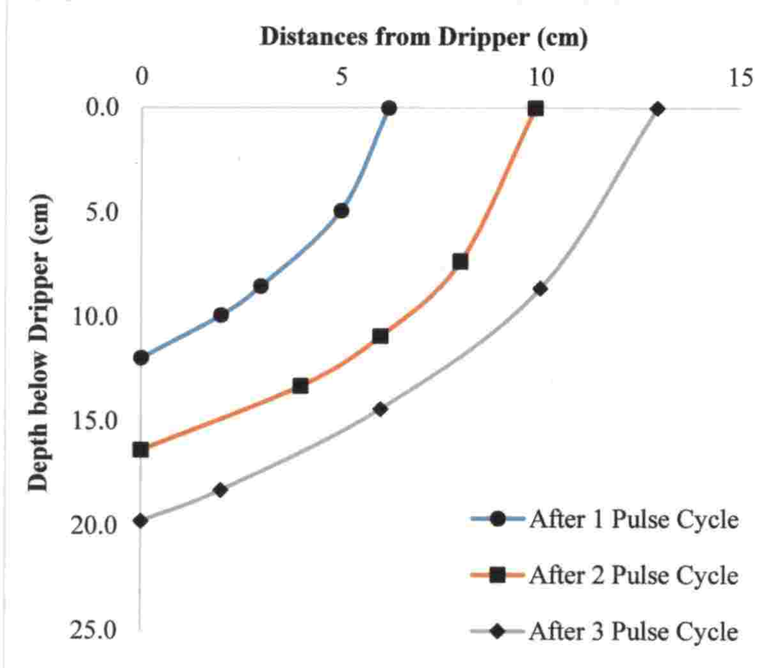

Fig. 4.25 Wetting front movement after various pulse cycles under pulsed drip irrigation using 2 LPH dripper

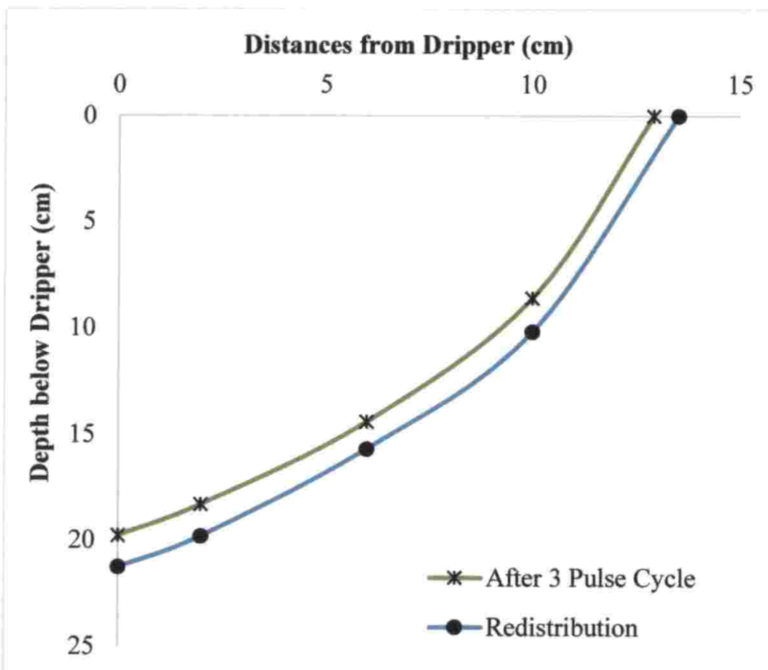

Fig. 4.26 Wetting front movement after redistribution under pulsed drip irrigation using 2 LPH dripper

4.11.1.2 Wetting front movement under 4 lph pulse drip irrigation

The horizonatl expansions of the wetted soil bulb at soil surface under 4 lph dripper after 1st, 2nd and 3rd pulse cylces is shown in the Fig. 4.27. The width of the wetted bulb at soil surface was observed as 13.0 cm, 20.6 cm and 26.8 cm respectively after 1st, 2nd and 3rd cycles. The horizontal expansion rate of wetted bulb was found decerasing during the later pulses as comapred to previous ones. The depth of wetted bulb below 4 lph dripper at soil surface was found as 9.6 cm, 13.5 cm and 16.5 cm respectively. The vertical expansion rate of the wetted bulb was found slower during suucceeding pulse cylces as comaperd to previous ones as the infiltration rate during latter pulse cylces would be lower as comapred to that of previous ones.

The Fig. 4.28 depicts the soil wetted bulb size at the end of 3rd pulse cycle and after redistributions of soil water after 24 h under 4 lph pulse drip irrigation. The horizontal width at soil surface and vertical depth below 4 lph dripper were found increased from 26.8 cm to 28.4 cm and 16.5 cm to 18.1 cm respectively.

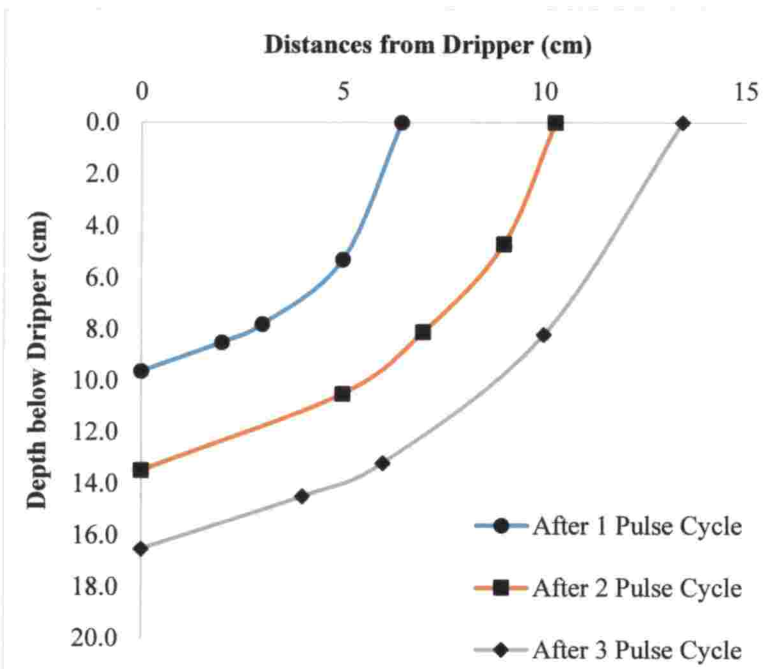

Fig. 4.27 Wetting front movement after various pulse cycles under pulsed drip irrigation using 4 LPH dripper

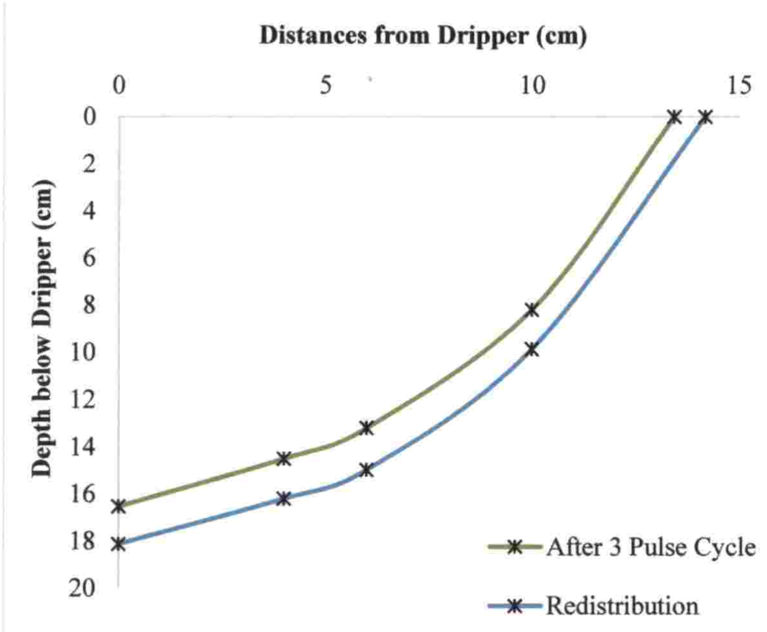

Fig. 4.28 Wetting front movement after redistribution under pulsed drip irrigation using 4 LPH dripper

The increase in the width was found lower as compared to vertical depth, may be due to higher influence of gravity forces as compared to soil matric forces. The results are close to that of reported by Rosa, *et al.* (2004), Thabet and Zayani (2008).

4.11.1.3 Wetting front movement under 8 lph pulse drip irrigation

It can be reflected in Fig. 4.29 that the horizonatl expansions of the wetted soil bulb at soil surface under 8 lph dripper after 1st, 2nd and 3rd pulse cylces were observed as 15.2 cm, 23.4 cm and 33.2 cm respectively after 1st, 2nd and 3rd cycles. The horizontal expansion rate of wetted bulb was found decerasing during the next pulse as comapred to earlier one. The depth of wetted bulb below 8lph dripper at soil surface was found as 7.5 cm, 10.7 cm and 13.3 cm respectively. The vertical expansion rate of the wetted bulb was found slower during latter pulse cylces as comaperd to former ones as the infiltration rate during latter pulse cylces would be lower as comapred to that of previous ones. The soil wetted bulb found at the end of 3rd pulse cycle was enlarged after redistributions of soil water after 24 h under 8 lph pulse drip irrigation as can be seen in the Fig. 4.30.

