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IRRIGATION EFFICIENCY IMPROVEMENT THROUGH ON-FARM WATER MANAGEMENT

Sponsored by

National Water Mission (NWM), Department of Water Resources (DoWR),
River Development and Ganga Rejuvenation (RD&GR), Ministry of Jal Shakti,
Government of India



Submitted by

Prof. Ashish Pandey, Principal Investigator
Prof. S.K. Mishra, Investigator, Prof. R.D. Singh, Investigator
Mr. Sandeep Kumar Chourasia, Research Scholar and SRF



DEPARTMENT OF WATER RESOURCES DEVELOPMENT AND MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE, UTTARAKHAND- 247 667

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Email: ashish.pandey@wr.iitr.ac.in



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RESEARCH TEAM

The following Ph.D. and M.Tech scholars of the Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, contributed to the project:

- (1) Sandeep Kumar Chourasia (SRF-Project)
- (2) Yogesh Kumar Kushwaha (SRF-MHRD)
- (3) Dhananjai Paswan Das (SRF-MHRD)
- (4) Abhishek Semwal (M.Tech, 2020-2022)
- (5) Suzan Karkee Chhetri (M.Tech, 2022-2024)

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Finally, for the successful completion of the project, the wholehearted support given and dedicated efforts made by the project staff and other research scholars/M. Tech students of WRDM, IIT Roorkee are well appreciated.

Prof. Ashish Pandey, Principal Investigator
Prof. S.K. Mishra, Investigator
Prof. R.D. Singh, Investigator

EXECUTIVE SUMMARY

The research project entitled “**Irrigation Efficiency Improvement Through On-Farm Water Management**” was sanctioned to the Department of Water Resources Development and Management, Indian Institute of Technology (IIT) Roorkee by National Water Mission (NWM), Department of Water Resources (DoWR), River Development and Ganga Rejuvenation (RD&GR), Ministry of Jal Shakti, Government of India, vide letter F.No.M-6101 3/1/201 8 (NWM), Dated 02/09/2019. The objectives of this research project are as follows: (1) To enhance water use efficiency at the farm level through various measures to minimize water losses in the watercourses and in the irrigated field. (2) To study the efficacy of various micro-irrigation methods such as sprinkler and drip and evaluate the water savings as well as enhanced water use efficiency at the farm level due to the adoption of these methods over the prevailing method of flood irrigation. (3) To evolve irrigation scheduling considering the crops, soil moisture, and prevailing climatic conditions using the Internet of Things (IoT). (4) To identify various factors that would help promote the adoption of the farmers' improved on-farm water management (OFWM) practices and various constraints that discourage the farmers from adopting those practices. (5) To review the role of existing Water Use Associations (WUA), suggest suitable modifications for encouraging better OFWM practices and equitable water distribution among the farmers, and conduct online demonstrations and workshops on OFWM practices.

The project report is organized into ten chapters, as follows.

Chapter 1: This chapter briefly describes the general subject background, irrigation efficiency status, the importance of irrigation efficiency improvement, and the need for this study. This background serves to motivate the study and support the attainment of its specific research objectives.

Chapter 2: This chapter deals with the study area of the project. It outlines the location of the study area and details of the farmer's field where the experiments were conducted. The description includes topography, which analyzes the patterns of land use and land cover. The chapter describes the cropping patterns and the climatic conditions of the region. This comprehensive description of the study area was useful for subsequent investigations and interventions of the project.

Chapter 3: This chapter provides a detailed analysis of the Gadarjudda Minor canal, covering its condition, soil, and water quality, and the performance evolution of the canal using performance indicators. It includes surveys of the canal's longitudinal and cross-sectional profiles, seepage analysis, and observations of unlined sections that lead to seepage and unauthorized alterations affecting water distribution. Major challenges identified include siltation and pollution from adjacent residential areas. Efforts to mitigate these problems include cleaning operations to enhance canal functionality.

Chapter 4: This chapter provides the monitoring and analysis of conventional agricultural and irrigation practices for wheat and sugarcane crops, detailing the entire process from field preparation to harvesting. It emphasizes irrigation efficiency, discussing water application timing, frequency, and volume. The evaluation of flood irrigation efficiency has been carried out for sugarcane and wheat crops.

Chapter 5: This chapter describes developing an IoT-based smart irrigation system that enables real-time data collection and transmission to cloud storage and an Android app. This system provides

farmers remote access to monitor soil conditions such as moisture, temperature, and humidity and control irrigation with alerts based on soil moisture thresholds, enhancing responsiveness and timely intervention.

Chapter 6: This chapter comprehensively analyzes micro and conventional irrigation systems applied to wheat and sugarcane crops in the farmer's field. To assess the effectiveness of micro-irrigation methods, the farmers' field was divided into two sections: one managed by a research team and the other by the farmers themselves. The study found that precise scheduling and soil moisture monitoring using micro-sprinkler systems increase water saving.

Chapter 7: This chapter deals with soil moisture estimation using remote sensing indices. In-situ soil moisture observations have been carried out, and with the use of the SAR (Sentinel-1) and Optical (Sentinel-2) data, soil moisture can be estimated using the Modified Water Cloud Model (MWCM) model over the wheat plot. Based on localized results, it can be illustrated that the NDMI outperformed the other vegetation descriptors. The chapter concluded that the MWCM model results with NDMI as vegetative descriptors showed an acceptable performance.

Chapter 8: This chapter explores factors that promote or hinder the adoption of improved irrigation practices among farmers, alongside the role of Water Use Associations (WUAs). A farmer questionnaire survey revealed that despite a good education level among farmers, which aids in skill development, several challenges persist. These include the absence of a registered WUA in the Gadarjudda minor canal area to support farmers, limited awareness of government schemes, maintenance issues with irrigation systems, inadequate water flow in canals, and the dispersal of farmers' lands across various locations, etc.

Chapter 9: This chapter describes various awareness activities organized in this project. Farmers receive practical demonstrations and educational resources through these initiatives, empowering them to make informed decisions about their irrigation practices.

Chapter 10: This chapter provides the conclusions and recommendations of the study. Major conclusions, recommendations, limitations & future research scope of the study are briefly discussed.

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ABBREVIATIONS

ACC	: Active Canal Capacity
ADC	: Analog-to-Digital Converter
ADCP	: Acoustic Doppler Current Profiler
AMFU	: Agro-Meteorological Field Unit
BWUE	: Bureau of Water Use Efficiency
CADWM	: Command Area Development and Water Management
CCA	: Culturable Command Area
CRI	: Crown Root Initiation
DAP	: Diammonium Phosphate
EC	: Electrical Conductivity
E_c	: Conveyance Efficiency
ET_c	: Evapotranspiration
ET_o	: Evapotranspiration
EVI	: Enhanced Vegetation Index
EW	: Extra-Wide Swath
FAO	: Food and Agriculture Organization
FC	: Field Capacity
FDR	: Frequency Domain Reflectometry
GM	: Gravimetric Method
GRD	: Ground Range Detection
GUI	: Graphical User Interface
IEM	: Integral Equation Model
IoT	: Internet of Things
LAI	: Leaf Area Index
LULC	: Land Use Land Cover
MWCM	: Modified Water Cloud Model
NDMI	: Normalized Difference Water Index
NDVI	: Normalized Difference Vegetation Index
NSE	: Nash Sutcliffe Efficiency
NWZ	: North-West Zone
OFWM	: On Farm Water Management
PIM	: Participatory Irrigation Management

PMKSY	: Pradhan Mantri Krishi Sinchayee Yojana
PWM	: Pulse-Width Modulation
PWP	: Permanent Wilting Point
RMSE	: Root Mean Square Error
RRMSE	: Relative Root Mean Square Error
RVI	: Radar Vegetation Index
SAR	: Synthetic Aperture Radar
SLC	: Single Look Complex
SM	: Strip Map Model
SMC	: Soil Moisture Content
SNAP	: Sentinel Application Platforms
SPM	: Small Perturbation Model
SS	: Suspended Solids
SSM	: Surface Soil Moisture
TDR	: Time Domain Reflectometry
TDS	: Total Dissolved Solids
TSS	: Total Suspended Solids
UGC	: Upper Ganga Canal
WCM	: Water Cloud Model
WSN	: Wireless Sensors Network
WUA	: Water User Association

CHAPTER 1

INTRODUCTION

1.1 Background

Water is becoming increasingly scarce worldwide, and more than one-third of the world population will face absolute water scarcity by the year 2025 (Seckler et al. 1998; Seckler et al. 1999; Rosegrant et al. 2002). The worst affected areas would be the semi-arid regions of Asia, the Middle East, and Sub-Saharan Africa, all of which already have a heavy concentration of population living below the poverty line. The situation in India is also critical, where absolute water scarcity already affects a substantial part of the population. In India, the proportion of water scarcity is likely to increase with the growth in population as demand for water increases in all the water-consuming sectors. Agriculture is the largest water-consuming sector, accounting for more than 80 % of freshwater withdrawals (IEA, 2021). India is amongst the largest irrigator countries in the world today. However, there is an increasing concern about some of the irrigation potential created not being brought into the functional system, low operating efficiency, less crop productivity, etc.

With the growing awareness of water conservation, studies have been carried out to estimate the percentage of water losses in each part of the distribution system. At present, the average overall project efficiency of several canal irrigation projects in the rice growing areas in the world has been estimated to be 23% and that of non-paddy crops to be 40 % (Walters and Boss, 1989; Kinzli et al., 2010; Mohammadi et al., 2019). In India, the areas irrigated by surface application methods, such as check basins, border strips, furrows, etc., have lower application efficiencies, i.e., about 30 to 50 percent only (CWC, 2010; Rajput et al. 2016). Surface application methods are not designed to match the stream size, soil type, slope, etc. By adopting efficient irrigation practices, losses can be reduced. It is reported that on-farm irrigation efficiency for trickle irrigation can theoretically approach 90 to 95% (Bucks et al. 1982; Srivastava et al., 2010). The problem of water scarcity in India is due to spatial variation in demand and supply of water. In India, several demand management strategies in the irrigation sector have been introduced to increase water use efficiency (Vaidyanathan 1998; Dhawan 2002). However, the net impact of these strategies in increasing water use efficiency so far has not been very impressive in the field.

Many farmers irrigate their crops in India without adhering to irrigation scheduling criteria (George et al., 2000; Lakhia et al., 2024). This prevailing practice leads to various detrimental consequences. Excessive irrigation water usage contributes to waterlogging, wastage of valuable water resources, plant diseases, and soil salinity; conversely, inadequate water supply results in crop water stress.

Farmers continue to employ traditional methods based on assumptions about the crop's water requirements, and farming practices have not evolved significantly over time (Gsangaya et al., 2020). To meet future demand while minimizing water usage, farmers must adopt precise irrigation scheduling techniques that rely on smart irrigation utilizing soil moisture sensors (Kim et al., 2008). These techniques play a critical role in enhancing agricultural production, optimizing irrigation efficiency, reducing water wastage, and mitigating harmful environmental impacts. The adoption of advanced irrigation methods is essential for efficient water management, precise irrigation scheduling of crops, and avoiding wasteful water use on the farm (Krishnan et al., 2020). By incorporating these strategies, farmers can better use their water resources, achieve their crop yield targets, and contribute to sustainable agricultural practices.

1.2 Need of Present Study

Irrigation consumes the maximum amount of water compared to industrial uses and municipal supply. Improvement in irrigation efficiency will enhance water availability to meet the increasing demands of the other sectors. By adopting more efficient irrigation methods, there is a substantial opportunity to conserve water, thereby making more of this precious resource available to satisfy the escalating needs of other sectors. Improvements in irrigation efficiency can reduce water wastage, ensuring that water can be more effectively distributed across agricultural, industrial, and residential needs. This strategic optimization contributes to sustainable water management and supports the broader objective

In rainfed areas of India, groundwater is the main resource utilized to irrigate agricultural fields. Due to the extensive use of groundwater for growing water-intensive crops, the groundwater stands overexploited in many areas of India (Bhamoriya and Mathew, 2014, Suresh et al., 2019). These are categorized into dark zones, and some areas are on the verge of becoming dark zones. In the agricultural sector, wherein the groundwater is used for irrigation, the water use efficiency is found to be of the order of 50 to 60 % only following the flood irrigation method (Chand et al., 2020). Although some states like Maharashtra and Gujrat have started using drip and sprinkler methods of irrigation on a larger scale, which enhances water use efficiency by more than 90%, the overall situation with respect to areas under micro-irrigation is within 10%.

of achieving water security in the face of growing demand and finite water supplies. Through targeted interventions and the adoption of advanced technologies in irrigation systems, it's possible to significantly reduce water use, which in turn can help mitigate the pressures on water resources and facilitate a more equitable allocation among various users.

According to Wolff and Stein (2003), inappropriate water management is an old problem in On Farm Water Management (OFWM). But this problem now ranks higher on the agenda; as the world is faced with a significant increase in population, food security becomes more of an issue, and land and water resources become scarcer. Over-irrigation is a common problem. Traditional irrigation supply and conveyance systems management often contribute to high water loss. On many farms, the low irrigation efficiency is further accentuated by farmer's traditional irrigation methods and practices. In the past, extensive research in many countries has shown that in irrigated agriculture, OFWM practices require appropriately designed on-farm distribution systems.

Innovative technologies are required to ensure greener and more sustainable food production. They are needed to improve crop yields, implement efficient irrigation strategies, use water resources of marginal quality, and produce more innovative ways to use fertilizer and water. Agricultural development in the least developing countries (LDCs) lies mainly in the hands of smallholders. The majority of farmers are actually not aware of improved OFWM practices such as channel-to-field irrigation. This is also one of the reasons why they practice field-to-field irrigation, resulting in water wastage. To make farmers properly aware as well as convinced about improved OFWM practices, it will be required to have suitable extension methods like training, seminars/workshops, and demonstration plots on the practices, etc., through people's participation, to ensure collective adoption of various agricultural practices, including improved OFWM methods by farmers.

1.3 Objectives

The objectives of the present study, as envisaged at the stage of proposal formulation, were as follows:

- (i) Enhance water use efficiency at the farm level through various measures to minimize water losses in the watercourse and in the irrigated field.
- (ii) To evolve irrigation scheduling considering the crops, soil moisture, and prevailing climatic conditions using Internet of Things (IoT).
- (iii) To study the efficacy of various micro-irrigation methods such as sprinkler and drip and, evaluate the water savings as well as enhanced water use efficiency at farm level due to adoption of these methods over the prevailing method of flood irrigation.
- (iv) To identify various factors which would help to promote adoption of the improved OFWM practices by the farmers, and various constraints which discourage the farmers for adopting those practices.
- (v) To review the role of existing Water Use Associations (WUA) and suggest suitable modifications for encouraging better OFWM practices and equitable water distribution among the farmers and online demonstration and organization of workshops on OFWM practice.

CHAPTER 2

STUDY AREA

2.1 Introduction

The current study focuses on the Gadarjudda minor canal, which begins 5.6 km from the Deoband Branch Canal (DBC). The DBC is the first branch canal to divert from the Ashafnagar cross regulator of the Upper Ganga Canal (UGC). The Upper Ganga Canal begins at the Bhimgoda Barrage, which diverts water from the Ganga River located in the Haridwar district of Uttarakhand. The UGCA is the oldest canal system for irrigation in India. This intricate network of canals is crucial for irrigation, facilitating water distribution across a vast agricultural region and supporting local farming communities by providing a reliable source of water for their crops. Gadarjudda minor is located at latitude 29°48'18" N and longitude 77°49'48" E. The location map of the minor is shown in Fig. 2.1. The schematic layout of the minor is shown in Fig. 2.2. This minor canal, with an ungated inlet, extends over 5.4 kilometers and is designed to irrigate a command area (CCA) of 485 hectares. It serves seven villages: Gadarjudda, Jhibran, Nangla Aimad, Thaska, Nagla Sikander, Kumrada, and Udalheri.

The canal's first 480 meters are earthen lined, while the remainder up to the tail end features brick masonry lining. The Deoband Branch itself has a design discharge capacity of 24.78 cumecs. Detailed features of the Gadarjudda Minor command area are presented in Table 2.1. In this table, the design discharge values for the Deoband Branch and Gadarjudda Minor were obtained from the official website of the Irrigation and Water Resources Department, Ministry of Jal Shakti, Government of Uttar Pradesh, India (<https://www.idup.gov.in/en/article/ganga>). The remaining data in the table were collected through field surveys conducted during the study.

2.2 Experimental Field

In the command area of the Gadarjudda minor, experiments were conducted in a farmer's field situated in the village of Nagla Aimad, located in the Narsan block of Haridwar district, Uttarakhand. Positioned at coordinates 29°46'53.9"N latitude and 77°50'9.4"E longitude and at an elevation of 261 meters above mean sea level, this 1.14 acre (0.46 hectare) agricultural field was specifically chosen as the experimental plot. The experimental field is irrigated through a watercourse, which is 0.48 m wide and 0.46 m deep. There are six outlets open to the experimental plot for providing irrigation water to the crops in the watercourse. Whenever water is unavailable in the minor the farmer irrigates the field with the groundwater pump located in the plot. Fig. 2.3 shows the layout map of the study area. This site provides a practical setting for evaluating agricultural practices under local environmental conditions, aiding in developing and refining irrigation techniques suitable for the region.