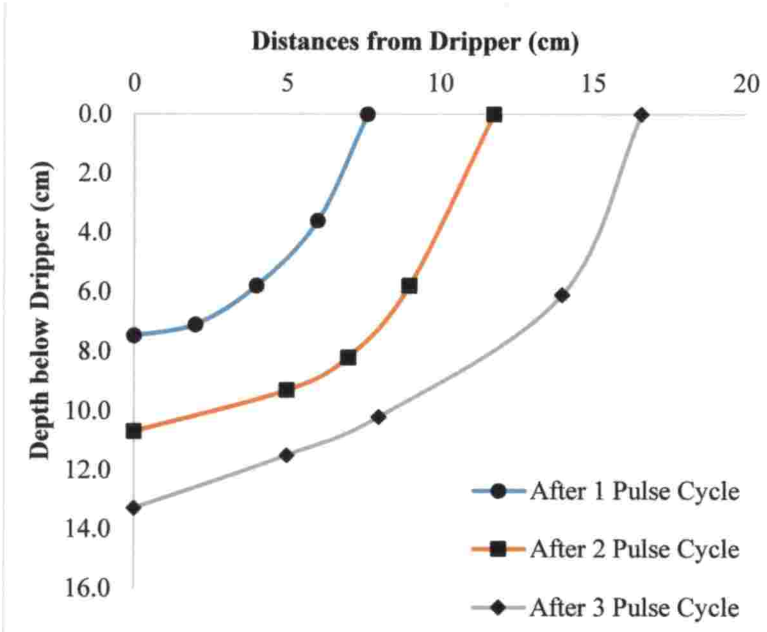

Fig. 4.29 Wetting front movement after various pulse cycles under pulsed drip irrigation using 8 LPH dripper

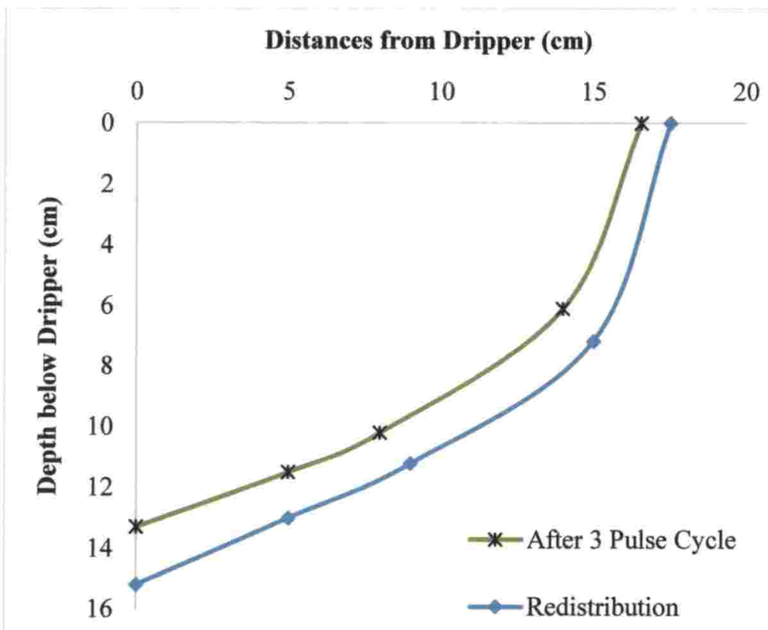

Fig. 4.30 Wetting front movement after redistribution under pulsed drip irrigation using 8 LPH dripper

The horizontal width at soil surface increased from 33.2 cm to 35.1 cm while vertical depth below surface at middle was increased from 13.30 cm to 15.2 cm respectively. The increase in the width was found lower as compared to vertical depth after redistributions of soil water which may be due to dominencies of gravity forces as compared to soil matric forces. The results are close to that of reported by Dhanapal, *et al.* (1995), Rosa, *et al.* (2004).

4.11.1.4 Effects of discharge on wetting front movement under pulse drip irrigation

The size of wetted bulbs obtained after different pulse cycles under various dripper discharge rates are depicted in Table 4.23. The width of the wetted bulb was found increased under 4 lph dripper by 4 % after 3rd pulse cycle and 5 % after reditribution of soil water over that of 2 lph dripper. Similarly it was increased by 24 % under 8 lph drippers after 3rd pulse cycle and 24 % after redistribton of water as comapred to 4 lph dripper. The width of wetted bulb under 8 lph dripper over 2 lph dripper was observed to be increased by 29 % after 3rd pulse cycles and 30 % after redistribution of soil water.

The depth of the wetted bulb was found decrease to 0.83 times under 4 lph dripper after 3rd pulse cycle and to 0.85 times after reditribution of soil water as compated to that of 2 lph dripper. Similarly it was decreased to 0.81 times under 8 lph drippers after 3rd pulse cycles and to 0.84 times after redistribton of water as comapred to 4 lph dripper. The depth of wetted bulb under 8 lph dripper over 2 lph dripper was observed to be reduced to 0.67 times after 3rd pulse cycles and to 0.71 times after redistribution of soil water.

Table 4.23 Effects of dripper discharge rate on size of wetted soil bulb

After Pulse Cycle	Wetted soil bulb size under dripper of					
	2 lph		4 lph		8 lph	
	Width	Depth	Width	Depth	Width	Depth
	cm	cm	cm	cm	cm	cm
1st	12.4	12.0	13.0	9.6	15.2	7.5
2nd	19.8	16.4	20.6	13.5	23.4	10.7
3rd	25.8	19.8	26.8	16.5	33.2	13.3
After Redistribution	27.0	21.3	28.4	18.1	35.1	15.2

It can be reflected in the Table 4.23 that the wetted bulb size having 27 cm width at surface and 21.3 cm depth below 2 lph dripper can be obtained after redistributions of soil water in 24 h after 3 pulse cycles of 20 minutes on and 20 minutes off times. The root zone of the deep rooted crops namely vine crops like pumpkins, winter sqaush and water melons, okra, tomato, castor, coton etc can be best suited to such size and shape of soil wetted bulb.

The wetted bulb size having 28.4 cm width at surface and 18.1 cm depth below 4 lph dripper can be obtained after redistributions of soil water in 24 h after 3 pulse cycles of 10 minutes on and 30 minutes off times. The root zone of the moderately rooted crops like beans, carrot, cucumber, egg plant etc can be best suited to such size and shape of soil wetted bulb.

Using the 8 lph pulse drip irrigation, the wetted soil bulb of 35.1 cm width at soil surface and 15.2 cm depth below dripper could be obtained at end of reditribtions of soil water in 24 h after applying 2 liters of volumes through 3 pulse cycles of 5 minutes on and 35 minutes off times. The such size of wetted soil bulbs can be best matched to the root zone of shallow rooted crops like onion, garlic, ginger, potato, radish, sweet potato, strawberries, beets, corn, turnips, spinach, lettuce, peas, and fennel.

4.11.2 Soil moisture distribution under pulse drip irrigation

The redistributions of moisture below soil surface during the rest time of pulse cycle and after end of irrigation depend on hydraulic conductivities in three directions of various soil layers, texture, drainable porosity, evaporation from soil surface, pulse flow and pulse ratio etc. The moisture redistribution after 24 hours of last pulse cycle was measured by gravimetric method for all 3 dripper discharge rates and found as depicted in Fig. 4.31, 4.32 and 4.31 respectively for 2 lph, 4 lph and 8 lph respectively.

4.11.2.1 Soil moisture distribution under 2 lph pulse drip irrigation

The Fig. 4.31 depicts that the soil wetted bulb having width of 12 cm at surface and depth of 5 cm below 2 lph pulsed dripper hold at least 22 % moisture content after 3rd pulse cycle. The moisture content more than 18 % was found in the wetted bulb of the horizontal width of 21 cm and depth of 17 cm. The wetted bulb having width of 30 cm and depth of 22 cm contained the moisture content above 15 %. The results revealed that the water moves more in downward direction than horizontal under pulse irrigation using 2 lph dipper with 20 minutes on and 20 minutes off times. The results reported by Elmaloglou and Diamantopoulos (2007), Elmaloglou and Diamantopoulos (2008) and through the model studies for the loamy sand soil were also found in close agreements with the results found in the present field experiment for the sandy loam soil.

4.11.2.2 Soil moisture distribution under 4 lph pulse drip irrigation

The soil wetted bulb having depth of 10 cm below 4 lph dripper and width of 14 cm on soil surface hold at least 22 % moisture content after 3rd pulse cycle as can be seen in Fig. 4.32. The moisture content more than 18 % was found in the wetted bulb of the horizontal width of 26 cm and depth of 16 cm. The wetted bulb having width of 38 cm and depth of 18 cm contained the moisture content above 15 %. The results revealed that the dripped water from pulsed 4 lph dripper after 3 pulsed cycles of 10 minutes on and 30 minutes off times could form the wetted bulb with nearly equal size in both directions which contained minimum of 15 %. The results reported by Elmaloglou and Diamantopoulos (2007), Diamantopoulos and Elmaloglou (2012) through the model studies for the loamy sand soil were also found in close agreements with the results found in the present field experiment for the sandy loam soil.

4.11.2.3 Soil moisture distribution under 8 lph pulse drip irrigation

The soil wetted bulb having horizontal width of 17 cm at surface and depth of 10 cm below 8 lph pulsed dripper contained minimum of 22 % moisture content as can be reflected in Fig. 4.33. There might be insufficient aeration in such wetted bulb during the on times of pulse cycles. However, the on times of pulse cycles was only 5 minutes for the 8 lph pulsed drip irrigation. In fact, the most of the crops can sustained such partial anaerobic conditions for such as minor duration of only 5 minutes. The soil moisture content more than 18% was found in the soil of the wetted bulb of 14 cm depth below dripper and 32 cm width at soil surface. The soil bulb having horizontal diameter of 46 cm on soil surface and depth of 16 cm below dripper could be wetted with minimum moisture content of 15 % by operating 8 lph dripper for 3 pulse cycles having 5 minutes on and 35 minutes rest times. The horizontal dimensions of the wetted bulb were observed higher than the under 8 lph pulsed dripper as compared to that of 2 lph dripper and 4 lph. The results reported by Elmaloglou and Diamantopoulos (2007) through the model studies for the loamy sand soil were also found in close agreements with the results found in the present field experiment for the sandy loam soil.

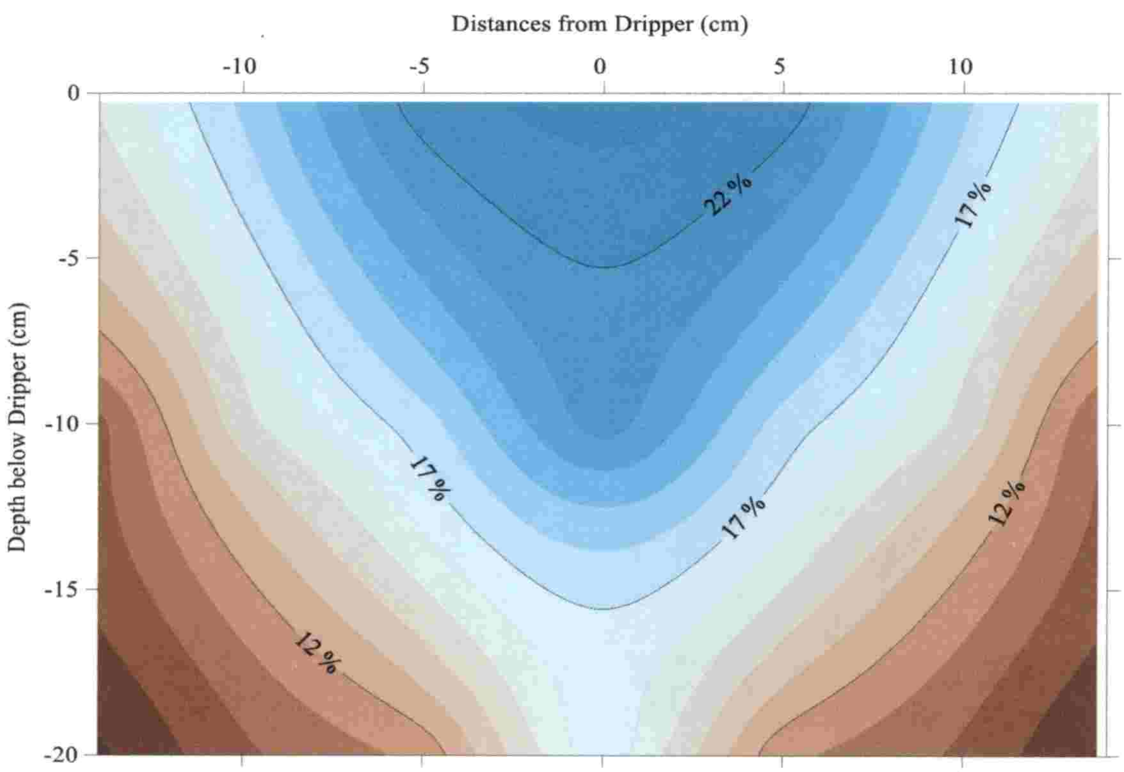

Fig. 4.31 Moisture Distribution below dripper for 2 LPH discharge after 3rd pulse cycle of pulsed irrigation

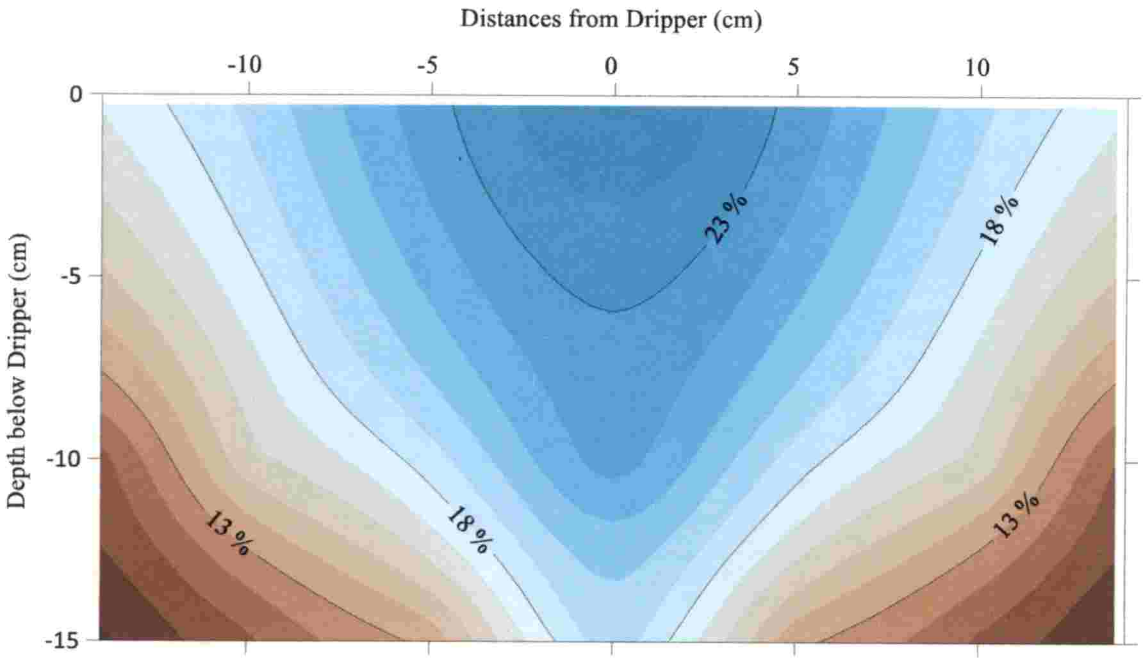

Fig. 4.32 Moisture Distribution below dripper for 4 LPH discharge after 3rd pulse cycle of pulsed irrigation

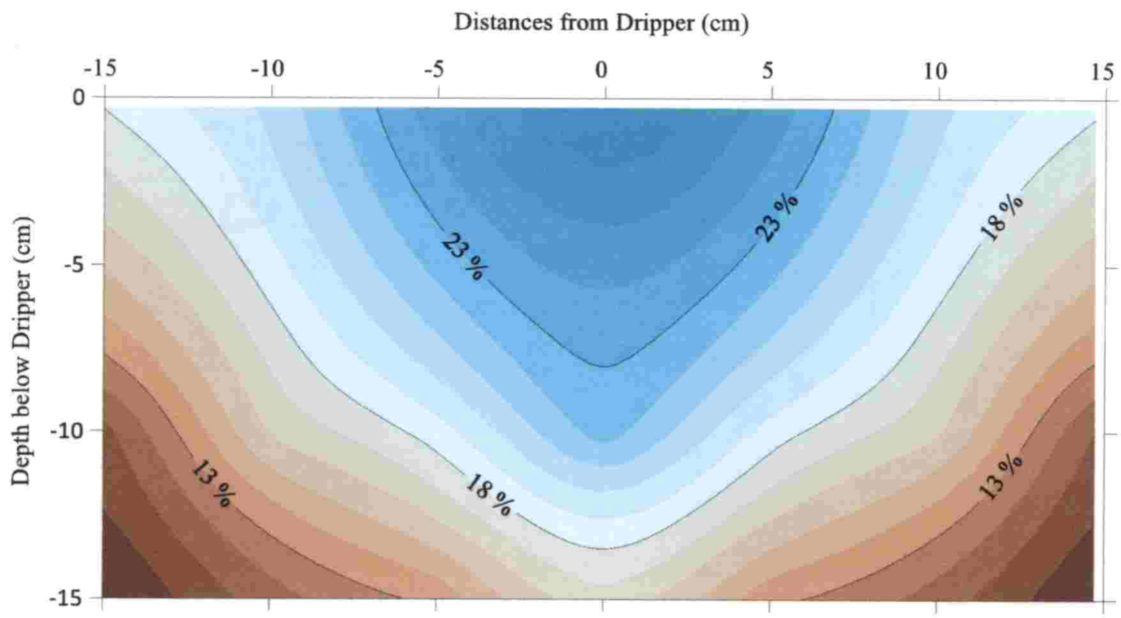

Fig. 4.33 Moisture Distribution below dripper for 8 LPH discharge after 3rd pulse cycle of pulsed irrigation

4.11.2.4 Moisture distribution effects on discharge under pulse drip irrigation

The Fig. 4.31, Fig. 4.32 and Fig 4.33 indicated that there can be a markedly effects of pulsed drip irrigation on the soil moisture distributions. Using the higher discharge dripper, the soil moisture distribution can be widened in horizontal directions. The pulsed drip irrigation adopting higher discharge rate keeping the same amount of irrigation water could help reduce the deep percolation losses. The depth of wetted zone was found lesser under higher discharge rate due to lower on time and higher off times as compared to that of lower discharge rates. In fact, the differences were found less as the soil water during rest times of pulse cycles moved more in downward directions as compared to horizontal direction in sandy loam soil.

4.11.3 Soil aeration distribution under pulsed drip irrigation

The soil aeration distribution seems to be nearly equal over the completely wetted bulb for pulsed irrigation as compared to continuous irrigation, which can be the great advantage of pulse irrigation. The plant roots require the oxygen for the respiration processes continuously during the entire growth periods. During and after irrigation, the soil moisture can be at saturation capacity in case of heavy soils and just below saturation in light soils. In such cases, the air will be replaced by soil water and plant roots feel deficiency of oxygen. This situation to get reversed, it may take 24 hours in heavy soils and 6 to 12 hours after irrigation terminations in light soils depending on the texture of the soils. This problem can be lessened through pulsed drip irrigation in which the aeration may take place during rest times of pulse cycles.

The soil moisture distributions after end of last and 3rd pulse cycle (20 minutes ON followed by 20 minutes rest for 2 lph, 10 minutes ON followed by 30 minutes rest for 4 lph and 5 minutes ON followed by 35 minutes rest for 8 lph dripper of drip irrigation duration were measured. The soil aeration was determined adopting the procedure described in Section 3.8.3 of Chapter III. The soil aerations existed after end of last pulse cycle were determined for all 3 dripper discharge rates and found as depicted in Fig. 4.34, 4.35 and 4.36 respectively for 2 lph, 4 lph and 8 lph respectively.

The Fig 4.34, Fig. 4.35 and Fig. 4.36 reflected that smaller soil bulbs having only the width of 3 cm, 4 cm and 9 cm at surface and depth of 2 cm, 3 cm and 3 cm below dripper had contained soil aeration below 25 % after last and 3rd pulse cycles of drip irrigation adopting 2 lph, 4 lph and 8 lph drippers respectively. The soil aeration around 25 % is not desirable for continuous respiration of the most of the field crops, which are most sensitive to waterlogging.

The soil aeration of at least 50 % remained in the soil beyond the wetted soil bulb having only the width of 20 cm, 24 cm and 28 cm at soil surface and depth of 12 cm, 13 cm and 14 cm after the 3rd pulse cycles of pulse drip irrigation adopting the 2 lph, 4 lph and 8 lph drippers respectively.

There were more than 75 % aeration after end of last pulse cycle of pulse drip irrigations using 2 lph, 4 lph and 8 lph drippers in the soil mass beyond the soil bulb having width of only 40 cm, 50 cm and 60 cm at surface and depth of 21 cm, 22 cm and 23 cm respectively.

The soil moisture and soil aeration distribution were found more uniform in the wetted bulb under pulsed drip irrigation as compared to continuous drip irrigation. In addition, the depth of wetting front below dripper was found less as compared to continuous irrigation. The effects of the discharge rates on the soil aeration was not found much. The soil aeration was found better under pulse drip irrigation as compared to continuous drip irrigation. The results reported by Elmaloglou and Diamantopoulos (2007), and Diamantopoulos and Elmaloglou (2012) through the model studies for the loamy sand soil were also found in close agreements with the results found in the present field experiment for the sandy loam soil.