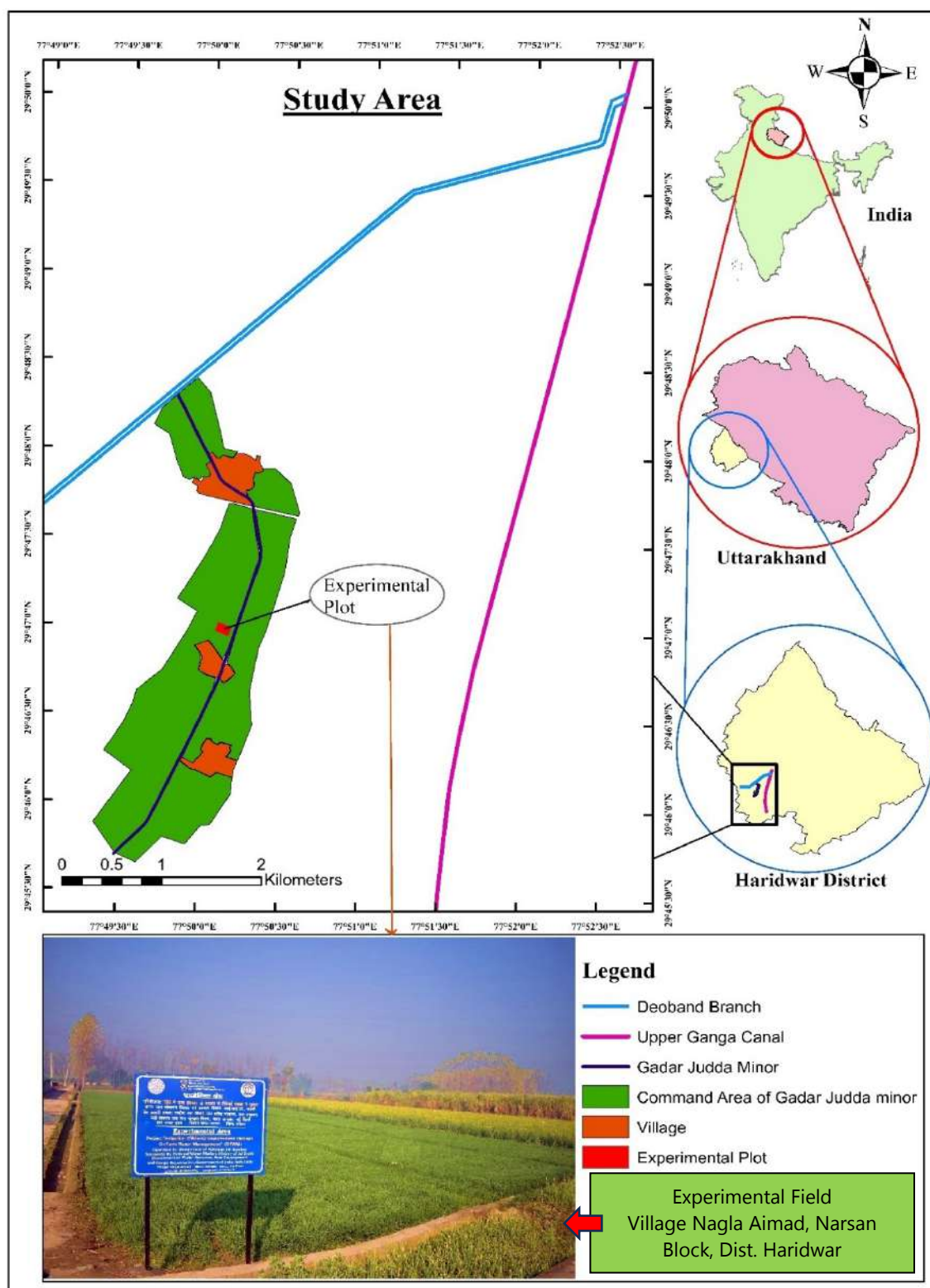


Fig. 2.1: Study area and experimental field location

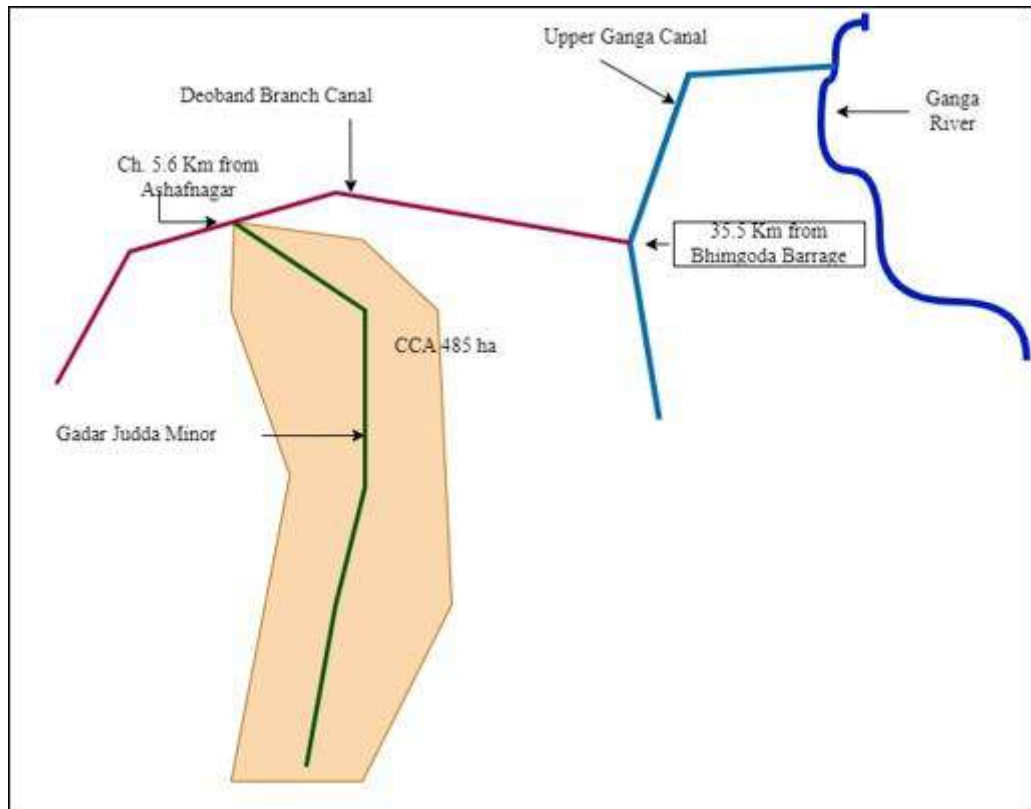


Fig. 2. 2: Schematic Layout of Gadarjudda Minor

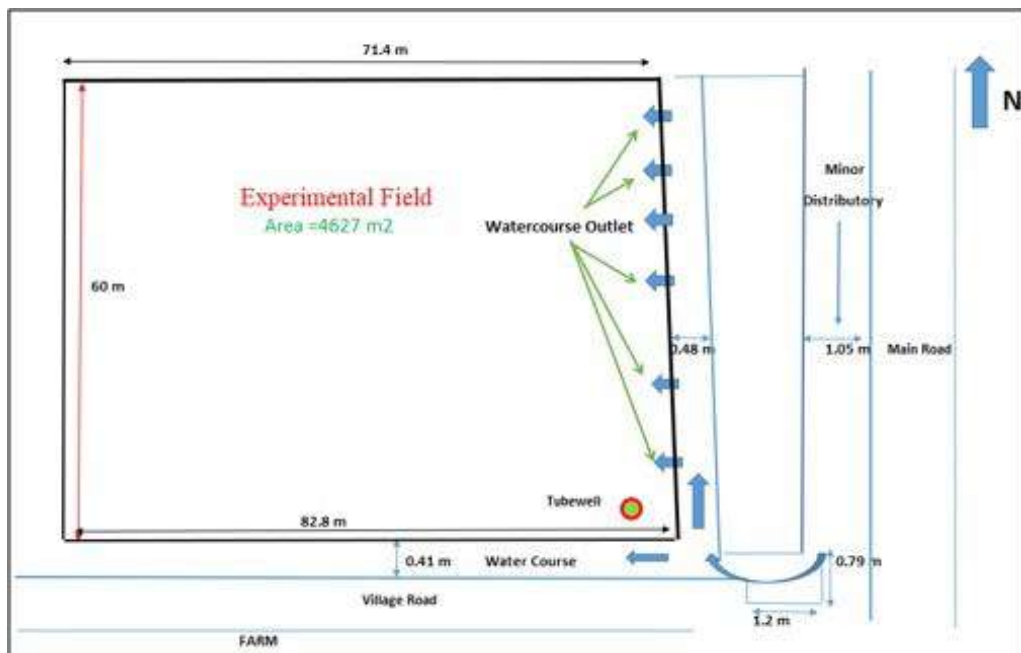


Fig. 2.3: Schematic Layout of the experimental field

Table 2.1: Salient features of Gadarjudda minor

Data	Description
Main Canal	: Upper Ganga Canal
Branch Canal	: Deoband Branch
Minor Name	: Gadarjudda Minor
Design Discharge (Deoband Branch)	: 24.78 cumec
Design Discharge (Gadarjudda minor)	: 0.283 cumec
Inlet Type	: Ungated
CCA	: 485 ha.
Nearest Market/ Distance Villages	: Manglore/ 3 km (i) Gadarjudda, (ii) Jhibran, (iii) Nangla Aimad, (iv) Thaska, (v) Nagla Sikander, (vi) Kumrada and (vii) Udalheri.
Outlets	: 25 Nos.
Outlet Type	: Non modular pipe outlet
Canal Length	: 5.4 Km
Canal Lining	: Earthen upto 480 m : Brick masonry lining 480 m onward upto tail end

2.3 Topography

The slope map and elevation map of the study area are shown in Fig. 2.4. The topography of the study area shows majorly flat lands up to 4% slope suitable for micro-irrigation systems. Steepest slopes, ranging from 6-13%, could present challenges for water management and agricultural practices due to potential erosion and runoff. The elevation map shows the elevation increases from 258 to 263 meters. Topography with mild slopes and a slight elevation increase is favorable for agricultural activities.

2.4 Land Use Land Cover (LULC)

The land use land cover map of the Gadarjudda minor command area is prepared using Landsat 8 imagery of the year 2024. The land use/landcover map of the study area was derived using GIS supervised classification and is shown in Fig. 2.5. As per the classification, Agricultural land is 71%, built-up area 6%, Trees planted in agricultural land 22%, and local ponds 1%. From the initial design of the 485 ha command area, only 343 ha was covered with crops. This is because of an increase in the number of trees planted in agricultural fields, now covering 109 ha out of the total CCA. Small ponds for fish farming cover a total of 5 ha area.

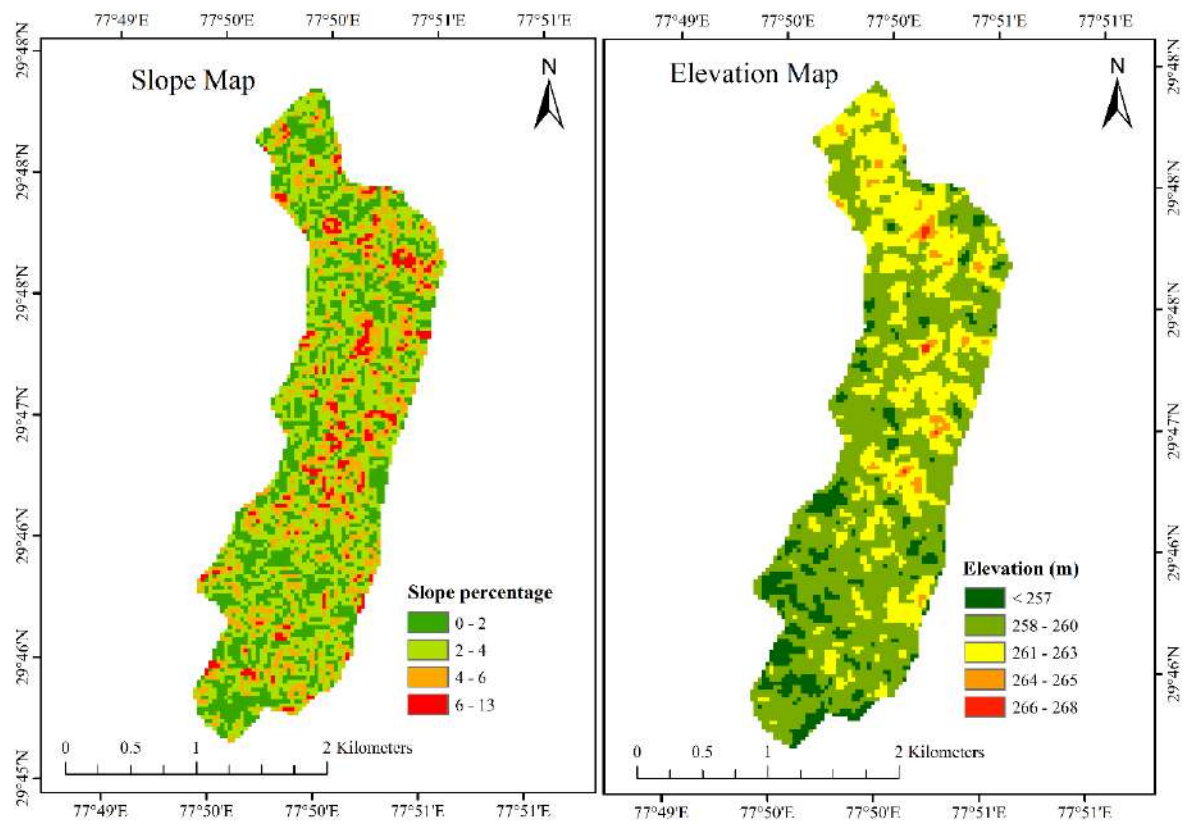


Fig. 2.4: Slope and Elevation map of the study area

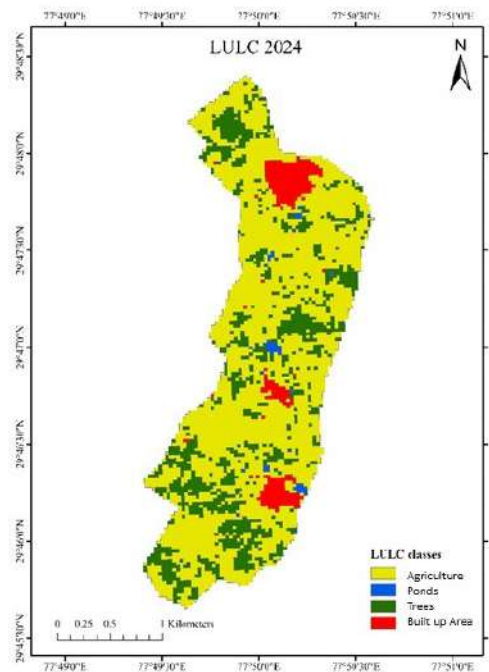


Fig. 2.5: LULC map of the study area

2.5 Cropping Pattern

The major crops in the study area include sugarcane, wheat, rice, mustard, and fodder crops. In this region, growing more than one crop on the same field is common practice within a year. Sugarcane is the most widely cultivated crop in the Gadarjudda minor command area, primarily due to its economic value and suitability to the region's climate and soil conditions. Three main types of crop rotation are popular in this area: paddy-wheat-sugarcane, paddy-wheat-berseem, and paddy-sugarcane-sugarcane, with paddy-wheat-sugarcane being the most common. For this study, the focus was on two primary crops of the area, i.e., sugarcane and wheat.

2.6 Climate and Weather

Seasonal temperature and rainfall patterns significantly influence crop growth, irrigation demand, and scheduling in the northern plain's hot sub-humid (dry) ecoregion (Venkateswarlu et al., 1996). Summers (March–June) bring high temperatures (22.5°C–35.9°C), increasing evapotranspiration and irrigation needs, while the monsoon season (July–September) reduces irrigation demand but requires careful scheduling to prevent waterlogging. Winters (October–February) see lower temperatures (7.6°C–17.7°C), decreasing evapotranspiration and allowing for more precise irrigation. Based on 1991–2023 data from the Agro-Meteorological Field Unit, IIT Roorkee (Table 2.2), June is the hottest month, January the coolest, and the region receives an average annual rainfall of 1114 mm, with 80% occurring between June and September. Relative humidity ranges from 40% (April) to 80% (August), and wind speed varies between 0.5 km/h (November) and 1.8 km/h (May). These climatic variations highlight the need for adaptive irrigation strategies to optimize water use and ensure sustainable crop production.

Table 2.2: Mean monthly climatic variables

Month	Tmin (°C)	Tmax (°C)	Rhmax (%)	Rhmin (%)	Rh average (%)	Wind Speed (Kmph)
Jan	7.6	17.7	89.51	67.02	78.26	1.11
Feb	10.2	24	85.18	47.91	66.55	1.39
Mar	15.4	30	73.57	40.31	56.94	1.69
Apr	18.9	35.6	51.16	29.41	40.29	1.51
May	22.5	35.8	60.76	39.92	50.34	1.79
Jun	24.8	35.9	68.96	49.31	59.13	1.73
Jul	25.3	32.9	86.76	71.75	79.25	1.34
Aug	25.6	33.1	88.51	71.21	79.86	1.29
Sep	24.3	33.1	87.47	64.88	76.18	1.00
Oct	19	31	85.45	54.31	69.88	0.93
Nov	12.5	26.7	85.10	49.56	67.33	0.47
Dec	8.2	21.7	86.84	51.22	69.03	0.77

CHAPTER 3

SURVEY OF COMMAND AREA AND FIELD INVESTIGATION

3.1 Background

Ensuring a thorough assessment of the current condition of the canal before proceeding with a study is necessary. Various factors such as structural integrity, water flow capacity, soil physical properties, water quality, and potential maintenance requirements can be identified by comprehensively evaluating the canal's condition.