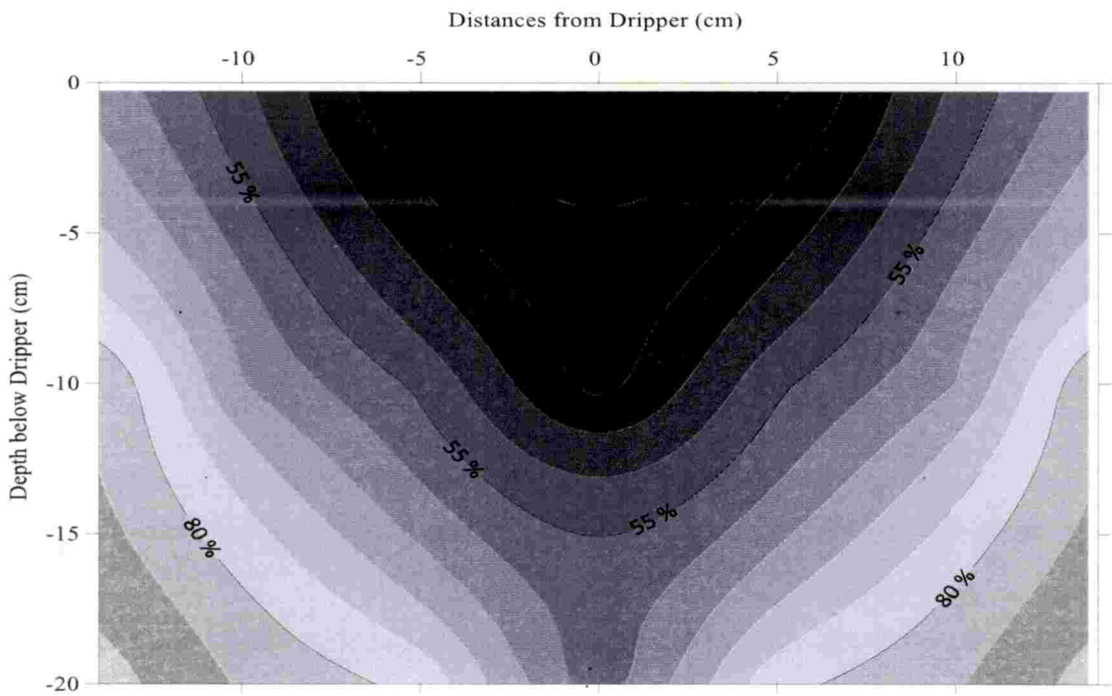

Fig. 4.34 Aeration percentage below dripper for 2 LPH discharge after 3rd pulse cycle of pulsed irrigation

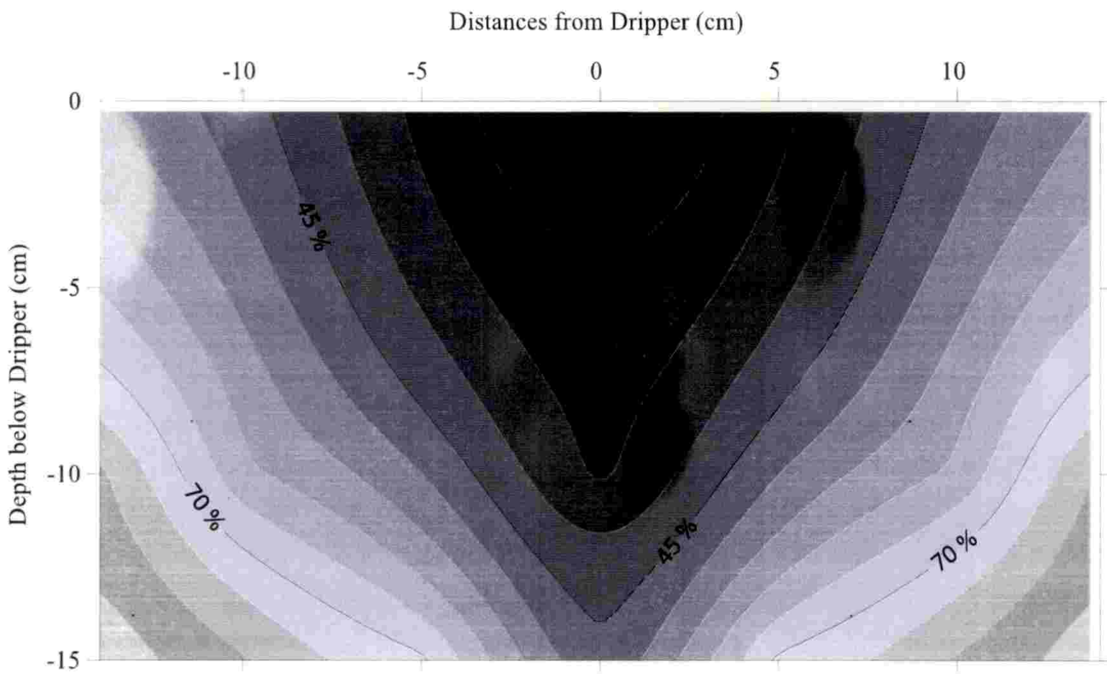

Fig. 4.35 Aeration percentage below dripper for 4 LPH discharge after 3rd pulse cycle of pulsed irrigation

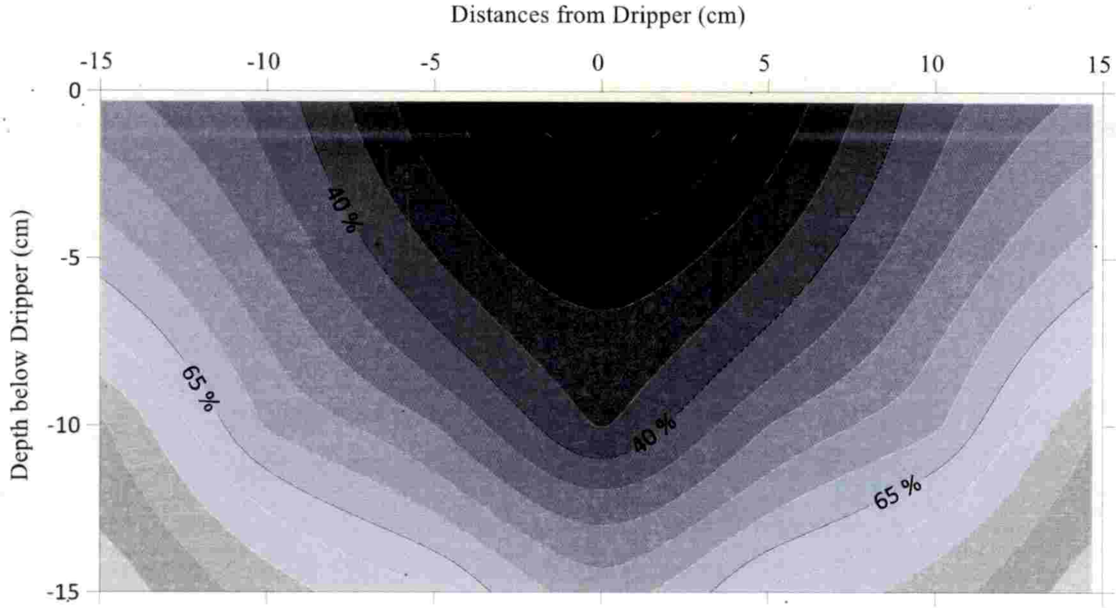

Fig. 4.36 Aeration percentage below dripper for 8 LPH discharge after 3rd pulse cycle of pulsed irrigation

4.12 COMPARISON OF CONTINUOUS AND PULSED DRIP IRRIGATION SYSTEM

The size of wetted bulb obtained under continuous and pulsed drip irrigation at various times having equal volume of irrigation water applied using drippers of different discharge rate are compared in Table 4.24. The size of wetted bulb under continuous drip irrigation should be similar to that of under pulsed drip irrigation at the end of on time 1st pulsed cycles. However, it could be seen in Table 4.24 that it differed slightly, which might be due to different sites in the experimental field because the soil properties may vary slightly within the field itself also.

The size of the wetted bulb observed under 2 lph dripper was having the horizontal spread of 29.7 cm and vertical depth of 19.4 cm under continuous drip irrigation while horizontal spread of 25.8 cm and vertical depth of 19.8 cm under pulsed drip irrigation while applying the same amount of 2.0 litres water.

Similarly, after applying the same amount of 2.0 litres water using 4 lph dripper, the wetted bulb found were having horizontal spreading of 31.9 cm and depth of 15.8 cm under continuous and 26.8 cm and 16.5 cm under pulsed drip irrigation.

The wetted soil bulb obtained after applications of 2 litres irrigation water through 8 lph dripper was of 36.4 cm horizontal spreading and 12.2 cm vertical depth in case continuous while 33.2 cm horizontal spreading and 13.3 cm vertical depth in case of pulsed drip irrigation.

It can be inferred through the comparisons of the size of the wetted bulbs that the wetted bulb of more water spreading and lesser vertical depth can be obtained in continuous as compared to pulsed irrigation under the same dripper discharge and same amount of irrigation water applications. The reason is that the dripped water in the macro pores of the wetted bulb in excess of the field capacity continues to moves more in downward due to gravity as compared to horizontal during rest times of pulse cycles and that phenomenon increases the vertical depth and reduces the horizontal spreading. In the beginnings of the ON time of each pulse cycles, it takes some time to fill the emptied macro pores and during OFF time of previous pulsed cycles, which can be the main reason of lesser surface spreading in pulsed drip irrigation. While in case of continuous irrigation, even the macro pores remain full of water until termination of irrigation.

Also, it can be confirmed after interpretations of the results on the size of the wetted bulbs obtained under continuous and pulsed drip irrigation adopting drippers of different discharge that the horizontal spreading can be increased while deep percolation can be reduced under higher discharge pulse drip irrigation as compared to lower discharge continuous irrigation for the same amount of water application.

The off times of pulse irrigation cycles give the scope for the macro pores' soil water redistribution after on times of every cycle so the final redistribution will be lesser compared to continuous. The enhancement in the size of wetted bulb due to redistribution of soil water in pulsed drip irrigation can be less as compared to continuous irrigation.

Table 4.24 Comparison of size of wetted soil bulb obtained under continuous and pulsed drip irrigation

Dripper discharge rate	Cumulative time of irrigation	Volumes of water applied	Wetted soil bulb size under			
			Continuous drip irrigation		Pulsed drip irrigation	
			Width	Depth	Width	Depth
lph	Minutes	Litres	cm	cm	cm	cm
2	20	0.667	11.9	11.9	12.4	12.0
	40	1.333	24.0	15.5	19.8	16.4
	60	2.000	29.7	19.4	25.8	19.8
4	10	0.667	12.4	9.5	13.0	9.6
	20	1.333	20.7	13.1	20.6	13.5
	30	2.000	31.9	15.8	26.8	16.5
8	5	0.667	15.1	7.4	15.2	7.5
	10	1.333	24.8	10.3	23.4	10.7
	15	2.000	36.4	12.2	33.2	13.3

The evaluation part was terminated here and the results came out of the research were discussed above. It was found that there were some limitations and fruitfulness for conducted research, anyhow the present research was step towards modern techniques using information and communication technologies for agricultural applications. The summary of whole research and some point came out with research were concluded in the next chapter.