3.2 Minor Canal Survey

A comprehensive canal survey was conducted from February to May 2022 to gather detailed information of the Gadarjudda minor canal. The canal's longitudinal (L-section) and cross-sectional (X-section) profiles has indicated an average bed slope of 1 in 1600, consistent throughout the canal's course with some exceptions. Notably, at specific chainage points, namely at 0+095, 0+300, 0+750, and 3+000, there are upward deviations in the bed slope. These deviations suggest changes in the gradient that may affect water flow velocity within the canal. Fig. 3.1 shows the L-section and X-section of Gadarjudda minor.

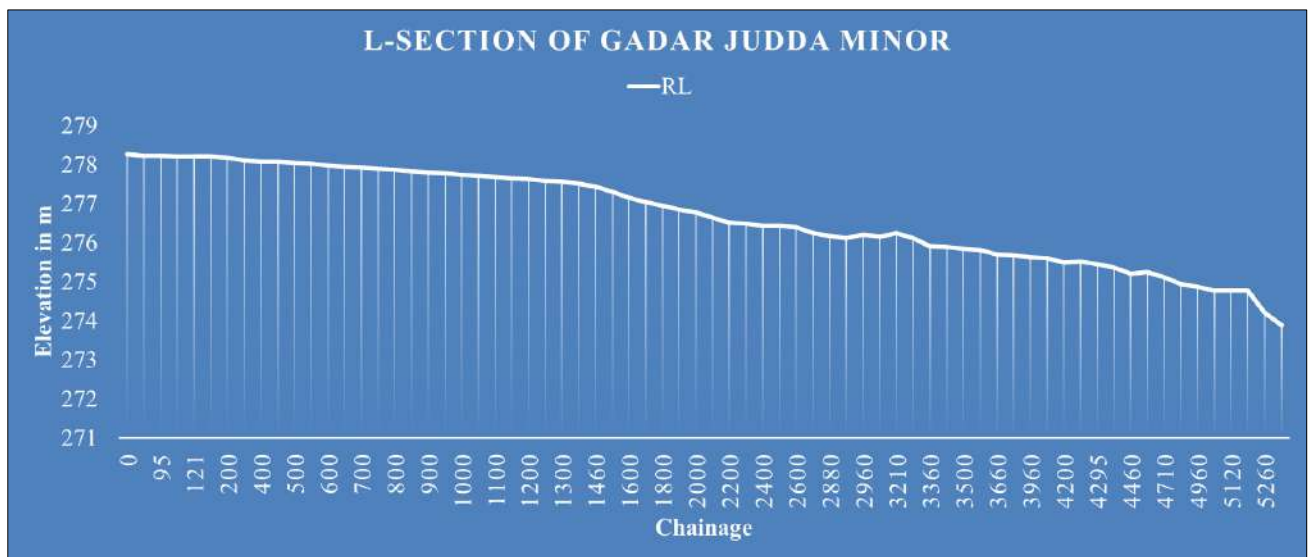


Fig. 3.1: L-section and X-section of Gadarjudda minor

Initially, the canal infrastructure shows an unlined formation up to chainage point 0+490, which suggests a natural or earthen bank and bed, potentially leading to higher seepage and erosion rates. Beyond this point, there is a transition to a more structured canal lining composed of rectangular brick masonry. This lining continues to the tail-end, providing a more robust, less permeable boundary that likely improves water conveyance efficiency and minimizes losses. The observations have identified

nineteen non-modular, non-gated pipe outlets in the Gadarjudda Minor. Six outlets have been identified as unauthorized modifications to the canal banks, including cutting by local farmers for illicit water extraction. These alterations have potentially affected the canal's discharge and distribution patterns.

The survey notes an absence of control devices along the Gadarjudda minor canal. Control devices, such as gates or valves, are essential for regulating flow, maintaining desired water levels, and managing sediment. Their absence could lead to a lack of precision in water distribution and difficulties in maintenance and operational management, which might adversely impact the overall functionality and sustainability of the canal system. The diversion of water from the Deoband branch into the canal has been inefficient, leading to an inconsistent supply that does not align with the canal's water distribution schedule, also known as the canal roaster. This inefficiency is exacerbated at the tail end of the canal, where water availability is critically low, failing to reach the extremities of the system. To mitigate this shortfall, 6 deep tube wells have been augmented to the minor canal beyond chainage point 3+500. However, this indicates an over-reliance on groundwater to compensate for the insufficient surface water supply. This strategy may not be sustainable in the long term.

3.2.1 Canal Infrastructure

The survey revealed that the canal's upkeep had been neglected for years, badly affecting how well it worked. It was noticed that parts of the canal's protective linings were broken. These linings are essential for preventing water leaks, and their damage interferes with water flow, leading to erosion and structural issues. Fig. 3.2 shows the breakage in the minor canal.



Fig. 3.2: Breakage in Gadarjudda minor

3.2.2 Extensive Weeds Growth

The canal encountered multiple challenges that hindered its functionality and compromised water quality for irrigation purposes. One significant issue was the extensive growth of weeds and accumulation of sediment within the canal, leading to blockages that impeded the flow of water. Consequently, this obstruction reduced the water available for distribution to farmers, adversely affecting agricultural productivity and crop yields. Fig. 3.3 shows that the extensive weeds and vegetation in the minor canal



Fig. 3.3: Extensive weeds and vegetation in the canal

3.2.3 Garbage and Sewage Disposal into the Canal

The canal faced contamination from sewage and garbage originating from nearby residential areas. The influx of sewage and garbage introduced harmful pollutants into the water, posing a severe threat to the health. Sewage compromised the water quality and increased the risk of waterborne diseases. Fig. 3.4 shows the sewage and garbage disposal in Gadarjudda minor.



Fig. 3.4: Sewage and garbage disposal in Gadarjudda minor

3.2.4 Canal Bank Encroachment

The issue of canal bank encroachment is also one of the challenges the canal system faces, posing additional obstacles to efficient water management and agricultural sustainability. Encroachment occurs when individuals cultivate crops or engage in other activities, such as depositing cow dung along the canal's banks, encroaching upon its designated boundaries. This encroachment undermines the structural integrity of the canal banks, potentially leading to erosion and instability. Fig. 3.5 shows the canal bank encroachment.



Fig. 3.5: Bank Encroachment (Cow dung cakes and Garlic cultivation)

3.2.5 Tree Plantation Near the Canal

Planting poplar trees near the canal poses significant challenges to watercourse infrastructure. The primary concern associated with tree plantation near canals is root intrusion. The expansive root systems of trees, such as poplars, can penetrate and compromise the structural integrity of canal embankments and watercourse linings. As these roots grow and spread, they disrupt the stability of canal banks, leading to structural damage to the canal infrastructure. Fig. 3.6 shows the planting of poplar trees near the watercourse.



Fig. 3.6: Planting poplar trees near the watercourse

3.2.6 Theft of Canal Water

The issue of water theft from the canal for commercial purposes exacerbates the challenges farmers face and undermines the integrity of the water distribution system. Water theft occurs when individuals or entities illegally divert water from the canal for activities unrelated to agricultural use, such as commercial ventures. This unlawful practice deprives legitimate farmers of their rightful access to water and disrupts the equitable distribution of water resources within the irrigation network. Fig. 3.7 shows the unauthorized withdrawal of canal water.



Fig. 3.7: Unauthorized withdrawal of water

3.2.7 Conclusions

The observations made during the survey are given below;

- There is no flow-controlling structure like the head regulator
- Canal overtopping at head reach
- Village waste drain dumped into the canal
- Garbage Deposition in the Canal
- Unauthorized pipe off-taking from the minor
- Growing of trees near the canal damaged the canal
- Due to the siltation of the canal its size, shape, and cross-section are changed
- Extensive weeds and vegetation grown in the canal
- Encroachment of service road and canal bank in the head, middle, and tail reach
- The designed canal slope seems to be badly affected by siltation
- The service road was not maintained in the head and middle reach
- Canal bank, brick lining, etc. were found to be damaged in many places
- Proper land levelling and flow control structures were not installed

The observed structural damage, water pollution from household waste, weed overgrowth, tree plantation near the canal, encroachment on canal banks, and theft of canal water for commercial

purposes collectively depict the deteriorating state of the canal. These issues compromise water flow, degrade water quality, and threaten the integrity of the canal infrastructure, exacerbating challenges for agricultural users. Visual evidence through photographs underscores the urgency of addressing these issues through collaborative efforts among stakeholders.

3.3 Siltation in Watercourse

A watercourse survey was carried out, and it was noticed that in most of the outlets, canal lining is present only up to the first 100-150 meters, the rest of the watercourse is earthen. The watercourses aren't in proper shape and size, resulting in water losses during the conveyance. The condition of the water courses looks poor due to lack of maintenance, growing weeds, vegetation, and deposition of debris and sediments in the water course. Mud and other materials were observed to have settled at the bottom while different parts of the water channel were examined. Upon measuring the sediment accumulation, it was observed that, on average, a layer of approximately six centimeters in thickness had built up. Table 3.1 illustrates the locations where the sediment depth and respective measurements were carried out. This accumulation of sediment, referred to as siltation, is a serious issue because it fills up the watercourse and reduces the amount of water it can carry. Originally the channel was 34 centimeters deep, but now, approximately six centimeters of that is just this settled silt.

Table 3.1: Location and siltation depth

S.No.	Location (Latitude and longitude)	Siltation depth (cm)
1	29°46'52.70"N, 77°50'10.19"E	7.5
2	29°46'53.07"N, 77°50'9.29"E	5.5
3	29°46'53.36"N, 77°50'8.50"E	5.0
4	29°46'53.69"N, 77°50'7.73"E	6.0
5	29°46'54.11"N, 77°50'6.84"E	6.5
6	29°46'54.54"N, 77°50'5.88"E	5.5
7	29°46'55.29"N, 77°50'4.29"E	6.6
	Avg	6.08



Fig. 3.8: Siltation in watercourse and overtopping due to siltation

3.3.1 Cleaning of the Watercourse

The siltation in the watercourse is a huge problem, resulting in a significant reduction of the watercourse's carrying capacity. In the farmer awareness program, the farmers were suggested for regular cleaning and proper watercourse maintenance. After that, the farmers cleaned and maintained the watercourse. It has been observed that after cleaning the watercourse, the depth & velocity of flow were increased by 15% and 9.8%, respectively. In comparison, the overall carrying capacity of the watercourse was enhanced by 26.36%. Table 3.2 shows the comparison of watercourse discharge with and without siltation.

Table 3.2: Comparison between the flow of water with siltation and without siltation

Parameter	With Siltation	Without Siltation	Remarks
Depth (cm)	30	34.5	15 % increased
Width (cm)	49	49	-
Area of cross-section (cm ²)	1470	1690.5	15 % increased
Length of watercourse (m)	77.5	77.5	-
Velocity (m/s)	0.253	0.278	9.88 % increased
Discharge (lps)	37.191	47.00	26.36 % increased

3.4 Conveyance Efficiency

The conveyance efficiency denotes the capacity of the canal system to carry water from the head to the outlet point, with expected water loss in the canal due to seepage, deep percolation, cracks, and evaporation losses. Seepage analysis using the inflow-outflow method is an established technique for assessing water loss within canal systems, specifically by measuring water inflow and outflow amounts of water over a certain canal stretch. This method assumes no water is extracted through outlets between the measurement points to ensure accuracy. The resulting difference in volume is primarily attributed to seepage losses. Using digital velocity meters and an Acoustic Doppler Current Profiler (ADCP),

For this study, conveyance loss is considered the same as seepage loss, which is the major water loss in any canal conveyance system. Karad et al. (2013) mentioned the calculation of seepage loss in cumec per million-meter square by inflow-outflow method:

$$\text{Seepage loss (I)} = \frac{Q_{\text{inlet}} - Q_{\text{outlet}}}{A} \quad (3.1)$$

Where, I is seepage loss in cumec/Mm² of wetted area, Q_{inlet} is discharge at inlet point in cumec, Q_{outlet} is discharge at outlet point in cumec, A is wetted area in Mm².

Alebachew et al. 2018, measured conveyance efficiency using relation 6.3.

$$\text{Conveyance efficiency (Ec)} = \frac{Q_{\text{outlet}}}{Q_{\text{inlet}}} \times 100 \quad (3.2)$$

Where, Ec is conveyance efficiency in %, Q_{inlet} is discharge at inlet point in cumec, Q_{outlet} is discharge at outlet point in cumec.

The conveyance efficiency of Gadarjudda minor is calculated using equations 3.1 and 3.2. Seepage from head, middle and tail reach is computed separately and presented in Table 3.3.

Table 3.3: Calculation of conveyance efficiency of Gadarjudda minor

Reach	Inflow (m ³ /s)	Outflow (m ³ /s)	Loss (m ³ /s)	Avg. wetted perimeter (m)	Rate of loss		Ec (%)
					Loss/ inflow (%)	Cumec per Mm ²	
Head (500-670 m)	0.29	0.25	0.035	3.33	12	61.03	88
Middle (2635-2970 m)	0.11	0.08	0.032	2.08	28	45.21	72
Tail (3500-4210 m)	0.02	0.01	0.004	1.32	22.4	3.73	77.56
Overall (500-4210 m)	0.29	0.17	0.122	2.51	42.4	16.19	57.6

Seepage loss in head reach is greater than in other reaches, with 61.03 cumec per Mm². This is because the more wetted area, as compared to other reaches, is exposed to canal water, which is eventually lost during the conveyance process. The tail end had a very low water depth, depicting a lower loss in cumec per Mm². The efficiency at the head, middle, and tail reaches was calculated based on short distances where no outlets were observed. However, the overall efficiency is calculated from 500 m to 4210 m and includes all reaches. The inflow at the 500 m point is 0.29 m³/s, and the outflow at the 4210 m point is 0.167 m³/s, resulting in an overall conveyance efficiency of 57.6%. This confusion arises because the overall efficiency considers the entire conveyance system, including the discharge from outlets along the way. Study shows excessive water loss in conveyance because of aging infrastructure and poor maintenance; such water loss reduces water availability for end users. Fig. 3.9 shows the measurement locations in the head, middle, and tail reaches.

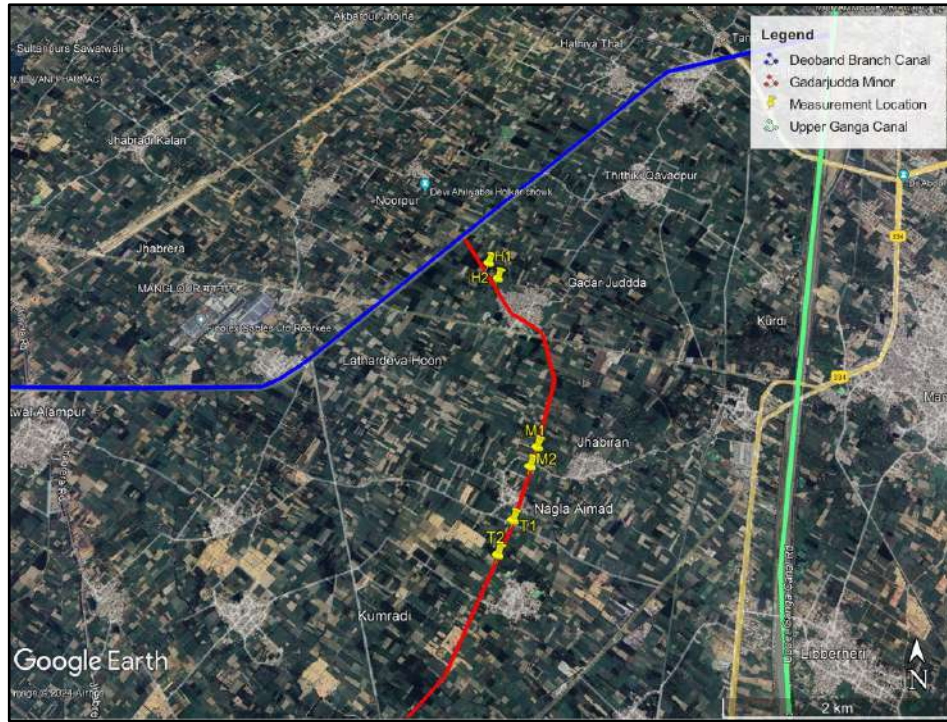


Fig. 3.9 Measurement locations in the head, middle, and tail reaches

3.5 Maintenance and Management Condition

For the delivery of water to the farmer's field and in the required quantity, the canal system needs periodic maintenance and repair. Irrigation canals operate effectively as long as they are maintained clean and free from any leakage. Failure to deal with the problems of the canal system may result in the growth of vegetation and an increase in siltation. According to Akkuzu et al. (2008), the effectiveness of an irrigation canal system is based on both the operational management and the state of the canals. An effective maintenance program has the potential to extend the lifespan of canals. Therefore, it is essential to maintain regular repair work in the canal system.

The maintenance of an irrigation canal system typically occurs during the intervals between two irrigation seasons or periods of low water demand. In Gadarjudda, minor maintenance work on desilting is carried out in October every year. (Akkuzu et al., 2008; Gabr et al., 2023; Karad et al., 2013), Suggested a method to check the maintenance condition of the canal by evaluating Manning's roughness (n) and active canal capacity (ACC). The relation to calculate roughness and ACC is shown in equations 3.3 & 3.4.

$$\text{Manning's Roughness } (n) = \frac{R^{2/3} \times S^{1/2}}{V} \quad (3.3)$$

$$\text{Active Canal Capacity (ACC)} = \frac{n(\text{projected})}{n(\text{actual})} \times 100 \% \quad (3.4)$$

Where, n = Manning's roughness coefficient, R = hydraulic radius (m), S = slope (m/m), V = velocity in m/s, ACC is actual canal capacity in %, $n(\text{projected})$ = the accepted value of n for the material used in lining, and $n(\text{actual})$ = calculated n value from equation 3.3. The value of $n(\text{projected})$ is taken as 0.018 for brick masonry lining (Chow, 1959) shown in Table 3.4.