CHAPTER V

SUMMARY AND CONCUSSIONS

The agriculture sector has a lion's share in the economy of India. India is a country that is based on agriculture, as 2/3^{rds} of its population depend on agriculture or allied activities for their livelihood. The ever-increasing population with rise in the standard of living has put tremendous pressure on the land and water resources of the country. The global climatic change phenomena worsened the land and water management problems in all spheres of human life. Due to all these issues, the complexities in the water management have increased. This demands efficient utilizations of the scarce irrigation water, as agriculture has more than 80% share in the total fresh water utilization of India. The efficient irrigation water applications reduce not only the water losses but also nutrient leaching as well as soil and groundwater pollution with savings of fertilizer.

The wild flooding irrigation application method leads to excessive water use, lower agricultural production and high cost of cultivation. This increases the financial burden of the farmers. Hence, the rural people engaged in agriculture are now attracted and migrated to other more remunerative works as compared to farming. This has created labour shortage in the agriculture sector and this situation is getting worsened day by day. This calls for labour saving efficient irrigation methods like automated drip irrigation systems.

The major irrigation systems in the country have an efficiency of around 40% only and it is essential to improve this to save water to bring more area under cultivation for feeding the increasing population. Hence, efficient irrigation systems like drip and sprinkler irrigation systems that have high irrigation application efficiencies need to be popularised to increase the irrigation water application efficiency.

There is considerable water savings and yield increase under the conventional continuous drip irrigation system. But still there is a scope to increase the yields by alleviating crop stress due to root asphyxia by increasing the aeration of the crop root zone by having a low water application rate. There is water saturation in the root zone due to continuous water application at high rates under normal drip irrigation with a high discharge rate emitter, leading to root asphyxia. The macropores which should contain air are flooded with water, preventing root respiration. The inadequate aeration leading to lack of oxygen in the crop root zone could hamper the growth of crops under traditional continuous drip irrigation system. The solutions to alleviate the aeration problem in crop root zone include irrigating the crops with aerated/oxygenated irrigation water and using pulse drip irrigation system to reduce the water application rate of the high discharge drip emitters. The pulse irrigation applies water in ON and OFF cycles, which effectively reduces the average application rate of the emitter to permit aeration in the root zone.

Therefore, there is a dire need of development of a sensor based automated pulse drip irrigation system which could increase the soil aeration and water use efficiency and reduce the labour requirement for the irrigation water application. The application of information and communication technologies (ICT) in agriculture was a big leap in technological advancement which made available low-cost sensors and electronic hardware programming platforms accessible to the common man. It is a common thing for a farmer in a remote rural area to control the electric pump installed in a distant field using GSM based automation technology by his basic cell phone. The revolution in smart phone technology and its proliferation in Indian villages with the Digital India initiative of the Government of India have made the rural farmer technology aware. With the current advent of the Internet of things (IoT), the extension of Internet connectivity into physical devices and everyday objects, industries developing sensor technologies for measurement, storage, retrieval and communicating to other devices are mushrooming which will make more accurate sensors at very affordable costs. Such soil moisture content sensors could be used with open source electronic platforms like Arduino or Raspberry pi etc. with relays to actuate the solenoid valves supplying water for irrigation.

The development of an automated pulse irrigation system through moisture sensors and Arduino, its evaluation and comparison with continuous drip irrigation system with respect to the wetted bulb below the emitter was the main aim for the present research work. The system is designed to automatically control the irrigation water application based on the matric potential established in the crop root zone and for irrigating it with different pulses of ON/OFF cycles.

The properties of the soil in the experimental field were determined. The texture of the soil was determined using sieve analysis and hydrometer analysis. The specific gravity of the soil was determined using the pycnometer method. The in-situ voids ratio and the dry density of the soil were obtained using the core cutter method. The void ratio was calculated based on these soil properties. The plastic limit and liquid limit of the soil were determined using the standard method. The saturated hydraulic conductivity of the soil was determined using the constant head permeability meter. The soil water characteristics curve (SWCC) was obtained using the pressure plate apparatus for the desorption process and the open capillary tube method for the sorption process. The soil water characteristics curve (SWCC) was developed using the observed data of the soil moisture at various soil suction values during desorption and sorption processes. The hysteresis effect of soil moisture characteristic was assessed. The saturation, field capacity, permanent wilting point and residual soil moisture contents were determined using the developed soil moisture characteristics curve. The soil properties were used to estimate the parameters of the various SWCC models.

The observed data on soil water retention characteristics during desorption and sorption processes were used to fit the various SWCC models namely van Genuchten (1980), Gardner (1958), Fredlund and Xing (1994) (1) and Fredlund and Xing (1994) (2). The fitted models were used to estimate the soil moisture characteristics curve and it was compared with the observed curve. The best fit model was judged based on the performance indices namely Nash-Sutcliffe model efficiency (NSE) and goodness of fit/coefficient of determination (R^2).

The sensor based automated pulse drip irrigation system was developed using the various components like three low cost Soil Moisture Sensors, Arduino UNO, Breadboard with required Jumper Wires, three Relays with Electrical interface, three Solenoid Valves, LCD I2C (2×16) Display, Batteries and a Real Time Clock. The sensors were first calibrated against observed gravimetric moisture content values and then validated with known moisture content values. After the calibration and validation, the sensor was connected with Arduino controller and relays to control the solenoid valves. The Arduino program coding in its language was developed for the displaying, sensing of the soil moisture status using calibrated sensors, and for actuating the solenoid valves through relays. The pulse cycles with time parameters of cycles for the drippers of various discharge rates needed for pulse irrigation was also included in the Arduino programming code. The code can be easily modified to input the various parameters as per the requirement during the different growth stages of various crops.

The wetting front advance was observed at various times under continuous drip irrigation and under pulse drip irrigation for the 2 lph, 4 lph and 8 lph drip emitters. The radial and vertical distribution of wetted bulbs were measured at various times after the commencement of the irrigation application. The wetting front movements and moisture contents were measured at 1 hour, 2 hours and 3 hours since the commencement of irrigation for the 2 lph, 4 lph and 8 lph online drippers under continuous drip irrigation and under pulse drip irrigation. The pulse cycles adopted were 20 minutes ON time followed by 20 minutes OFF time for 2 lph drippers, 10 minutes ON time followed by 30 minutes rest for 4 lph drippers, and 5 minutes ON time followed by 35 minutes rest for 8 lph drippers. Three cycles of pulses were applied. Drippers with different discharge rates of 2, 4 and 8 lph applied equal volumes of water after the end of each pulsed cycles. The moisture contents at different parts of the wetted bulb was measured. The soil aeration was determined using the data of soil moisture contents in the wetted soil bulb as well as the saturation and residual moisture contents. The evaluations were made based on comparison of wetted soil bulb size, soil moisture distribution and soil aeration distribution observed under the pulse and continuous drip irrigation applications for various time periods, pulse cycles, dripper discharge rates and volume of water applied.

The following conclusions could be made after churning thoroughly through the outcomes of the present research work:

1. The textural class of the soil in the experimental field is sandy loam having proportions of clay, silt and sand particles as 7.32 %, 36.59 % and 56.10 % respectively.
2. The volumetric soil moisture contents at saturation, field capacity, permanent wilting point and the residual moisture content were 43.5%, 25.88%, 12.05% and 8.1% respectively.
3. The void ratio of the soil is found to be 0.77 and the saturation hydraulic conductivity of the soil is 0.2808 m/day.
4. The soil moisture retention characteristics of the sorption and desorption phases indicated a hysteresis of approximately two log cycles.
5. Among the four models, the van Genuchten models given below, were found to fit the observed data the best, with Nash-Sutcliffe model efficiencies of 98.75% (R^2=0.986) for the desorption phase and 92.26% (R^2=0.946) for the sorption phase respectively of the soil moisture characteristics curve.

$$\theta = 0.08167 + \frac{0.3533}{\left[1+\left(\frac{\Psi}{2.5591}\right)^{1.3096}\right]^{0.2364}} \quad \text{for Desorption phase}$$

$$\theta = 0.08057 + \frac{0.3500}{\left[1+\left(\frac{\Psi}{0.1685}\right)^{1.4380}\right]^{0.3046}} \quad \text{for Sorption phase}$$

Where, θ_r, θ_s and θ are the residual moisture content, saturated soil moisture content and moisture content (cc/cc) at any suction pressure Ψ (kPa).

6. The lowest coefficient of manufacturing variation was observed as 0.99 % for the 2 lph rated drippers followed by 1.23 % and 2.48 % respectively for the 4 and 8 lph rated drippers and all were falling under the "excellent class" category.

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7. The highest horizontal spread and vertical depth of the wetted soil bulb was observed under the 8 lph dripper followed by the 4 lph and 2 lph drippers at all the different time periods since the commencement of continuous irrigation.

8. The horizontal spread of the wetted bulb on the ground surface was found to be 14.9 cm, 21.3 cm and 28.1 cm respectively after 1 h, 2 h and 3 h of continuous irrigation for the 2 lph dripper, while the corresponding vertical depth of the wetted bulb below the dripper was 19.4 cm, 26.3 cm and 31.4 cm respectively.

9. The wetted soil bulb below the 4 lph dripper had horizontal spreading of 25.8 cm, 37.0 cm and 48.4 cm respectively on the ground surface and vertical depths of 21.7 cm, 29.9 cm and 36 cm respectively below the dripper after 1 h, 2 h and 3 h periods of continuous irrigation.

10. Wetted soil bulb having horizontal spreading on the ground surface of 41.6 cm, 55.2 cm and 72.9 cm and vertical spreading of 24.3 cm, 33.8 cm and 41.1 cm below the 8 lph dripper was observed after 1 h, 2 h and 3 h of continuous irrigation respectively.

11. When the redistributions of the soil water in 24 hours after termination of the 3 h continuous irrigation were examined, the elongations of the horizontal extents of the wetted bulb under 2 lph, 4 lph and 8 lph drippers were 4.74 %, 3.69 % and 3.43 % and the elongations of the vertical extents were 7.38 %, 7.79 % and 8.51 % respectively.

12. The moisture content values in the wetted soil bulb were higher and the soil aeration values were lower under the higher discharge rate drippers, compared to that of the lower discharge rate drippers. The values of soil aeration was found to be better during pulse irrigation, compared to that of continuous drip irrigation.

13. The horizontal spreading of the wetted bulb on the ground surface was found to be 12.4 cm, 19.8 cm and 25.8 cm, while the vertical depth below the dripper was 12.0 cm, 16.4 cm and 19.8 cm respectively after 1st, 2nd and 3rd cycles of

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pulsed drip irrigation (20 minutes ON followed by 20 minutes OFF) application for the 2 lph dripper.

14. The 4 lph pulse drip irrigation could wet the soil bulb with horizontal spreading of 13.0 cm, 20.6 cm and 26.8 cm on the ground surface and vertical depth of 9.6 cm, 13.5 cm and 16.5 cm below the dripper respectively after 1st, 2nd and 3rd cycles (10 minutes ON followed by 30 minutes OFF).
15. Wetted soil bulbs having horizontal spreading of 15.2 cm, 23.4 cm and 33.2 cm on the ground surface and vertical depth of 7.5 cm, 10.7 cm and 13.3 cm below the 8 lph dripper were respectively obtained after 1st, 2nd and 3rd cycles (5 minutes ON followed by 35 minutes OFF) of pulse drip irrigation.
16. The radial spreading of the wetted bulb was found higher under continuous irrigation application as compared to that of pulse irrigation for the same volume and dripper discharge rate.
17. The vertical depth of the wetted bulb was found higher under the pulse irrigation as compared to that of the continuous irrigation application for the same volume and dripper discharge rate.
18. The radial spreading was higher for higher discharge rate drippers, compared to that of the lower discharge rate ones at any given time at which the same volume of water was applied by the drippers of different discharge rates under the pulse drip irrigation.
19. The vertical depth of wetted bulb was found to be lower for the higher discharge rate drippers compared to that of the lower discharge rate ones at any given time at which the same volume of water was applied by the drippers of different discharge rates in the case of pulse drip irrigation.
20. The developed automated pulse drip irrigation system is found to be effective in scheduling the irrigation based on the soil moisture status, improving the soil aeration status and reduces the deep percolation losses.

CHAPTER VI

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APPENDIX I

BASIC SOIL PROPERTIES DETERMINATION

Table 1 Bulk Density and Dry Density

Depth	Wt. wet soil (g)	Wt. of dry soil (g)	Wt. of core cutter (g)	Radius of core cutter (cm)	Length of core cutter (cm)	Moisture Content (%)	Bulk Density (g/cc)	Volume (cc)	Dry Density (g/cc)
10 cm	2130.8	2052.4	945.8	5	10	7.08	1.20	785	1.41
20 cm	2109.4	2018.6	923.8	5	10	8.29	1.51	785	1.40
30 cm	2181.2	2082.6	982	5	10	8.96	1.53	785	1.40
40 cm	1414.2	1356.8	823.4	3.5	10	10.76	1.54	384.65	1.38
50 cm	1224.4	1183.8	855.2	2.75	10	12.36	1.55	237.46	1.38
–	–	–	–	–	–	**Average**	1.53	–	1.39

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Table 2 Liquid Limit and Plastic Limit

Liquid Limit				
Wt. of container	Wt. of container + Soil	Wt. of container + Dry Soil	Moisture Content	No. of Blows
gm	gm	gm	(%)	
8.8	30.8	25.2	34.15	18
8.0	28.8	23.8	31.64	26
–	–	–	31.96	25

Plastic Limit			
Wt. of container	Wt. of container + Soil	Wt. of container + Dry Soil	Moisture Content
gm	gm	gm	(%)
14.8	32.6	29.0	25.35
14.0	29.8	26.6	25.39
13.8	34.0	30.0	24.69
Average			25.15

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APPENDIX II

COEFFICIENT OF MANUFACTURING VARIATION

Table 3 Observations for estimating the coefficient of manufacturing variations

Dripper No.	2 lph		4 lph		8 lph	
	Volume of water (cc) collected in 15 minutes	Discharge (lph)	Volume of water (cc) collected in 15 minutes	Discharge (lph)	Volume of water (cc) collected in 15 minutes	Discharge (lph)
1	495	1.980	990	3.960	1915	7.660
2	496	1.984	1012	4.048	1914	7.656
3	495	1.980	990	3.960	1956	7.824
4	499	1.996	1011	4.044	2023	8.092
5	504	2.016	1014	4.056	2047	8.188
6	506	2.024	985	3.940	2009	8.036
7	502	2.008	992	3.968	2010	8.040
8	497	1.988	1016	4.064	2028	8.112
9	498	1.992	1009	4.036	2038	8.152
10	489	1.956	1014	4.056	2024	8.096

Max Discharge	–	2.024	–	4.064	–	8.188
Min Discharge	–	1.956	–	3.940	–	7.656
Average	–	1.995	–	4.013	–	7.985
SD for Sample	–	0.0198169	–	0.0494251	–	0.1984401
SD for Population	–	0.0188	–	0.0468888	–	0.1882569
CVm (%)	–	0.9931945	–	1.2315643	–	2.4849747

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APPENDIX III

WETTING FRONT MOVEMENT UNDER CONTINUOUS DRIP IRRIGATION

Table 4 Wetting front movement under 2-lph continuous drip irrigation

10 min		20 min		30 min		60 min		120 min		180 min	
x	y	x	y	x	y	x	y	x	y	x	y
4.10	0	5.95	0	9.15	0	14.85	0	21.25	0	28.05	0
4	3.5	5.4	5.1	8	6.5	12	8	18	7.5	22	14.3
3	5.5	4	7.7	6	9.2	8	13.2	14	13.6	16	20.8
2	6.8	2	10	4	11.23	4	16.3	10	18.2	9	25.3
0	8.81	0	11.96	0	14.19	0	19.39	0	26.30	0	31.44

Table 5 Wetting front movement under 4-lph continuous drip irrigation

10 min		20 min		30 min		60 min		120 min		180 min	
x	y	x	y	x	y	x	y	x	y	x	y
6.22	0	10.36	0	15.93	0	25.86	0	37.00	0	48.84	0
6	3.5	8	6.9	13	7.9	20	9.8	31	8.9	35	15.6
4	7	6	9.6	10	11.3	15	15.3	20	19.2	24	23.6
2	8.8	4	11.4	7	13.2	10	17.8	13	23.2	15	28.6
0	9.52	0	13.09	0	15.78	0	21.70	0	29.85	0	35.97

Table 6 Wetting front movement under 8-lph continuous drip irrigation

10 min		20 min		30 min		60 min		120 min		180 min	
x	y	x	y	x	y	x	y	x	y	x	y
12.42	0	20.69	0	31.81	0	41.57	0	55.23	0	72.90	0
10	5.7	16	7.3	24	9.9	35	9.8	43	15.5	59	20.3
7	7.9	11	10.3	18	13.6	21	18.9	29	24.2	39	30.6
5	8.8	8	11.6	12	15.2	14	21.5	19	28.7	26	35.7
0	10.27	0	14.32	0	17.40	0	24.27	0	33.84	0	41.12

Table 7 Size of wetted bulb for continuous irrigation system

Time (min)	Horizontal wetted diameter (cm)			Vertical wetted depth (cm)			
	2 LPH	4 LPH	8 LPH	Time (min)	2 LPH	4 LPH	8 LPH
0	0.00	0.00	0.00	0	0.00	0.00	0.00
10	8.20	12.44	24.83	10	8.81	9.52	10.27
20	11.90	20.72	41.37	20	11.96	13.09	14.32
30	18.30	31.86	63.63	30	14.29	15.78	17.40
60	29.70	51.71	83.14	60	19.39	21.70	24.27
120	42.50	74.00	110.46	120	26.30	29.85	33.84
180	56.10	97.68	145.81	180	31.44	35.97	41.12

APPENDIX IV

WETTING FRONT MOVEMENT UNDER PULSE DRIP IRRIGATION

Table 8 Wetting front movement under 2-lph pulsed drip irrigation

After 1 Pulse Cycle		After 2 Pulse Cycle		After 3 Pulse Cycle	
x	y	x	y	x	y
6.2	0.0	9.9	0.0	12.9	0.0
5.0	4.9	8.0	7.3	10.0	8.6
3.0	8.5	6.0	10.9	6.0	14.4
2.0	9.9	4.0	13.3	2.0	18.3
0.0	12.0	0.0	16.4	0.0	19.8

Table 9 Wetting front movement under 4-lph pulsed drip irrigation

After 1 Pulse Cycle		After 2 Pulse Cycle		After 3 Pulse Cycle	
x	y	x	y	x	y
6.5	0.0	10.3	0.0	13.4	0.0
5.0	5.3	9.0	4.7	10.0	8.2
3.0	7.8	7.0	8.1	6.0	13.2
2.0	8.5	5.0	10.5	4.0	14.5
0.0	9.6	0.0	13.5	0.0	16.5

Table 10 Wetting front movement under 8-lph pulsed drip irrigation

After 1 Pulse Cycle		After 2 Pulse Cycle		After 3 Pulse Cycle	
x	y	x	y	x	y
7.6	0.0	11.7	0.0	16.6	0.0
6.0	3.6	9.0	5.8	14.0	6.1
4.0	5.8	7.0	8.2	8.0	10.2
2.0	7.1	5.0	9.3	5.0	11.5
0.0	7.5	0.0	10.7	0.0	13.3

Table 11 Size of wetted bulb for pulsed irrigation system

Horizontal wetted diameter (cm)				Vertical wetted depth (cm)			
Time (min)	2 LPH	4 LPH	8 LPH	Time (min)	2 LPH	4 LPH	8 LPH
0	0.0	0.0	0.0	0	0.0	0.0	0.0
After 1 Pulse Cycle	12.4	12.9	15.2	After 1 Pulse Cycle	12.0	9.6	7.5
After 2 Pulse Cycle	19.7	20.5	23.5	After 2 Pulse Cycle	16.4	13.5	10.7
After 3 Pulse Cycle	25.8	26.9	33.2	After 3 Pulse Cycle	19.8	16.5	13.3