Table 3.4: Value of Manning's roughness for brick masonry (Chow, 1959)

Type of Brick Masonry	n (minimum)	n (normal)	n (maximum)
1. Glazed	0.011	0.013	0.015
2. Cement mortar	0.012	0.015	0.018

The minor canal is evaluated on a reach basis. In each reach, two points are selected so that no outlet lies in between to ensure uniform flow conditions, and the average in the wetted area, wetted perimeter, and velocity is taken for the calculation. The average slope is taken as the slope between two points. The UGC authority carries out yearly maintenance work. Minor is lined brick masonry, thus requiring silt removal from the bed and vegetation from the bed and side slopes. Management of the system below the outlet is the responsibility of the farmer. The Water User's Association is absent in the Gadarjudda minor due to the condition of the canal deteriorating year by year, as mentioned by farmers of the study area. The condition of the field channel is to deliver water to the distant command area. The value of Manning's roughness (n) calculated from equation 3.3 and ACC from equation 3.4 is shown in Table 3.5.

Table 3.5: Manning's roughness (n) and actual canal capacity (ACC) %.

Reach	Wetted Area (m ²)	Wetted Perimeter (m)	Hydraulic Radius (m)	Bed slope	Velocity (m/s)	Manning (n)	ACC (%)
Head	1.15	3.30	0.35	0.0013	0.5	0.035	51.1%
Middle	0.54	2.08	0.26	0.0009	0.4	0.030	59.1%
Tail	0.49	1.98	0.25	0.0004	0.2	0.040	44.6%

Manning's roughness value is measured more than the recommended value by Chow (1959). This shows increased roughness in the channel section. The result shows ACC value ranging between 44 - 59%. This indicates a reduced canal capacity because of unattended repair and maintenance work in the minor canal.

3.6 Soil Physical Properties

A field survey was conducted, and soil samples were collected from the experimental plot. The collected samples were analyzed for their physical properties, i.e., soil type, bulk density, field capacity, permanent wilting point, and infiltration rate, in the irrigation water management laboratory

at the Department of Water Resources Development and Management, IIT Roorkee. The detailed procedure of experiments and results are discussed below.

3.6.1 Bulk Density of Soil

This test has been carried out using the core cutter (Blake et al., 1986). A small area, approximately 30 cm square, was exposed to the soil layer and leveled. On top of the cutter, the steel dolly was mounted, and the latter was pulled vertically down into the soil layer, and the cutter was dug out of the surrounding soil. Using the sharp edge, the ends of the soil core were shaped flat with the ends of the cutter. Then the core cutter with soil was put into the oven for 24 hours at 105 °C. After that, the weight of the dry soil was taken, and the bulk density of the soil was determined. The bulk density of soil has been found as 1.54 g/cc.

3.6.2 Texture Analysis

The percentage of sand, silt, and clay were analyzed using the Hydrometer method (Bouyoucos, 1962). Complex cations that bind clay and silt particles into aggregates were treated with sodium hexametaphosphate. In the solution, organic matter was suspended after the sand settled out and again after the silt settled. The density of the soil suspension was measured using a hydrometer designed to read in grams of solids per liter. Corrections were made to the density and temperature of the dispersing solution. The clay percentage of the soil is 12.08%, the silt percentage is 41.45%, and the sand percentage is 46.57%. With the help of the USDA soil triangle, the percentage of silt, clay, and Sand shows that the soil of the field is Loamy soil.

3.6.3 Field Capacity (FC) and Permanent Wilting Point (PWP)

FC of the soil is the moisture content after the removal of gravitational water. The soil moisture tension at FC varies from soil to soil and generally varies from 1/10 to 1/3 atmosphere. Usually, moisture content at 1/3 atmospheric pressure is taken as Field capacity. The permanent Wilting Point is the water content at which plants can no longer extract sufficient water from the soil for their growth. Fifteen atmospheric pressure is commonly used for the determination of PWP. The procedure suggested by (Chakraborty et al. 2015) was adopted for the determination of field capacity and the permanent wilting point. Soil samples were collected using an auger, air-dried under shade, and then finely ground with a wooden hammer before being sieved through a 2 mm sieve.

Ceramic plates were saturated, and the soil was placed within rings on these plates, ensuring the water level just touched the upper edges of the rings for 24 hours. The samples were then transferred into a pressure plate apparatus, the chamber sealed securely with nuts and bolts, and the pressure adjusted to the required level until equilibrium was achieved, indicated by the cessation of water outflow. The

samples were immediately weighed to minimize water loss due to evaporation, dried in an oven at 105°C for 24 hours, and the moisture content was determined using the gravimetric method. The Field Capacity of the soil is found to be 24.45 %, and the permanent wilting point of the soil is found to be 14.56 %.

3.6.4 Infiltration Test

The double-ring infiltrometer is used to determine water infiltration of the soil (Johnson, 1963). The rings were partially (10 cm) inserted into the ground and filled with water, after which the speed of infiltration was measured every 10 min interval. The test takes approximately 8 hours to reach a constant infiltration rate. The infiltration rate of the soil is found to be 12 mm/hr. Fig. 3.10 shows the infiltration curve developed through the infiltration test.

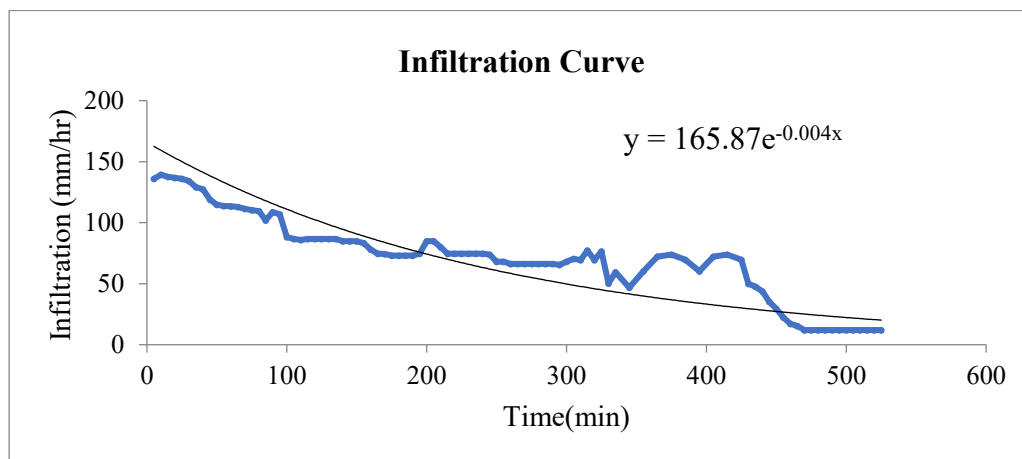


Fig. 3.10: Infiltration curve

3.7 Water Quality

The samples were collected from head reach (ch. 500 m), mid-reach (ch. 3500 m), and tail reach (ch. 4500 m), of the minor canal. One additional sample location at the experimental plot (ch. 2970 m) was also selected. A total of four locations were selected for the proper representation of the water quality of the minor canal. A total of eight samples were collected, two in each location. Samples were collected in pre-cleaned and sterilized polyethylene bottles to avoid contamination. Manual hand-grab sampling was carried out to collect water samples. The bottles were rinsed with the sample water before collection to avoid any residual contamination from the sample bottles. The water sample bottles were labeled and stored in the water quality lab refrigerator.

3.7.1 Laboratory Analysis

Water quality parameters pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Suspended Solids (SS) were examined in the laboratory. For pH, EC, and TDS multi-parameter device

(Orion Star A325) was used. Calibration of the multi-parameter was carried out. For pH calibration, buffer solutions of known pH values of 4, 7, and 10 were used to calibrate, whereas for TDS and EC, known standard calibration solutions of known TDS values were used. After calibration of the multi-parameter, the electrode of the device was inserted into the water sample fully immersed, and the measurement readings displayed were recorded. To avoid cross-contamination, distilled water was used to rinse the electrode between sample measurements.

Total suspended solids were determined in the laboratory by passing water samples through a pre-weighed glass fiber filter paper of 0.4 microns. 100 ml water sample was passed through the filter paper and placed in the filter holder with the assistance of a filter pump. The filter paper is then oven-dried at 104 °C for two hours and placed in a desiccator to cool down to room temperature. The oven-dried filter paper is weighed, and the value is recorded on a sheet. The calculation of TSS is done by the following relation. Calcium and magnesium were determined via EDTA titration and manganese and iron were analyzed using a Flame Atomic Absorption Spectrophotometer after sample digestion (Tüzen, 2003).

$$\text{TSS} = \frac{\text{Oven dried filter wt. (mg)} - \text{initial wt. of filter (mg)}}{\text{Volume of sample (L)}} \quad 3.5$$

3.7.2 Results

The results from laboratory tests are illustrated in Fig. 3.11. These results are analyzed in comparison with the guidelines given by Pradhan Mantri Krishi Sinchayee Yojana: Per Drop More Crop (PMKSY-PDMC), the US Regional Salinity Laboratory, and the guidelines provided by the Food and Agriculture Organization (FAO). Table 3.6 shows the comparison with standards. The recorded pH values range from 7.17 to 7.44, within a moderately acceptable limit. The electrical conductivity of the water was measured to be below 250 µS/cm, indicating superior water quality in line with the criteria established by the US Regional Salinity Laboratory and the FAO.

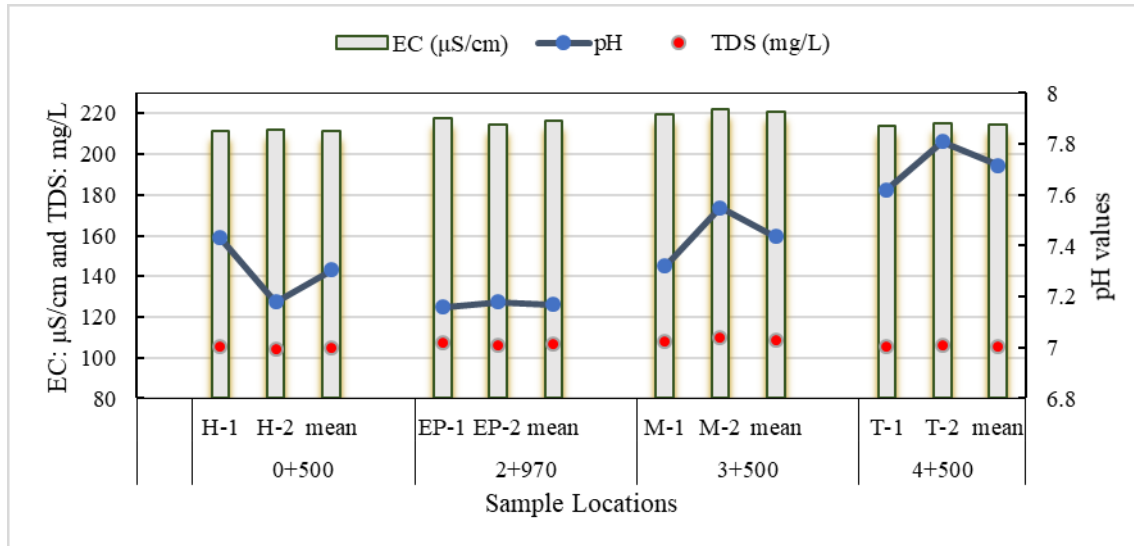


Fig. 3.11: Water quality parameters

Total dissolved solids (TDS) measured at different canal points, specifically at the head, middle, and tail sections, were recorded as 104.8 mg/L, 108.85 mg/L, and 105.65 mg/L, respectively. This shows a slight variation in TDS levels along the length of the canal. Additionally, the total suspended solids (TSS) content was higher at the canal's head compared to downstream sections, indicating a greater concentration of suspended solids in the upper reaches of the water flow.

According to the guidelines suggested by PMKSY-PDMC concerning irrigation water quality, particularly regarding the risk of emitter clogging, the levels of both TDS and TSS were deemed to be within acceptable limits. This assessment suggests that the water quality of the minor canal is classified as 'slight' for both TDS and TSS metrics, which implies minimal risk of clogging and suitable conditions for irrigation purposes.

The chemical analyses of the canal water indicate a generally moderate level of contamination across the measured locations, with implications for micro-irrigation suitability. Manganese averages around 0.55 mg/l, which is within the moderate range. Iron levels average approximately 0.91 mg/l, which is also in the moderate range, suggesting possible clogging risks in micro-irrigation systems if not properly filtered. The average concentration of Calcium and Magnesium is about 26.75 mg/l, indicating moderate hardness.

The water quality is suitable for micro-irrigation but requires proper filtration and regular maintenance to prevent clogging and scaling in the infrastructure. The water quality results confirm compliance with national and international standards, supporting its use in agriculture with minimal intervention.

Table 3.6: Water Quality Standard Comparison

S.N.	Parameter	Location chainage (m)	Measured Value	Standard Comparison	Remarks
1	pH	500	7.31		
		2970	7.17	<7: Slight	
		3500	7.44	7-8: Moderate	Moderate
		4500	7.72	>8: Severe	
2	Electrical Conductivity ($\mu\text{S}/\text{cm}$)	500	211.60	<250: Excellent	
		2970	216.15	250-750: Good	
		3500	220.85	750-2250: Medium	Excellent
		4500	214.60	2250-4000: Bad >4000: Very Bad	
3	Total Dissolved Solids (mg/L)	500	104.80		
		2970	106.45	<500: Slight	
		3500	108.85	500-2000: Moderate	Slight
		4500	105.65	>2000: Severe	
4	Total Suspended Solids (mg/L)	500	42.00		
		2970	24.50	<50: Slight	
		3500	21.50	50-100: Moderate	Slight
		4500	8.50	>100: Severe	
5	Manganese (Mn) (mg/L)	500	0.15	<0.1: Slight	
		2970	1.10	0.1-1.5: Moderate	Moderate
		3500	0.90		
		4500	0.07	>1.5: Severe	
6	Iron (Fe) (mg/L)	500	0.90	<0.1: Slight	
		2970	1.20	0.1-1.5: Moderate	Moderate
		3500	0.80		
		4500	0.75	>1.5: Severe	
7	Calcium and Magnesium (Ca & Mg) (mg/L)	500	30.32	<20: Slight	
		2970	26.52	20-40: Moderate	Moderate
		3500	19.10		
		4500	32.25	>40: Severe	

Reference: PMKSY-PDMC (MoA&FW, 2023), USDA-ARS, and FAO guidelines (Ayers and Westcot, 1985)

3.8 Crop Water Requirement

Crop water requirement is the amount of water required by crops for their growth and development throughout the growing season. The estimation of crop water requirement (CWR) is essential to calculate the net irrigation requirement (NIR) and gross irrigation requirement (GIR). NIR is the water needed to restore the soil water content of the root zone up to field capacity, calculated as the difference between crop water requirement (CWR) and effective rainfall. GIR is the amount of water required, incorporating losses in the conveyance, application, and other cultural works. This study uses the globally accepted Penman-Monteith method in CropWat software to estimate Evapotranspiration (ET_o). In this study, effective rainfall, which is the fraction of rainfall stored in the soil for plant

growth, is calculated using the USDA Soil Conservation Service method with the CropWat model.

Fig. 3.12: Show the methodology used for ET_c and irrigation water requirement calculation.

ET_o is produced by the model using the FAO Penman-Monteith equation with climate data, and crop evapotranspiration (ET_c) is calculated using crop coefficient (K_c) values suggested by FAO (Allen et al., 1998) according to equation 3.6. Equations 3.7 and 3.8 are used to compute the Net Irrigation Requirement (NIR) and Gross Irrigation Requirement (GIR). Field efficiency is 60% for the flood irrigation method recommended by FAO (1989).

$$ET_c = K_c \times ET_o \quad (3.6)$$

$$NIR = ET_c - \text{Effective Rainfall} \quad (3.7)$$

$$GIR = NIR / \text{Field Efficiency} \quad (3.8)$$

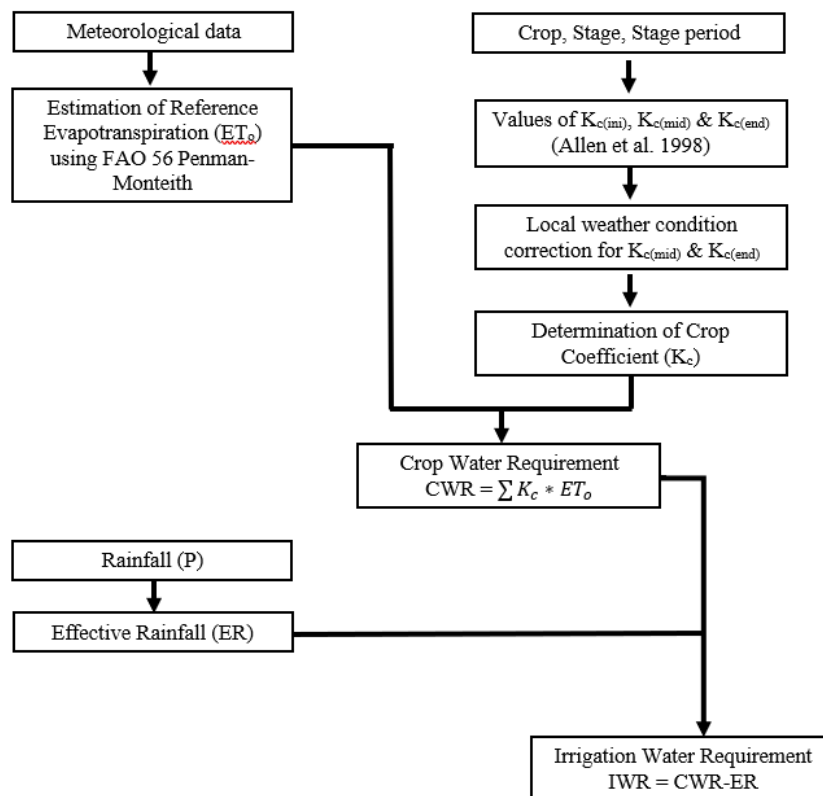


Fig. 3.12: Flowchart of the methodology used for ET_c and irrigation water requirement calculation (Pandey et al., 2021)

The crop water requirement estimated by the CropWat model is presented in Fig. 3.13, while NIR and GIR are calculated using Equations 3.7 and 3.8, respectively, as shown in Fig. 3.14. The maximum

NIR for sugarcane is observed in May. Similarly, for paddy, June has the highest irrigation water requirement. Mustard and Wheat demonstrate a high value of NIR in December, which is also the mid-season stage for both crops. Water deficits this month will affect crop yield. Hence, water requirements must be met by applying irrigation water during this period.