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APPENDIX V

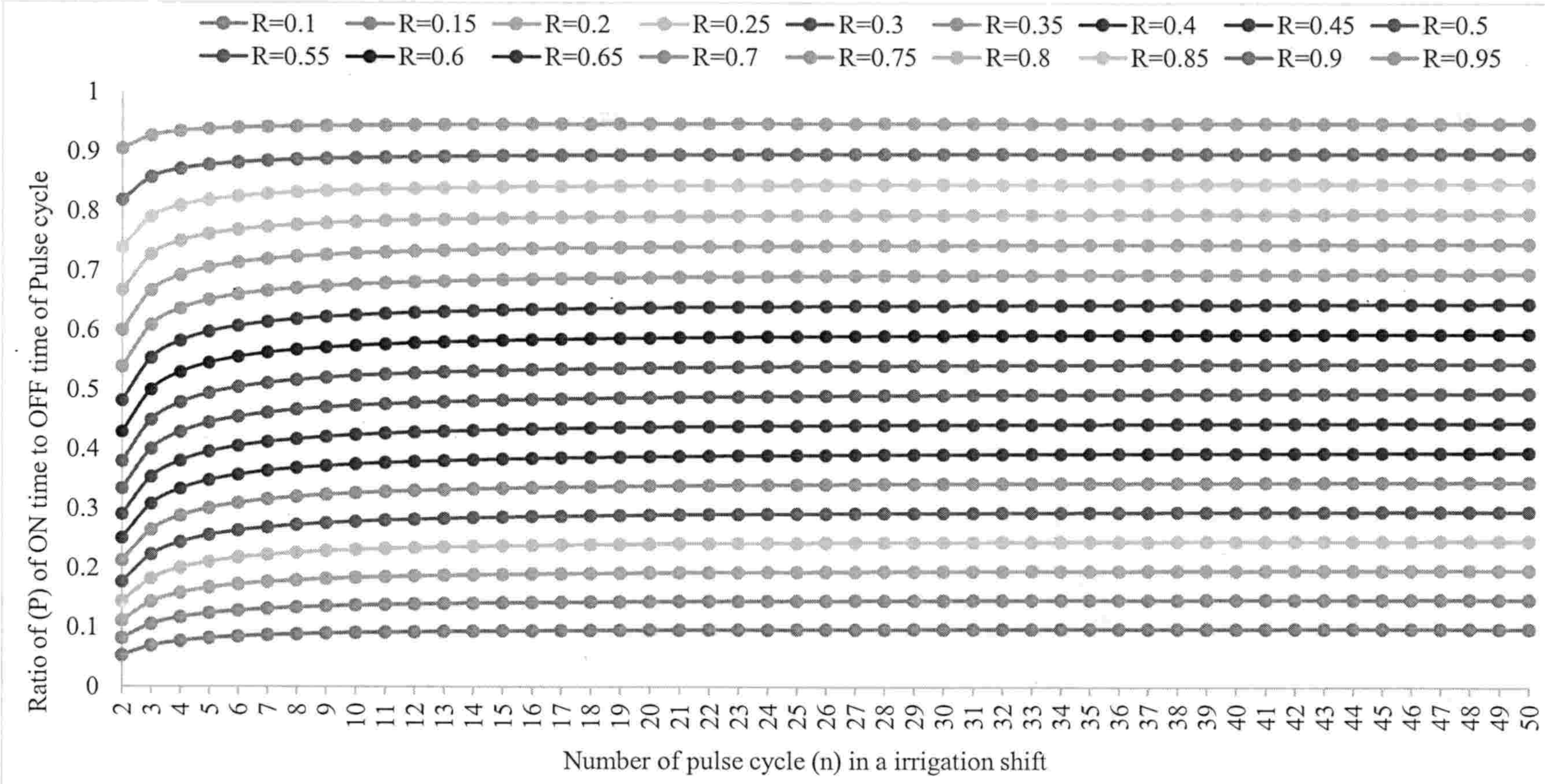

Fig. 1 Relationships between Ratio of (P) of ON time to OFF time of Pulse cycle and number of pulse cycle (n) in an irrigation shift for the different R (Ratio of actual to average irrigation rate)

APPENDIX VI

CALIBRATION OF SOIL MOISTURE SENSORS

Table 12 Calibration of Sensor 1

Known Moisture Content (% w/w db)	Reading in Sensor	Effective Degree of Saturation (%)	Measured Moisture (%)				Average	Moisture Content (v/v)
			W1	W2	W3	Moisture Content (% w/w db)		
10	522	15 %	15.2	29.8	27.6	17.74	17.02	0.2466
			14.0	35.4	32.4	16.30		0.2266
20	400	45 %	15.6	48.2	41.0	28.35	29.17	0.3940
			14.0	37.4	32.0	30.00		0.4170
30	321	87 %	14.2	66.0	52.6	34.89	35.16	0.4850
			7.4	46.4	36.2	35.42		0.4922
40	257	95 %	14.8	59.0	46.0	41.66	41.47	0.5791
			19.6	55.2	44.8	41.26		0.5736
60	240	97 %	14.2	48.2	37.8	44.06	43.12	0.6125
			8.00	31.6	24.6	42.16		0.5861

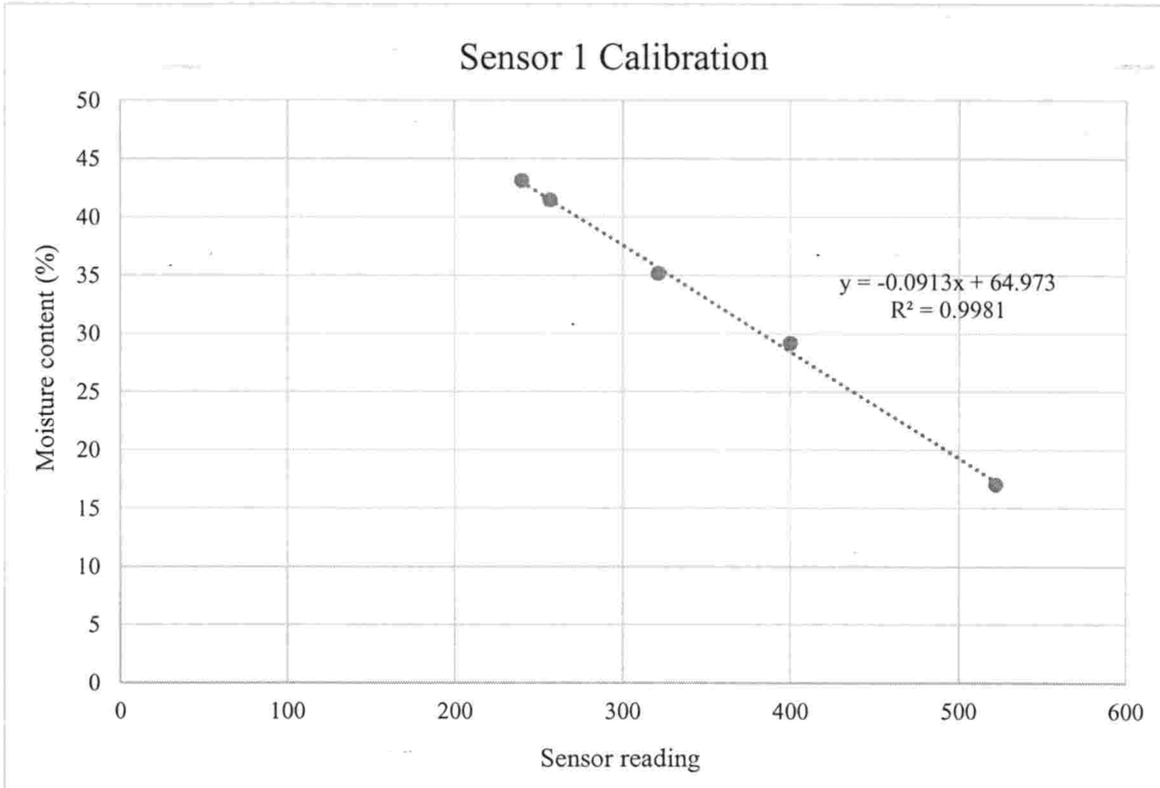

Figure 2 Calibration equation for Sensor 1

Table 13 Calibration of Sensor 2

Known Moisture Content (% w/w db)	Reading in Sensor	Effective Degree of Saturation (%)	Measured Moisture (%)				Average	Moisture Content (v/v)
			W1	W2	W3	Moisture Content (% w/w db)		
10	525	16 %	15.2	31.7	29.2	17.86	16.68	0.1786
			14.0	30.4	28.2	15.49		0.1549
20	392	46 %	15.6	37.1	32.2	29.52	29.09	0.2952
			14.0	32.4	28.3	28.67		0.2867
30	330	86 %	14.2	54.0	43.6	35.37	36.16	0.3537
			7.4	50.4	38.8	36.94		0.3694
40	270	92 %	14.8	42.0	33.8	43.16	42.91	0.4316
			19.6	50.7	41.4	42.66		0.4266
60	230	95 %	14.2	43.5	33.8	49.49	51.12	0.4949
			8.0	35.8	26.2	52.75		0.5275

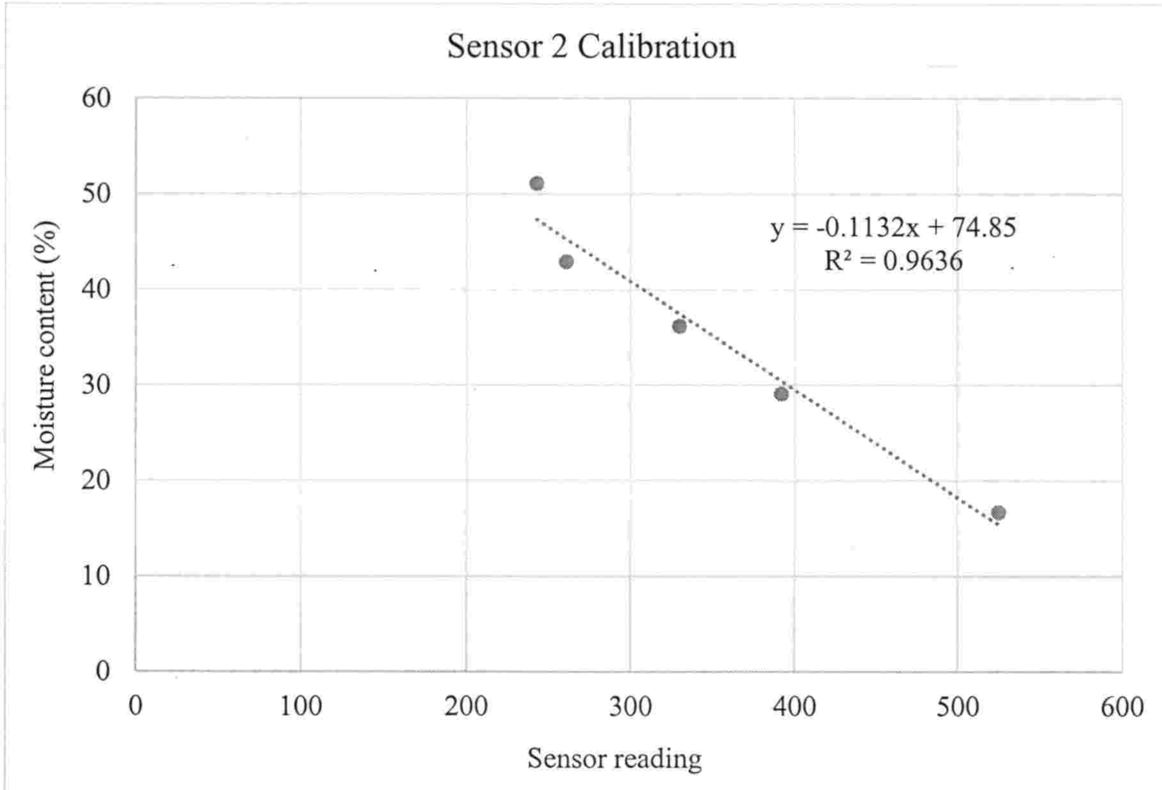

Figure 3 Calibration equation for Sensor 2

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Table 14 Calibration of Sensor 3