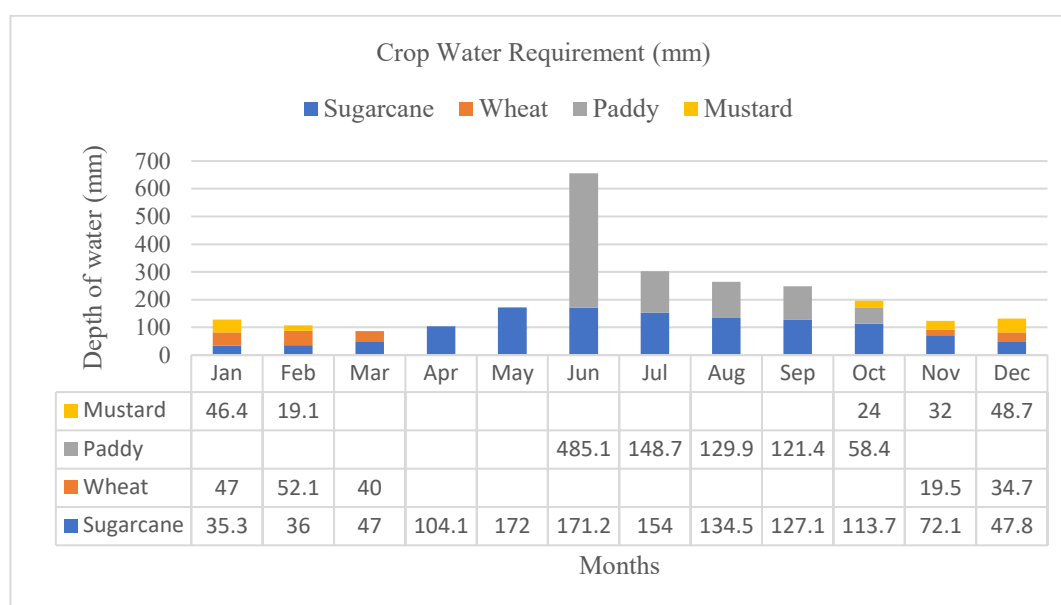


Fig. 3.13: CWR for existing cropping pattern of the study area

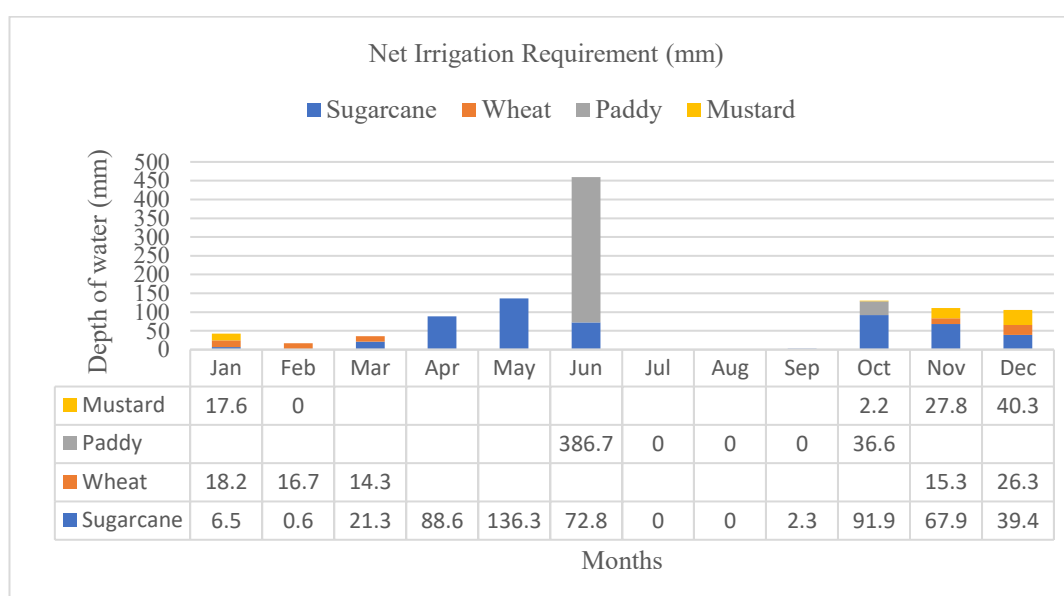


Fig. 3.14: Net irrigation requirement for existing cropping pattern of the study area

3.9 Water Use Performance Indicators

Water use performance indicators suggested by Bhat et al. (2024); Bos et al. (2005); Jha et al. (2022) have been used to assess the water use performance of the minor canal. Indicators such as Water Delivery Capacity Index (WDCI), Annual Volume of Irrigation Water Delivered (AVIWD), Annual Irrigation Water Supply per Command Area (AIWS/CA), Relative Water Supply (RWS), and Relative Irrigation Supply (RIS) are used to identify the water use performance of the minor canal. Table 3.7 presents the list of performance indicators used for this study.

Table 3.7. List of water use performance indicators

S.N.	Indicator	Detail	Reference
1	WDCI	$\frac{\text{act. capacity at the Head (m}^3/\text{s)}}{\text{Peak CWR at the Head (m}^3/\text{s)}}$	Jha et al., 2022
			Bos et al., 2005
2	AVIWD	$\frac{(\text{Discharge at head}) \times (\text{duration of water supply})}{\text{Water delivery efficiency}}$	Bhat et al., 2024
			Bos et al., 2005
3	AIWS/CA	$\frac{\text{AVIWD (m}^3\text{)}}{\text{Command Area (ha)}}$	Bhat et al., 2024
			Jha et al., 2022
4	RWS	$\frac{\text{Total water supply (irrigation + eff. rainfall)}}{\text{Crop water demand}}$	Bhat et al., 2024
			Jha et al., 2022
5	RIS	$\frac{\text{Total irrigation supply}}{\text{Irrigation demand (CWR – eff. rainfall)}}$	Bhat et al., 2024
			Jha et al., 2022

The water use performance indicators such as WDCI, AVIWD, and AIWS/CA are presented in Table 3.8. The WDCI for Gadarjudda minor shows a value of 0.62, which means the minor canal cannot deliver the required peak volume of water. The annual volume of irrigation water delivered is 0.756 MCM, and the annual irrigation water supply per command area is computed as 2,191.3 m³/ ha. Relative irrigation supply and relative water supply are estimated and tabulated in Table 3.9.

Table 3.8. Water use performance indicators for Gadarjudda minor

WUP indicator	Unit	Gadar Judda minor
WDCI	-	0.62
AVIWD	m ³	756,000
AIWS/CA	m ³ / ha	2,191.3

Furthermore, the RIS and RWS are crucial indicators for understanding the adequacy and reliability of the irrigation water provided, as estimated and illustrated in Fig. 3.15. RIS and RWS values are

greater than 1 for sugarcane, wheat, and mustard, indicating that these crops receive more irrigation water than required. In contrast, for paddy, both RIS and RWS are below 1, suggesting insufficient water supply for optimal growth. For paddy, the RIS value is 0.7, indicates the irrigation supply meets only 70% of the crop's water requirements. The RWS value for paddy is 0.88, indicating that the combined water supply from both irrigation and rainfall still falls short of the crop's total water needs, covering only 88% of the requirement. This shortfall highlights the need for improved irrigation strategies to ensure adequate water supply for paddy cultivation.

Adopting better water management practices, such as micro-irrigation, can significantly enhance the irrigation system's performance. This would lead to better crop yields, more sustainable water use, and potentially an increase in the irrigated area, benefiting the region's agricultural productivity.

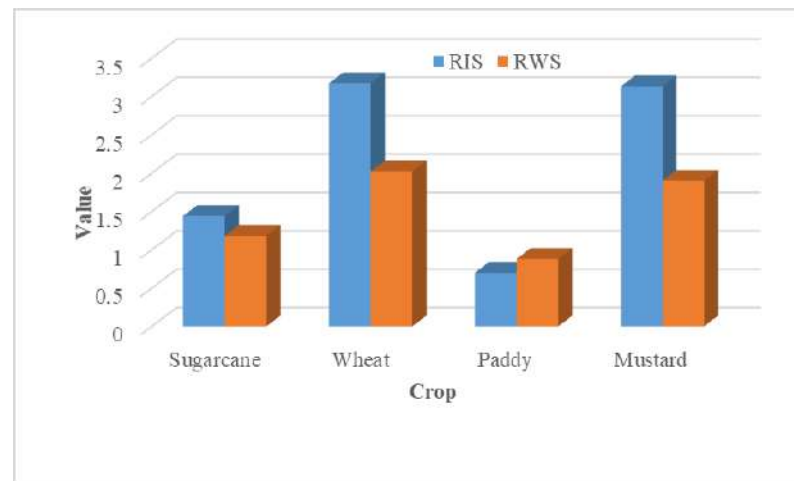


Fig. 3.15: RIS and RWS for Gadarjudda minor

3.10 Conclusions

This study outlines a comprehensive field investigation and survey of the command area, focusing on assessing the current state and operational challenges of the Gadarjudda Minor canal. Key findings from the survey include variations in bed slopes affecting water flow and sediment transport and numerous unauthorized modifications by local farmers. Significant issues identified include the lack of flow control mechanisms, which leads to inefficient water distribution, and the canal's poor maintenance, evident from vegetation overgrowth, sediment buildup, and pollution from nearby residential areas. Additionally, the canal system suffers from substantial seepage losses, particularly in unlined sections, severely reducing water conveyance efficiency. Remedial actions such as regular watercourse maintenance have shown improvements in carrying capacity. This survey underscores the urgent requirement for systemic improvements and strict regulatory measures to enhance the functionality and sustainability of the canal infrastructure.

CHAPTER 4

CONVENTIONAL AGRICULTURAL AND IRRIGATION PRACTICES

4.1 Background

This chapter deals with the existing crop management practices at the farm level for the primary crops of the region, i.e., wheat and sugarcane. These practices encompass field preparation, sowing, fertilizer application, irrigation, and harvesting. A particular focus of this study is the analysis of irrigation practices aimed at enhancing irrigation efficiency. In the Gadarjudda canal command area, farmers cultivate more than one crop on the same field within a year, and the cropping intensity is 110%. The predominant crop rotations are paddy-wheat-sugarcane, paddy-wheat-berseem, and paddy-sugarcane-sugarcane, with paddy-wheat-sugarcane emerging as the most common sequence among local farmers. Fig. 4.1 illustrates the crop growth cycle for the mandated crops of the study area. It also includes detailed phenological calendars describing each crop's different growing stages. While the general crop calendar outlines several growth phases, each crop's specific phenological stage occurs during particular periods.

The phenological calendar for wheat and sugarcane spans key developmental stages across different months. Wheat's cycle starts with sowing in mid-November, followed by germination, and progresses through tillering and growing in the cooler months. It reaches maturity by the end of March and is ready for harvesting in mid-April. Sugarcane is planted two times a year and has a longer growth period. It goes through germination, tillering, and a prolonged growing phase during the warmer months, maturing later in the year, with the harvest typically occurring in the subsequent year, using the entire warm season for development.

Crops	Year ₁			Year ₂												Year ₃		
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Sugarcane (Early)					germination	Tillering	Growing					Maturity				Harvesting		
Sugarcane (Late)	Germination	Tillering		Growing					Maturity				Harvesting					
Wheat		Sowing	Tillering	Crown root initiation	Booting	Flowering	Grain Filling/Ripening	Harvesting										
Rice									Basal	Tillering	Panicle	Milky	Booting	Harvesting				

Fig. 4.1: Phenological crop calendar for mandate crop

4.2 Crop Management Details of the Wheat Crop

Initially, farmers' agricultural and irrigation practices were monitored to understand the timing, frequency, and volume of water applied to their crops. Soil moisture levels were regularly monitored, especially during irrigation events, where the flow rate and duration of water application were measured. In the year 2020-21 rabi season, within our experimental field in the area of 1928 m², farmers cultivated wheat. Before sowing, primary tillage was conducted using a tractor-drawn cultivator. The wheat variety HD-2967 was then broadcast sown at a seeding rate of 155 kg/ha on November 3, 2020. Fig. 4.2 depicts the experimental wheat field followed by the sowing operations.



Fig. 4.2: Bund making in wheat field

4.2.1 Fertilizer Application

During the sowing phase, the farmers incorporated specific fertilizers to provide the essential nutrients for wheat crops. Farmers applied Diammonium phosphate (DAP), a fertilizer rich in phosphorus and nitrogen, at a rate of 155 kilograms per hectare. This application ensures that the seedlings have access to the phosphorus needed for root development and early growth stages and nitrogen for leaf growth. Along with DAP, they added Sulphur fertilizer at 10 kilograms per hectare. Sulphur is crucial for protein synthesis and an essential component of certain plant amino acids. Topdressing with urea was carried out to further support the crop's nitrogen requirement, particularly high during the growth phase leading up to grain formation. Urea, a high-nitrogen fertilizer, was applied at 78 kilograms per hectare during the first and second irrigation events. This method of splitting the urea application is known as topdressing and is typically done to supply nitrogen in sync with the crop's growth needs.

4.2.2 Irrigation in Wheat Crop

Throughout the wheat growing season, farmers irrigated the crop three times. The initial irrigation occurred 23 days post-sowing, utilizing groundwater pumped from a private bore well. Subsequent irrigations utilized canal water, with the experimental plot being advantageously located at the head reach of the watercourse, where water availability is typically higher. Despite this, each irrigation event

saw the application of more than double the crop's actual water requirements, leading to significant losses.

The net and gross irrigation requirements were calculated using equations 4.1 and 4.2 to quantify water usage. The fixed percentage method has been used to calculate effective rainfall. As FAO recommended, the maximum root zone depth for the wheat crop is one meter. Detailed data regarding each irrigation event, including the amounts and timing, were systematically recorded and are presented in Table 4.1. Despite the excess water application, the overall field application efficiency, which indicates how much of the water applied is used by the crop, was calculated to be 48%. Furthermore, the overall irrigation efficiency, which considers conveyance efficiency and field application efficiency, was found to be 45.58%.

The daily soil moisture status, depth of irrigation supply, rainfall, and root zone depth throughout the crop period are shown in Figs. 4.3 and 4.4 visually represent the wheat field during one of the irrigation events, illustrating the irrigation practice. The data and images indicate chances to improve irrigation methods, which could lead to using less water and preventing wastage.

$$\text{Net Irrigation Requirement (NIR)} = \frac{(M_{fc} - M_{bi})}{100} \times \text{BD} \times D \quad (4.1)$$

Where,

$$\begin{aligned} M_{fc} &= \text{Field capacity moisture content, percent} \\ M_{bi} &= \text{Moisture content before irrigation, percent} \\ \text{BD} &= \text{Bulk density of soil} \\ D &= \text{Root zone depth, cm} \end{aligned}$$

$$\text{Gross irrigation Requirement (GIR)} = \text{NIR} / \text{Field Efficiency} \quad (4.2)$$

Table 4.1: Irrigation details in Wheat crop (Area=1928 m²)

S.No	Parameters	Irrigation		
		1 st	2 nd	3 rd
1	Date	26/11/2020	25/01/2021	27/02/2021
2	Day after sowing	23	83	116
3	Irrigation source	Groundwater Pumping	Canal	Canal
4	Effective rainfall	10.50	18.97	9.10
5	Net irrigation requirement	45.5	38.00	60.00
6	Recommended field application efficiency by FAO	60		
7	Gross irrigation requirement	77.38	64.63	102.04
8	Flow rate (l/s) diverted from source	30.43	40.00	39.00
9	Flow rate (l/s) delivered to the field	29.67	37.80	36.35
10	Conveyance Efficiency (%)	97.50	94.50	93.20
11	Duration of irrigation (min)	110	70	100
12	Irrigation applied (m ³)	195.82	158.76	218.09
13	Depth of irrigation (mm)	101.56	82.34	113.12
14	Field Application Efficiency (%)	44.80	46.15	53.04
15	Irrigation efficiency (%)	43.68	43.61	49.44

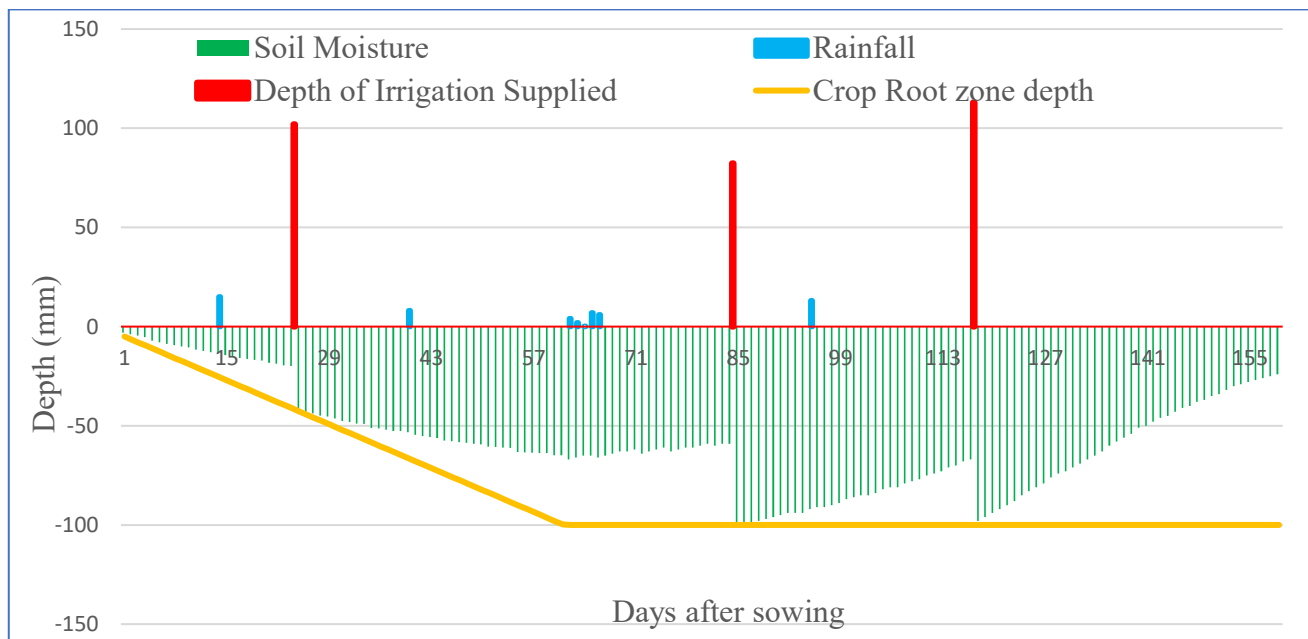


Fig. 4.3: Soil moisture, rainfall, and depth of irrigation



Fig. 4.4: Irrigated field

4.2.3 Yield and Yield Attribute of Wheat Crop

The farmers harvested the wheat crop after 160 days of the crop period, and Fig. 4.5 illustrates the harvesting practice. Yield data showed an outcome of 51.87 quintals per hectare, which is slightly below the average yield of the HD-2967 wheat variety, which is 53.10 quintals per hectare reported by Punjab Agriculture University, Ludhiana, as found in the study by Dhaliwal et al. (2014). Table 4.2 shows the different yield attributes of wheat crops as Crop Water Use Efficiency, as defined by Postel (1993), is the ratio of crop yield to the water consumed by the crop (Crop ET), which in this case is 20.52 kg/hectare/mm. Field Water Use Efficiency is the crop yield ratio to the total water applied in the field, calculated at 15.40 kg/hectare/mm for the wheat crop. Water productivity was determined to be 1.54 kg/m³, indicating the yield gained per unit of water used, showcasing the crop's efficiency.

$$\text{Crop Water Use Efficiency} = \frac{\text{Yield}}{\text{Crop Water Requirement (Crop ET)}} \times 100 \quad 4.3$$

$$\text{Field Water Use Efficiency} = \frac{\text{Yield}}{\text{Actual Water Used (Irrigation+Effective Rainfall)}} \times 100 \quad 4.4$$

Table 4.2: Yield attributes of wheat crop

S.No	Parameters	Value
1	Area (m ²)	1928
2	Yield (quintel/hectare)	51.87
3	Crop ET (mm)	253
4	Effective Rainfall (mm)	39
5	Irrigation Applied (mm)	297
6	Crop Water Use Efficiency (kg/hectare/mm)	20.50
7	Field Water Use Efficiency (kg/hectare/mm)	15.44
8	Water Productivity (kg/m ³)	1.54

4.3 Crop Management Details of Sugarcane

The farmers planted the sugarcane variety Co 0238, also known as Karan 4, in the field on September 18, 2020. Co 0238 recognized for its high yield and sugar content, is a product of selective breeding by the Sugarcane Breeding Institute's Regional Centre in Karnal. It was officially released for commercial cultivation in the North-West Zone (NWZ), which includes Haryana, Punjab, Western and Central Uttar Pradesh, Uttarakhand, and the Rajasthan Zone, in 2009.

In preparation for planting, the farmers engaged in meticulous field preparation, which involved two rounds of ploughing with a tractor for soil aeration and one round of leveling with a wooden block, traditionally pulled by bullocks. To ensure optimal plant growth and sugar yield, the farmers used a furrow opener attached to a tractor to maintain a precise row spacing of 1.18 meters. Fig. 4.5 illustrates the process of creating furrows specifically for sugarcane cultivation and the appearance of the field, showcasing the critical stages of the sugarcane planting process.



Fig. 4.5: Furrow making and transplanting of sugarcane

4.3.1 Fertilizer Application

During the sowing stage, the farmers employed a strategic approach to fertilization to ensure the crops received the essential nutrients necessary for robust growth. They applied Diammonium phosphate (DAP), a fertilizer that is an excellent source of nitrogen and phosphorus, at a rate of 130 kilograms

per hectare. In conjunction with DAP, they added potash, a key potassium provider, at 56 kilograms per hectare and a reagent at 19 kilograms per hectare to balance soil nutrients and enhance crop yield potential. During the irrigation phases further into the crop's lifecycle, farmers applied a topdressing of urea coupled with Sulphur at a calculated rate of 78 kilograms per hectare. Urea is a concentrated source of nitrogen, a crucial element for plant growth, while Sulphur is essential for enzyme activation and protein synthesis within the plant.

4.3.2 Irrigation in Sugarcane Crop

For the cultivation of sugarcane, the farmers applied a total of eleven irrigation applications for the entire crop period. By June 2021, nine of these had been carried out, after which ample rainfall occurred regularly, reducing the need for further irrigation. Following guidelines by the Food and Agriculture Organization (FAO), the maximum root zone depth for sugarcane is regarded to be 1.5 meters. This depth is critical as it defines the soil volume accessible to the plant's roots for water uptake. The comprehensive daily soil moisture profile, along with the specifics of irrigation supply, rainfall, and the root zone depth, are detailed in Fig. 4.6. The months from April to June particularly demanded more frequent irrigation due to higher temperatures and longer sunshine hours, which increase evapotranspiration. The specifics of each irrigation event, including timings and amounts, are given in Table 4.3. The first irrigation took place 37 days after the sugarcane planting, marking the commencement of the crop's water management schedule. While canal water was the preferred source for irrigation, its availability was inconsistent. As a contingency, groundwater was extracted from a private bore well on the field. The average application efficiency was recorded at about 49.53%. Figs. 4.7 and 4.8 show the various aspects of the irrigation process, depicting a tractor-operated pump and velocity measurements in the watercourse during irrigation.

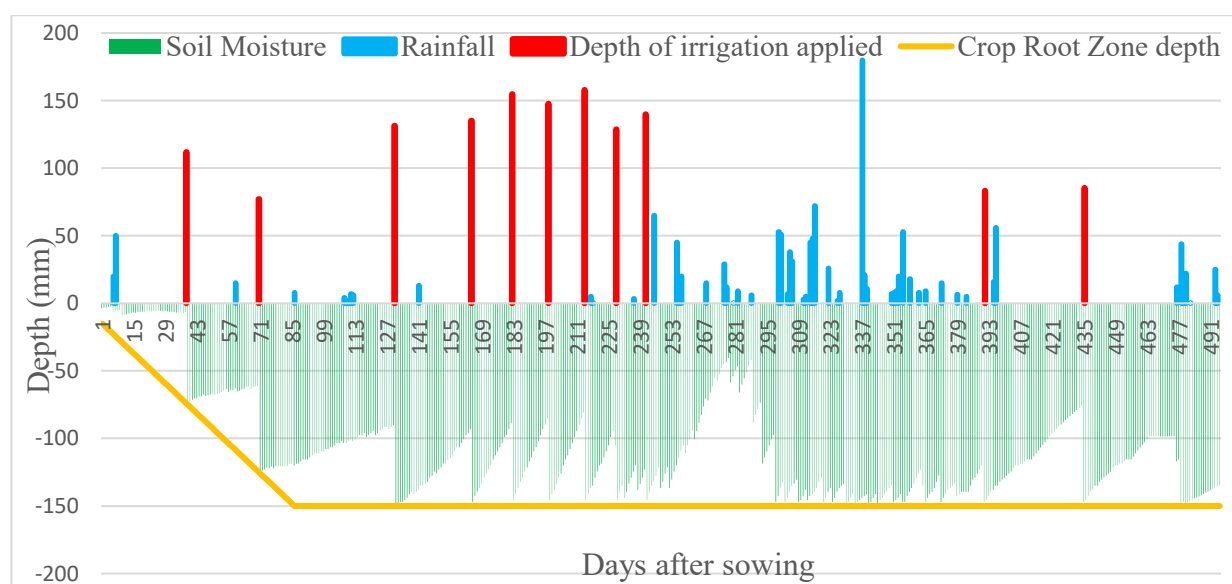


Fig. 4.6: Soil moisture, rainfall and depth of irrigation



Fig. 4.7: Tractor-operated pump and flow measurement



Fig. 4.8: Irrigated field

Table 4.3: Irrigation details of Sugarcane (Area=2699 m²)

S.No.	Parameters	Irrigation										
		1 st	2 nd	3 rd	4 th	5 th	6 th	7 th	8 th	9 th	10 th	11 th
1	Date	25/10/2020	26/11/2020	25/01/2021	28/02/2021	18/03/2021	03/04/2021	19/04/2021	03/05/2021	16/05/2021	13.10.2021	26.11.2021
2	Day after sowing	37	69	129	163	181	197	213	227	240	390	434
3	Irrigation source	Groundwater Pumping	Groundwater Pumping	Canal	Canal	Canal	Canal	Canal	Groundwater Pumping	Groundwater Pumping	Groundwater Pumping	Canal
4	Effective rainfall	49.00	10.50	18.97	9.1	0	0	0	3.57	2.31	707	50.4
5	Crop ET (mm)	72	45.00	77.37	78	68	72	77	72	70	479	63
6	Depth of irrigation requirement (soil moisture basis)	49.12	36	60.8	68	68	72	77	69	68	46	50
7	Recommended field application efficiency by FAO	60										
8	Gross irrigation requirement	83.54	63.16	106.67	119.30	119.30	126.32	135.09	121.05	119.30	80.70	87.72
9	Flow rate (l/s) diverted from source	29.53	30.43	40.00	39.00	38.00	35.00	30.00	28.00	27.00	37.00	35.00
10	Flow rate delivered to field	28.05	28.91	36.92	35.72	34.81	31.61	27.30	26.94	26.19	34.00	32.00
11	Conveyance Efficiency (%)	95.00	95.00	92.30	91.60	91.60	90.30	91.00	96.20	97.00	91.89	91.43
12	Duration of irrigation (min)	180	120	160	170	200	210	260	215	240	110	120
13	Irrigation supplied (m ³)	302.26	208.14	354.43	364.38	417.70	398.22	425.88	347.47	377.14	224.40	230.40
14	Depth of irrigation (mm)	112.00	77.13	131.33	135.02	154.78	147.56	157.81	128.76	139.75	83.15	85.37
15	Field Application Efficiency (%)	43.86	46.68	46.29	50.36	43.93	48.79	48.79	53.59	48.66	55.32	58.57
16	Irrigation efficiency (%)	41.66	44.34	42.73	46.13	40.24	44.06	44.40	51.55	47.20	50.84	53.55

4.3.3 Yield and Yield Attribute of Sugarcane Crop

The sugarcane was manually harvested after a substantial crop period of 490 days. This process involved the labor-intensive removal of leaves using a specialized sickle, ensuring that only mature cane has been collected for processing. The yield from the harvest was 100 tonnes per hectare. A previous study in the Hasanpur Sugar Mill area reported yields for the Co 0238 sugarcane variety ranging from 100 to 187.5 t/ha, highlighting the potential for improved yields with better irrigation and management practices (Government of India, Ministry of Consumer Affairs, 2013).

The efficiency of water use during the crop's growth period is quantified through two specific metrics as defined by Postel (1993). Table 4.4 shows the different yield attributes of sugarcane crops. Crop Water Use Efficiency is the yield obtained relative to the crop's evapotranspiration (Crop ET), which was 82.10 kilograms per hectare per millimeter for a sugarcane crop. Field Water Use Efficiency compares the yield with the total volume of water applied to the field, calculated to be 45.38 kilograms per hectare per millimeter for a sugarcane crop. Moreover, water productivity, which indicates the yield per unit of water used, was measured at 4.54 kilograms per cubic meter.

Table 4.4: Yield attributes of sugarcane crop

S.no.	Parameters	Values
1	Area (m ²)	2699
2	Yield (quintel/hectare)	1000
3	Crop ET (mm)	1218
4	Effective Rainfall (mm)	851
5	Irrigation Applied (mm)	1353
6	Crop Water Use Efficiency (kg/hectare/mm)	82.10
7	Field Water Use Efficiency (kg/hectare/mm)	45.38
8	Water Productivity (kg/m ³)	4.54

4.4 Conclusions

This study explores crop management practices for wheat and sugarcane in the study area, covering field preparation, sowing, fertilization, irrigation, and harvesting. It evaluates flood irrigation efficiency on farmers' fields, finding an average efficiency of 46% for both crops. The primary cause of low efficiency is excessive water application due to improper irrigation scheduling, leading to significant deep percolation losses beyond the root zone.

CHAPTER 5

DEVELOPMENT OF IoT-BASED SMART IRRIGATION SYSTEM

5.1 Internet of Things (IoT) in Agriculture

The network of physical objects, or "things," embedded with sensors, software, and other technologies to communicate and exchange data with other devices and systems through the Internet is known as the Internet of Things (IoT). Data can be collected and exchanged by these objects. An IoT network can empower farmers to be aware of these types of advanced technology to overcome enormous monitoring and labour crisis (Pramanik et al., 2022). The physical components that carry out the task, such as closing and opening valves and gates in response to water demand, are sensed, processed, communicated with, and actuated by an IoT-based irrigation system (Sales et al., 2015). This automation enables real-time data monitoring with the help of sensor nodes or wireless sensor networks (WSN). It can also operate with drip and sprinkler irrigation systems. Implementing smart things such as IoT in the irrigation management system has many benefits, but there are still some challenges. The biggest challenges IoT in agriculture faces include a lack of information, high adoption costs, security issues, etc. (Ojha et al., 2021).

To overcome the farmers' challenges, an IoT-based smart irrigation framework has been developed in this study that gathers information related to the soil parameters such as soil moisture and soil temperature. In this approach, an IoT-based architecture is developed for real-time irrigation monitoring at actual field conditions. This study presents a significant contribution to designing and testing a wireless sensor network, achieving the crucial objectives of reactivity, robustness, and prolonged network lifetime.

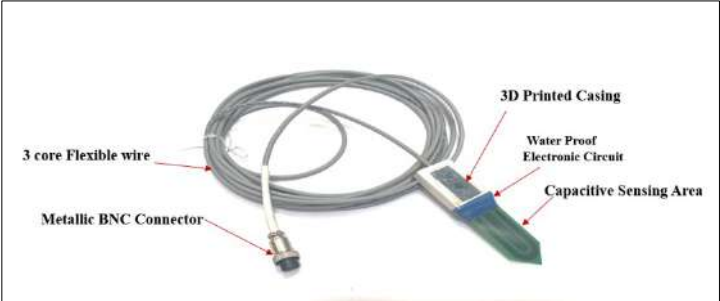
5.2 PCB-Based Capacitive Soil Moisture and Soil Temperature Sensor

Temperature and soil moisture play major roles in controlling the flow of water and heat energy between the atmosphere and the ground surface through evaporation and crop activity (Amiri et al., 2022; Jackson et al., 2008). A capacitive soil moisture sensor comprises two metallic surfaces separated by a dielectric material. When powered, it accumulates electrical energy within an electric field. The capacity to store this energy is termed capacitance, as defined by Eq. 5.1 (Chung, 2023).

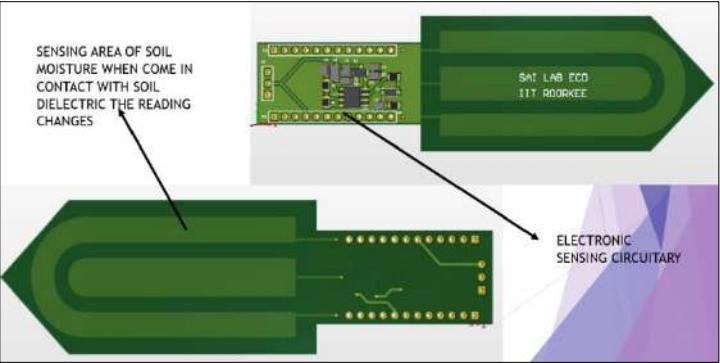
$$C = \epsilon_0 k \frac{A}{d} \quad (5.1)$$

where C = capacitance, ϵ_0 = electrostatic permittivity of the surroundings, k = dielectric constant, A = surface area of metal, d = the separation of two metallic surfaces.