Known Moisture Content (% w/w db)	Reading in Sensor	Effective Degree of Saturation (%)	Measured Moisture (%)				Average	Moisture Content (v/v)
			W1	W2	W3	Moisture Content (% w/w db)		
10	520	15 %	15.2	30.8	28.6	16.42	17.66	0.2282
			14.0	33.5	30.4	18.90		0.2627
20	405	45 %	15.6	43.7	37.2	30.09	29.83	0.4182
			14.0	38.1	32.6	29.57		0.4110
30	320	88 %	14.2	57.8	46.8	34.37	34.75	0.5755
			7.4	54.6	45.5	35.13		0.5743
40	261	96 %	14.8	68.5	52.6	41.40	41.36	0.4778
			19.6	48.1	36.2	41.32		0.4883
60	243	97 %	14.2	45.4	35.8	44.44	45.23	0.6177
			8.0	33.7	25.6	46.02		0.6397

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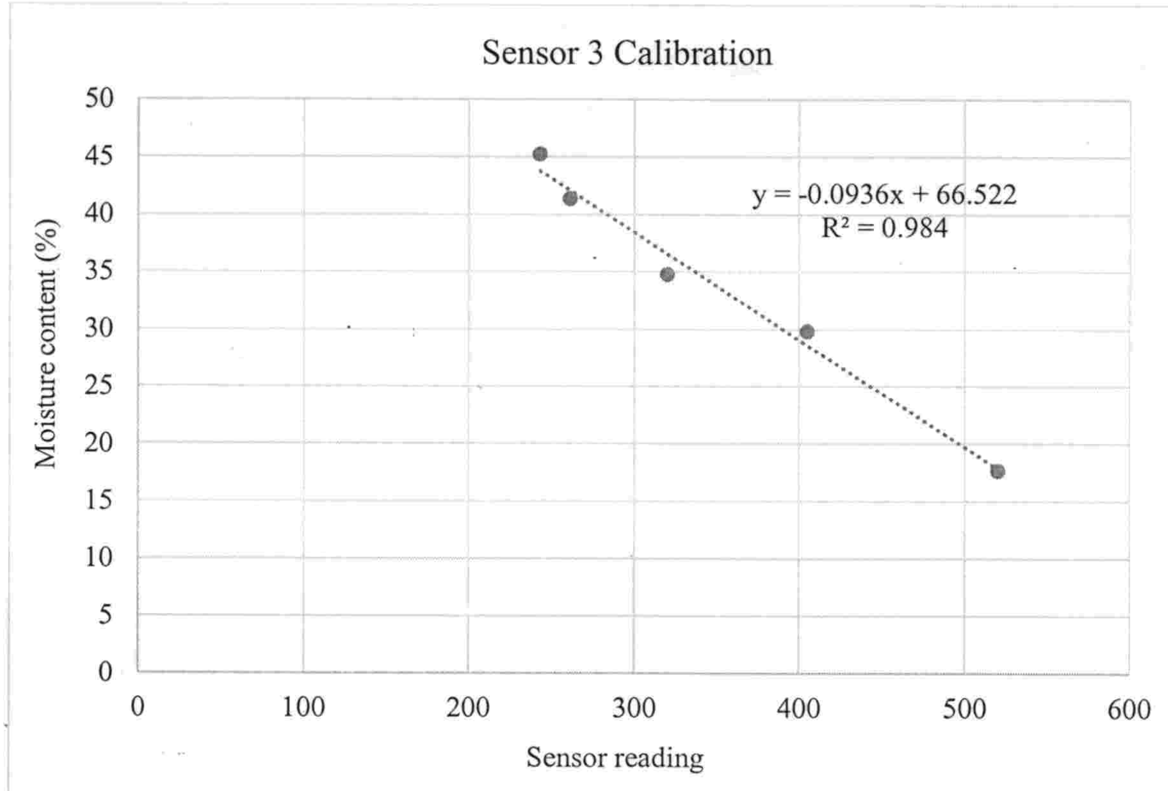

Figure 4 Calibration equation for Sensor 3

APPENDIX VII

PROGRAMMING CODE FOR AUTOMATED PULSE DRIP IRRIGATION SYSTEM

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
const int sensor_pin1 = A1;
const int sensor_pin2 = A2;
const int sensor_pin3 = A3;
long tme1=1200000;
long tme2=600000;
long tme3=1800000;
long tme4=300000;
long tme5=2100000;
int mst=A0;
int relay1=7;
int relay2=8;
int relay3=9;

LiquidCrystal_I2C lcd(0x3F,16,2); // set the LCD address to 0x27 for 16 chars
and 2-line display

void setup () {
 lcd.init();                                          // initialize the lcd
 lcd.backlight();
 pinMode(relay1, OUTPUT);
 pinMode(relay2, OUTPUT);
 pinMode(relay3, OUTPUT);
 }
```

```
void loop () {              // when characters arrive over the serial port...
lcd.clear();
lcd.setCursor(1,0);
float moisture_percentage1;
int sensor_analog1;
sensor_analog1 = analogRead(sensor_pin1);
moisture_percentage1 = ((-0.0913*sensor_analog1) + 64.973);
        if(moisture_percentage1<=13.59535383) {
digitalWrite(relay1, LOW); delay(tme1);
digitalWrite(relay1, HIGH); delay(tme1); }
sensor_analog1 = analogRead(sensor_pin1);
moisture_percentage1 = ((-0.0913*sensor_analog1) + 64.973);
        if(moisture_percentage1<=18.55353087) {
digitalWrite(relay1, LOW); delay(tme1);
digitalWrite(relay1, HIGH); delay(tme1); }
sensor_analog1 = analogRead(sensor_pin1);
moisture_percentage1 = ((-0.0913*sensor_analog1) + 64.973);
        if(moisture_percentage1<=18.55353087) {
digitalWrite(relay1, LOW); delay(tme1);
digitalWrite(relay1, HIGH); delay(tme1);
}
 else if(moisture_percentage1>=18.55353087) {
digitalWrite(relay1, HIGH);
}



lcd.clear();
```

```
lcd.setCursor(1,0);
float moisture_percentage2;
int sensor_analog2;
sensor_analog2 = analogRead(sensor_pin2);
moisture_percentage2 = ((-0.1132*sensor_analog2) + 74.85);
        if(moisture_percentage2<=13.59535383) {
digitalWrite(relay2, LOW); delay(tme2);
digitalWrite(relay2, HIGH); delay(tme3); }
sensor_analog2 = analogRead(sensor_pin2);
moisture_percentage2 = ((-0.1132*sensor_analog2) + 74.85);
        if(moisture_percentage2<=18.55353087) {
digitalWrite(relay2, LOW); delay(tme2);
digitalWrite(relay2, HIGH); delay(tme3); }
sensor_analog2 = analogRead(sensor_pin2);
moisture_percentage2 = ((-0.1132*sensor_analog2) + 74.85);
        if(moisture_percentage2<=18.55353087) {
digitalWrite(relay2, LOW); delay(tme2);
digitalWrite(relay2, HIGH); delay(tme3);
 }
 else if(moisture_percentage2>=18.55353087) {
digitalWrite(relay2, HIGH);
}



lcd.clear();
```


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```
lcd.setCursor(1,0);
float moisture_percentage3;
int sensor_analog3;
sensor_analog3 = analogRead(sensor_pin3);
moisture_percentage3 = ((-0.0936*sensor_analog3) + 66.522);
        if(moisture_percentage3<=13.59535383) {
digitalWrite(relay3, LOW); delay(tme4);
digitalWrite(relay3, HIGH); delay(tme5); }
sensor_analog3 = analogRead(sensor_pin3);
moisture_percentage3 = ((-0.0936*sensor_analog3) + 66.522);
        if(moisture_percentage3<=18.55353087) {
digitalWrite(relay3, LOW); delay(tme4);
digitalWrite(relay3, HIGH); delay(tme5); }
sensor_analog3 = analogRead(sensor_pin3);
moisture_percentage3 = ((-0.0936*sensor_analog3) + 66.522);
        if(moisture_percentage3<=18.55353087) {
  digitalWrite(relay3, LOW); delay(tme4);
  digitalWrite(relay3, HIGH); delay(tme5);
 }
 else if(moisture_percentage3>=18.55353087) {
  digitalWrite(relay3, HIGH);
}
}
```


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DEVELOPMENT AND EVALUATION OF AN AUTOMATED PULSE IRRIGATION SYSTEM

By

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ABSTRACT OF THE THESIS

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DEPARTMENT OF IRRIGATION AND DRAINAGE ENGINEERING

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ABSTRACT

Irrigation sector consumes more than 80% of the fresh water resources in India. The irrigation efficiencies of the major irrigation systems in India are around 40%, increasing of which could save large amounts of water. The irrigation efficiencies could be increased through the adoption of cost-effective and efficient irrigation technologies, which will reduce water demands, increase agricultural production, minimize soil and water pollution and reduce the cost of agricultural production. Drip/Trickle irrigation is a highly efficient irrigation method which could save tremendous amounts of water when adopted in the place of the wild flooding irrigation. Pulse drip irrigation technology enables lower application rates - that will permit sufficient aeration in the root zone and alleviate plant stress due to inadequate root respiration– from an emitter with a higher application rate by intermittent water applications. This study attempted to develop and evaluate a sensor based automated pulse drip irrigation system which is affordable to the low-income farmers of the nation. The soil properties of the experimental field were used to estimate the parameters of several soil water characteristics curve (SWCC) models. Among the models; van Genuchten (1980) model of SWCC, was found to be the best in representing the soil moisture retention characteristics of the soil used in the study. An open-source electronics platform, the Arduino was used for the development of the automation system using moisture content sensors and solenoid irrigation valves controlled through relays, by writing program coding in the Arduino programming language. The sensors were calibrated to read the moisture content, which was compared to the management allowed deficit (MAD) and field capacity (FC) soil moisture content values to control the start and stop of irrigation water application. Pulse irrigation design methodology was used to derive the ON and OFF time periods for the pulse cycle. The system was programmed to start the water application as per the designed pulse cycle at a moisture content defined by the MAD moisture content and to stop the water application at the field capacity (FC) moisture content sensed by the moisture sensor. The wetting front movements and the soil moisture contents in the root zone were measured at different time

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intervals of 1 hour, 2 hours and 3 hours after the start of water application using both continuous irrigation and pulse drip irrigation under 2 LPH, 4 LPH and 8 LPH online drip emitters. The soil aeration was also determined for these treatments and was found to be better during the pulse irrigation as compared to the continuous drip irrigation. The pulse irrigation application was also found to be decreasing the deep percolation loss of water. The developed automated pulse drip irrigation system is found to provide the required aeration in the root zone with reduction in deep percolation loss of water.