In this study, Fr4 capacitive-based soil moisture sensors were developed, evaluated, and calibrated for agricultural fields. These sensors can be either fixed or movable, like handheld probes. Fig. 5.1 (a) and (b) show the capacitive soil moisture sensors developed in the Department of Electronics and Communication Engineering, IIT Roorkee (SAI Lab ECD). The Fr4 capacitive sensors measure variations in the analog output within the 0.60 to 5 volts range. An in-built Analog-to-Digital Converter (ADC) in the microcontroller was employed to convert the analog values into digital readings. The ADC operates with a 5V DC input voltage, facilitating the conversion of analog signals into digital data for further processing and analysis. This configuration makes it possible to record and use exact digital readings from the Fr4 capacitive sensors, thereby improving the sensitivity and dependability of the data gathered.



(a)



(b)

Fig. 5.1: (a) Developed capacitive soil moisture sensor in the lab with three core flexible wires, and
(b) Internal circuit diagram of a sensor

Table 5.1: Technical Features of designed Capacitive Soil moisture Sensor

Running Voltage	3.2 - 5.25 VDC
Output Voltage	0- 4.0 VDC
Operating Current	5 mA
Configuration	3-pin BNC Interface
Size, mm (L×W×H)	97×22×5
Weight (gm)	25 gm (without wire)
Accuracy	±0.3% for volumetric water content, θ from 0 to 0.50 m ³ m ⁻³
Sensor Output	Analog and PWM
Frequency	100 MHz

Table 5.1 shows the technical features of the designed capacitive soil moisture sensor. It accurately detected changes in moisture levels with a high level of precision, providing an accuracy of $\pm 0.01\%$. This sensor can withstand high temperatures of up to $+70\text{ }^{\circ}\text{C}$, making it suitable for diverse environmental conditions. It offers two versions of sensor output: analog and pulse-width modulation (PWM), providing flexibility in data acquisition and integration with different systems. One of the notable advantages of this sensor is its affordability, as it is 18 times cheaper than other industry-grade sensors available in the market. In this design, the PWM was used. In this study, Fr4 board and ESP32 microcontroller have been utilized. The designed capacitive sensor integrates an ID-FF (Interdigital Fringe Field), and the copper layer in the PCB and the Fr4 board is kept at a thickness of 1.5 and 0.07 mm, respectively. This makes it a cost-efficient option for agricultural applications, enabling wider accessibility for farmers. The sensor's overall Printed Circuit Board (PCB) is fabricated in a four-layer design, ensuring efficient signal transmission, reduced interference, and improved performance (Shamkhalichenar et al., 2020). Fig. 5.2 shows a four-layer visualization of the PCB. This multilayer PCB design enhances the reliability and stability of the sensor. An effective capacitive soil moisture sensor operates using a minimal power supply within the 3.2–5.25 VDC voltage range that suits battery-operated devices and solar panels for renewable energy. Farmers in remote rural areas who lack sufficient energy access will find this solution suitable. It has 4.0 VDC output range compatibility and supports all data collection platforms, which fits different monitoring devices and IoT-based irrigation systems. Using this feature, farmers can control their irrigation systems and monitor soil moisture levels in the field. The secure 3-pin BNC interface benefits users because it supports quick system installation and trouble-free maintenance. The simple setup design helps farmers who lack technical background operate this equipment. The lightweight design of sensors is helpful to the farmers for deploying sensors in their field area without harming the ground structure. Users can integrate the sensor into monitoring and control systems through its dual output mechanism of analog and pulse width modulation signals. Soil monitoring accuracy, improved irrigation techniques, and

enhanced decision-making capabilities emerge from these technical features, as shown in Table 5.1, to enhance resource management.

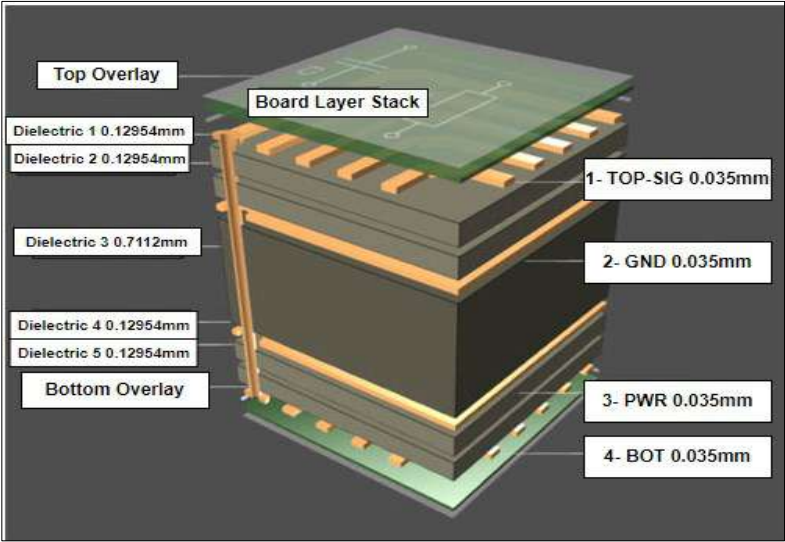


Fig. 5.2: Four-layer visualization of PCB (Shamkhalichenar et al., 2020)

Soil temperature is a key factor in soil parameters. In this study, DS18B20 Waterproof temperature sensors were used for the soil temperature measurements (Fig. 5.3). Due to its simplicity and cost-effectiveness, the combination of the DS18B20 Water-resistant temperature sensor and Arduino has been widely adopted as a kind of data acquisition (DAQ) system for soil temperature assessment (Koestoer et al., 2019). If the sensor is precisely calibrated, the Arduino can function as a reliable data-gathering device (Matijevic and Cvjetkovic 2016). The DS18B20 Waterproof sensor measure temperature within a wide range from -55 °C to +125 °C (Mahardika and Gunawan, 2022). Within the -10 °C to +85 °C temperature range, it offers an accuracy of 0.5 °C. In addition, it provides a high level of precision, including correctness of 0.0625 °C.

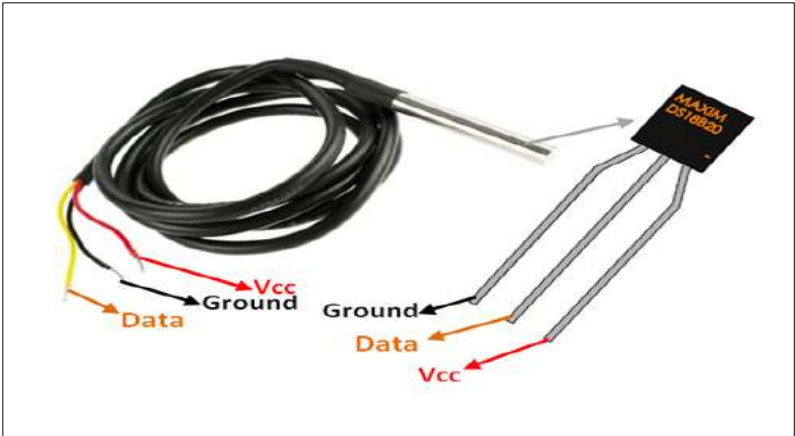


Fig. 5.3: DS18B20 temperature sensor

5.2.1 Testing and Performance Evaluation of Sensors

The capacitive soil moisture sensor was tested by comparing it with standard gravimetric procedures, which are well known for their precision in determining soil moisture content (Hrisko, 2020; Leib et al., 2003). Following standard procedures, soil samples were collected from the experimental field using an auger at various depths (15, 30, 45 cm) from the ground surface. These samples were placed in airtight aluminum cans and weighed both before and after drying in an oven at 105 °C for 24 hours.

There are the following steps for calibration of sensors-

1. Preparation: Take 1 kg of oven-dried soil and add 5% water, ensuring proper mixing.
2. Sensor insertion: The soil moisture sensor was inserted accurately into the soil, and the corresponding voltage readings were recorded.
3. Increasing water content: 5% water was added to the soil and thoroughly mixed. The corresponding soil moisture sensor readings were recorded in terms of voltage.
4. Repeat for various water content levels: Following the same procedure as in step 3, the water content was increased to 15%, 20%, 25%, and 30%. The corresponding moisture content values for the voltage, scale, or appropriate metric were recorded.

Fig. 5.4 shows the sensor nodes, soil samples, and data display unit. Eq. 5.2 can be utilized to compute the soil moisture content (SMC) on a dry basis-

$$SMC = \frac{W_w - W_d}{W_d} \times 100 \% \quad (5.2)$$

The performance evaluation of each sensor was conducted using statistical parameters to compare the moisture measurements with the gravimetric method (GM) (Muzdrikah et al., 2018). The Mean Difference (MD) was used to compute the average difference between sensor data and related GM measurements. Eq. 5.3 gives an expression for this.

$$MD = \frac{\sum_{i=1}^n (M_{si} - M_{gi})}{n} \quad (5.3)$$

where M_{si} = the i^{th} measurement obtained by a sensor, M_{gi} = the i^{th} measurement obtained using the gravimetric method, and n = the number of samples.

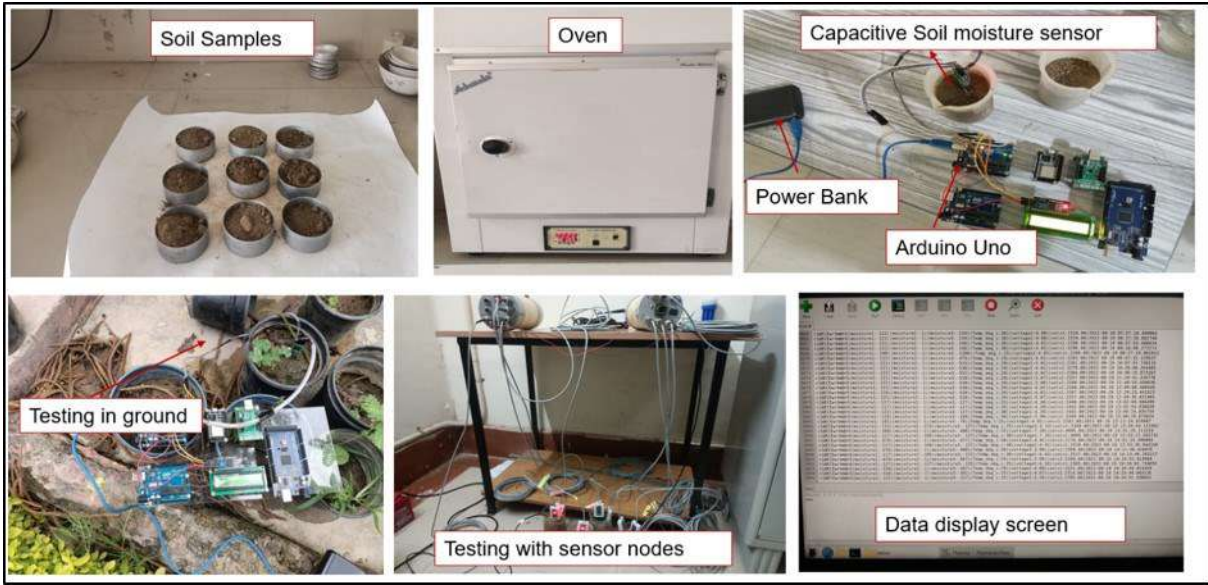


Fig. 5.4: Soil Samples and testing of a developed capacitive soil moisture sensor

The entire variation, represented as a percentage of the mean gravimetric measurement value, between the sensor value and the gravimetric measurements of soil moisture content. Eq. 5.4 was used to determine the relative root mean square error (RRMSE).

$$RRMSE = \sqrt{\left[\sum_{i=1}^n (M_{si} - M_{gi})^2 \right]} \times \frac{100}{M_g} \quad 5.4$$

where M_g = the corresponding mean of the gravimetric measurement was calculated by Eq. 5.5.

$$M_g = \frac{1}{n} \sum_{i=1}^n M_{gi} \quad 5.5$$

By computing the relative error (Re) between the values measured by the sensor (M_{si}) and the actual values obtained from the gravimetric method from soil sample (M_{gi}), the stability of the sensor's output was assessed. The relative error (Re) was ascertained by applying Eq. 5.6.

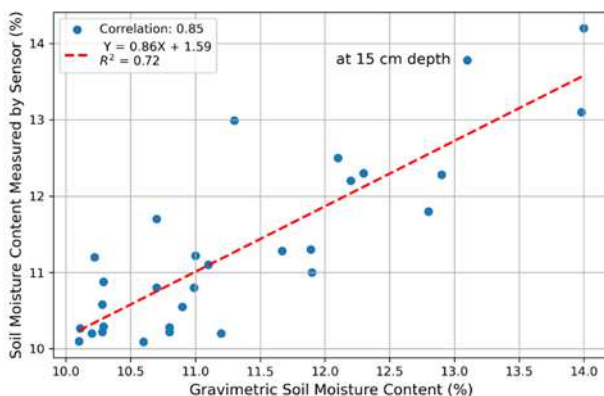
$$Re = \frac{(M_{gi} - M_{si})}{M_{gi}} \times 100 \% \quad 5.6$$

Using the coefficient of determination R^2 , the degree of similarity between sensors and gravimetric data was calculated. The sensors perform better, as indicated by MD and RRMSE values near zero (Gao et al., 2018). A paired t-test was utilized to calculate the average difference between calibrated sensors.

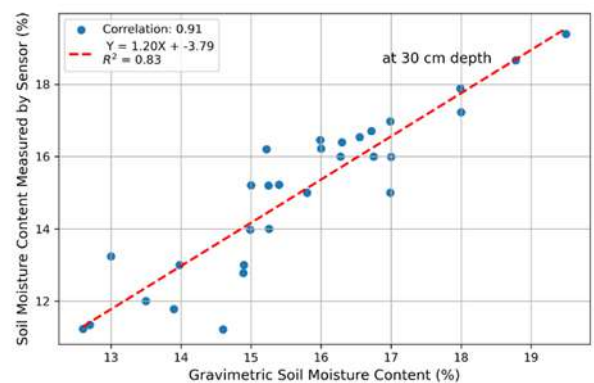
5.2.2 Performance Analysis

After successfully testing the capacitive soil moisture sensors, these were installed at different depths within wheat and sugarcane plots. By establishing a regression relationship between the sensor values and traditional gravimetric soil moisture measurements, a comparative analysis was conducted to assess the capacitive sensors' performance. This investigation enabled us to evaluate the precision and reliability of the capacitive sensors in accurately determining soil moisture levels at various depths in the agricultural plots. Fig. 5.5a, b, and c, at depths of 15, 30, and 45 cm, respectively, show the regression relationships between SMC, as determined through the standard gravimetric approach, and the capacitive soil moisture sensors installed at various depths in the wheat crop. The coefficient of determination (R^2) values for these sensor depths were 0.72, 0.83, and 0.83, respectively. Similarly, Fig. 5.6a, b, and c display the regression relationships between SMC and the capacitive soil moisture sensors installed at the same depths (15, 30, and 45 cm) in the sugarcane crop. The corresponding R^2 attributes for these depths were 0.66, 0.75, and 0.82, respectively. The highest regression was found at 30 and 45 cm depths in wheat crop and at 45 cm depth in sugarcane crop for loamy soil.

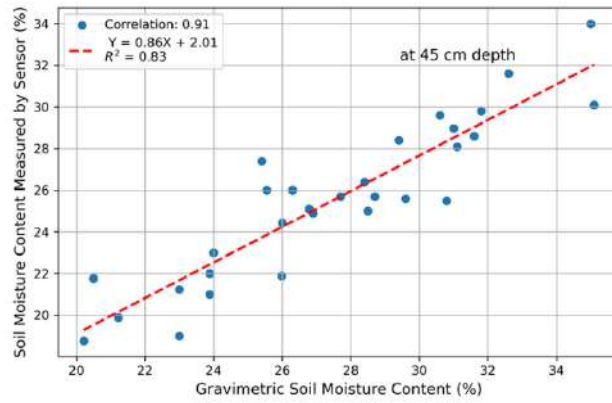
Sugarcane is typically grown in well-drained soils, but soil heterogeneity at specific depths (15 cm, $R^2 = 0.66$) can disrupt uniform water distribution and sensor accuracy. Sugarcane has deep roots, and uneven root penetration can create localized moisture gradients, reducing the predictability of moisture content at specific depths. If sensors are placed too far from the root zone or near irrigation lines, they may not capture typical soil moisture variations, leading to lower R^2 values. Factors such as temperature fluctuations, evaporation rates, and rainfall distribution can affect soil moisture levels differently at varying depths. Sugarcane is sensitive to moisture changes, and inconsistent rainfall patterns or high evapotranspiration rates can create depth-specific variations in soil moisture. The non-uniform moisture distribution in deeper soil layers may cause inconsistencies in sensor measurements and lower regression values.



(a)

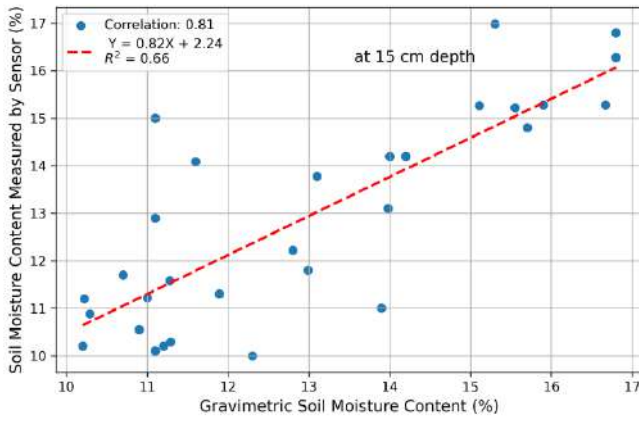


(b)

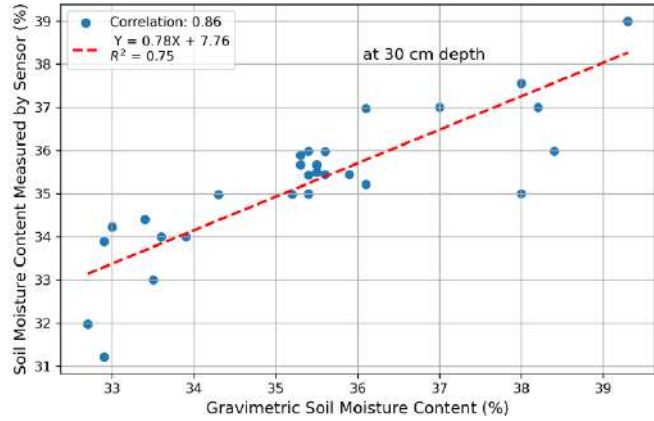


(c)

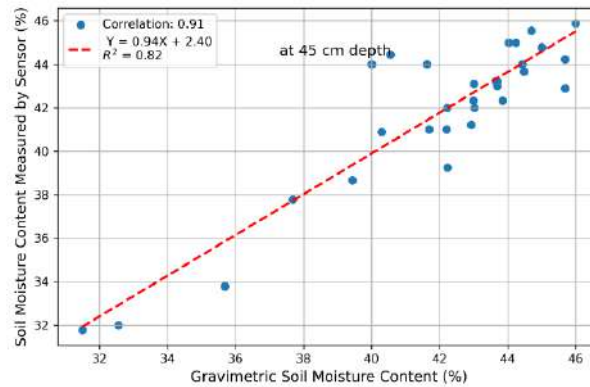
Fig. 5.5: Correlation between the SMC measured by the capacitive soil moisture sensor and the usual gravimetric method for the Wheat crop (a) At a depth of 15 cm, (b) 30 cm, (c) 45 cm



(a)



(b)



(c)

Fig. 5.6: Correlation between the SMC measured by the capacitive soil moisture sensor and the usual gravimetric method for Sugarcane crop (a) At a depth of 15 cm, (b) 30 cm, (c) 45 cm

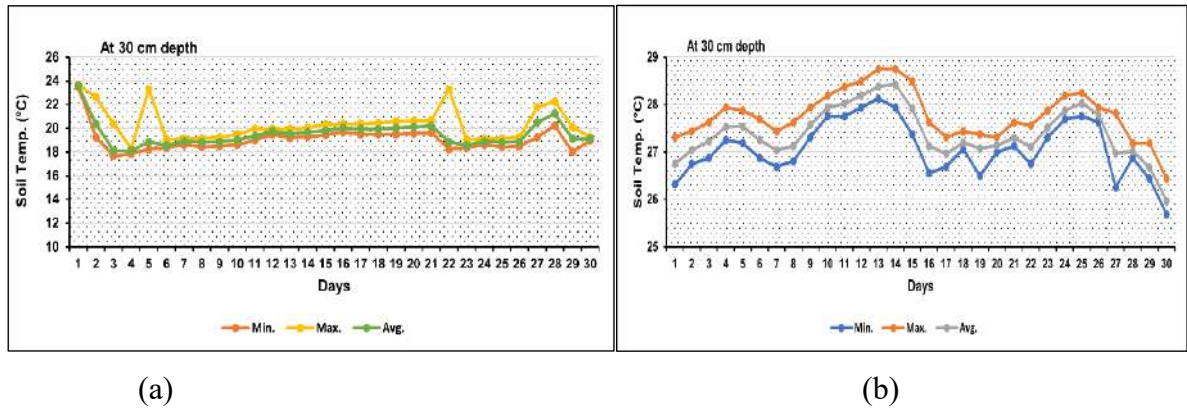


Fig. 5.7: Performance of soil temperature sensor at the field (a) at the wheat crop (b) at the sugarcane crop

These findings demonstrate the significant correlation between the readings from the capacitive sensors and the gravimetric measurements of soil moisture content at various depths. Fig. 5.7a and b shows the performance of soil temperature sensors at 30 cm depth. The proposed, designed capacitive sensor indicated a maximum relative error (Re) of 5.87% for the wheat crop, and it was less than 5% for all soil depths except 45 cm, as shown in Fig. 5.8a. Similarly, the maximum relative error (Re) was 5.22% for the sugarcane crop at 15 cm soil depth, as shown in Fig. 5.8b.

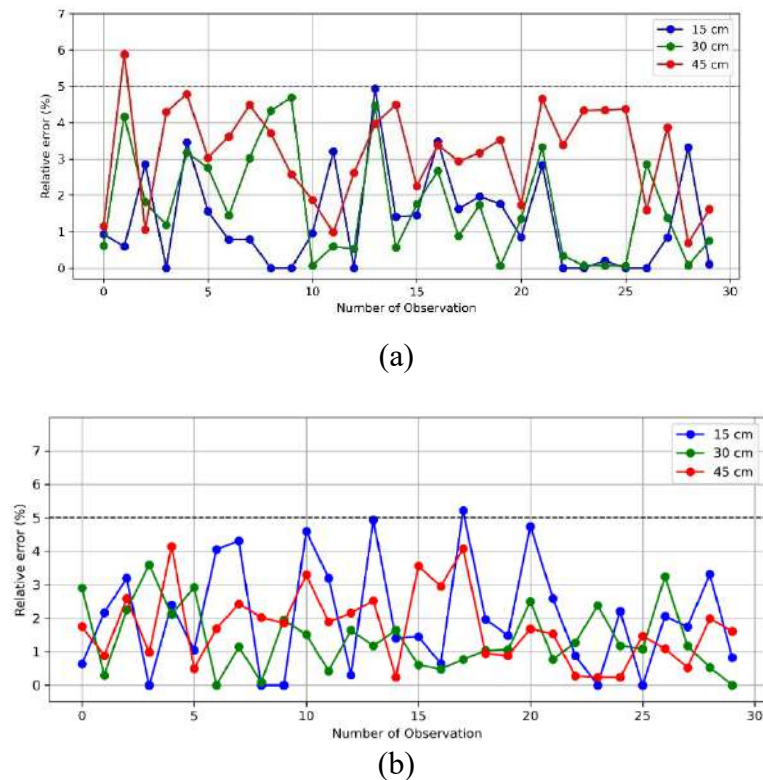


Fig. 5.8: Relative error (a) Wheat crop (b) Sugarcane crop at different depths

In Table 5.2, the average relative error has been evaluated within the number of observations. These results suggest that the proposed sensor's measurement accuracy is comparable to that of the

gravimetric approach, meeting the requirements for agricultural applications (Mittelbach et al., 2012). The performance summary is presented in Table 5.2, providing an overview of the overall performance of the capacitive sensors in estimating soil moisture content. The statistical significance of the capacitive soil moisture sensor was assessed utilizing a paired t-test with a significance level of 5% (p-value 0.05) (Kumar et al., 2022; Rowlandson et al., 2013).

Table 5.2: Performance Analysis of Capacitive Sensors at different depths

Sensor	Crop	Depth (cm)	MD	RRMSE	Intercept	Slope	Re (%)	R ²
Capacitive-based soil moisture sensor	Wheat	15	0.04	19.91	1.58	0.856	1.32	0.72
		30	0.69	9.15	-3.55	1.184	1.69	0.83
		45	1.96	7.95	2.01	0.855	3.14	0.83
	Sugarcane	15	0.01	14.16	2.19	0.829	2.04	0.66
		30	0.18	5.87	7.76	0.770	1.38	0.75
		45	0.02	8.28	2.39	0.937	1.73	0.82

The findings are shown in Table 5.3, indicating a significant discrepancy between measurements obtained with the capacitive-based soil moisture sensor and the gravimetric approach in wheat and sugarcane crops at depths of 15, 30, and 45 cm. Since the obtained p-values were less than 0.05. The findings indicate that the capacitive soil moisture sensor provides distinct and meaningful information about soil moisture levels at various depths in wheat and sugarcane crops, offering valuable insights for irrigation management and crop performance assessment. The comparative analysis between the proposed sensors and the gravimetric method indicated that the relative error at a depth of 45 cm was higher than those recorded at 15 cm and 30 cm depths for wheat crops. This discrepancy is attributed to the possibility of higher soil moisture levels at the 45 cm depth compared to the topsoil layers. A similar trend was observed for the sugarcane crop at a depth of 15 cm. This may be attributed to the proximity of the 15 cm soil layer to the surface, leading to a higher temperature in the topsoil compared to deeper layers at the testing time. The coefficient of determination (R²) of the regression equation between measured and fitted values indicated favourable outcomes, except for the 15 cm soil depth in the sugarcane crop.

Table 5.3: Paired t-test of the capacitive soil moisture sensor and the gravimetric method's soil moisture content

Sensor	Crop	Depth (cm)	Mean	Df (Degree of freedom)	t-value	P(T<=t) two-tail
Capacitive-based soil moisture sensor	Wheat	15	11.37	28	0.398	0.69
		30	15.67	28	-3.22	0.004
		45	27.52	28	-5.01	0.0016
	Sugarcane	15	12.87	28	0.582	0.95
		30	35.61	28	-3.07	0.007
		45	42.28	28	-2.18	0.001

5.3 Overview of Designed IoT-Based Irrigation System

Before delving into the detailed system architecture design, a brief overview and explanation of its overall operational functions are provided. The proposed system specifies a comprehensive operational framework within a standalone IoT-based architecture, comprising distinct sub-architectural layers, defined as sensing, edge server, and cloud. The sensing layer encompasses multiple data acquisition nodes, and sensors are strategically installed across an agricultural field. The primary function of this layer is to procure field-specific data, such as soil moisture and temperature, utilizing data acquisition nodes. These nodes assist the data transmission through protocols like Zigbee, LoRa, or Bluetooth to the edge layer. The edge layer integrates servers designed to receive data from the sensing layer. This layer is crucial for systematically storing the acquired data in a database and coordinating automated irrigation practices. Upon receiving data, the edge server promptly compares it with predefined threshold values of soil moisture. The edge layer utilizes internet gateways such as TCP/IP, UDP, or MQTT to transmit this data into the cloud. The cloud server contains servers and databases and is responsible for data analysis. After receiving the data, it is thoroughly analyzed, and historical data is kept in databases like SQL, PostgreSQL, or Storage web code. Additionally, the cloud server encompasses software for building an Android application. Users can install these applications on their mobile devices, providing a user-friendly interface that is combined with analytics. Fig. 5.9 shows the overview of the WSN-based irrigation scenario.

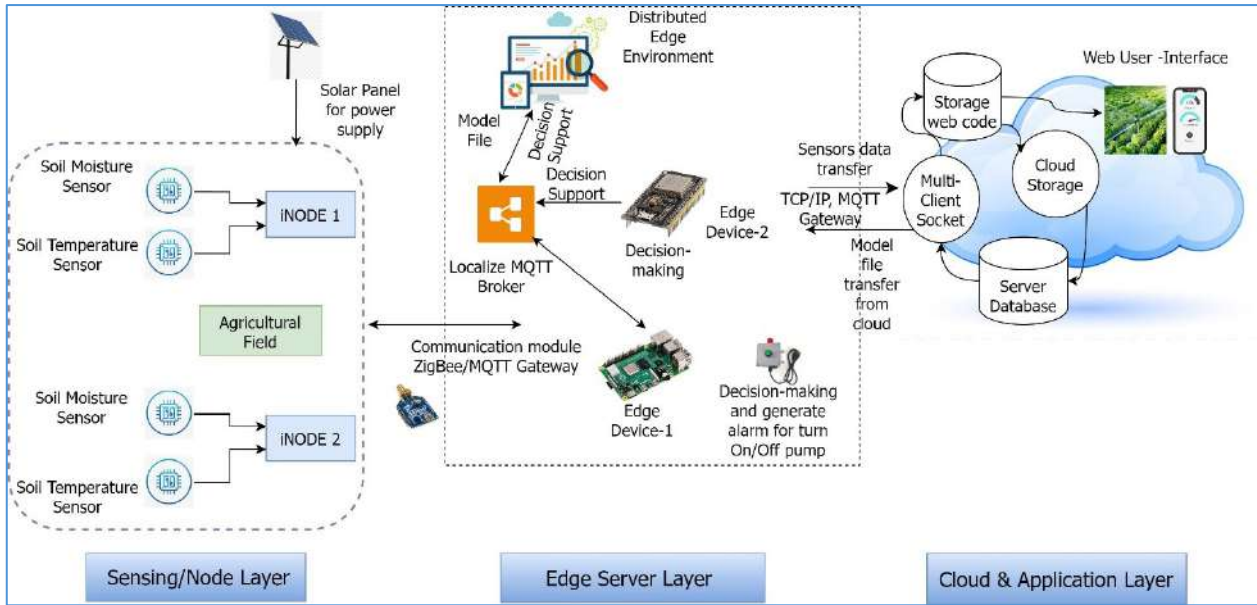


Fig. 5.9: IoT-based architecture operation scenario for irrigation monitoring.

5.4 Architecture Design of IoT-Based Irrigation System

5.4.1 Sensing/Node Layer

For irrigation applications, this layer consists of advanced sensors like soil moisture, soil temperature, humidity, as well as data acquisition controllers (such as the ESP-32 microcontroller) and interfaces to connect various communication modules (e.g., LoRa, ZigBee, Wi-Fi, etc.). The combination of these three components constitutes an IoT node/sensor node. In this study, only soil moisture and soil temperature sensors were utilized. These IoT nodes acquire contextual information using embedded heterogeneous sensors and offload the data to nearby available edge devices in a distributed edge environment. The hardware component of this layer is mainly focused on the IoT node, which is the core element of this module. The continuous collaboration and interoperability of sensor nodes' hardware and software components, which operate perfectly harmoniously, are essential to their efficient operation. The necessary hardware components for the device's operation include a module for communication, power circuits, general-purpose input-output (GPIO) interface channels, and microcontroller units (MCUs). On the other hand, the software is necessary for managing various tasks, such as data aggregation and energy optimization, to ensure that the node uses its power effectively. Together, the hardware and software elements build a reliable and effective system that successfully enables the sensor node to carry out its intended functions. Fig. 5.10 illustrates the sensor node hardware and software components architectural framework.

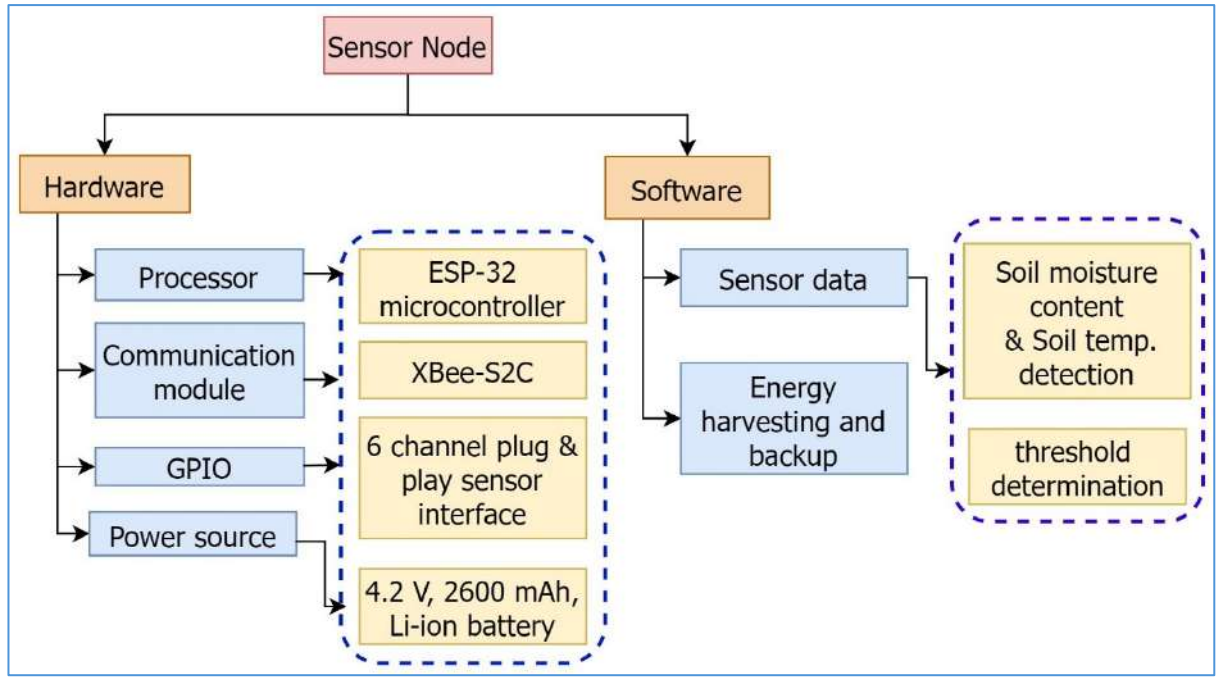


Fig. 5.10: The Sensor node architectural framework.

A. Hardware Design of Sensing Node layer

The hardware architecture of the sensing node layer design is shown in Fig. 5.11. The Xtensa dual-core 32-bit Fire Beetle ESP32-wroom MCU serves as a foundation for an IoT node (Hirsch et al., 2019). The inexpensive and energy-efficient node MCU FireBeetle-ESP32 has been selected. The ZigBee derivative, XBee-S2C trans-receiver (Roy et al., 2020), provides a 1.2 km data transmission range communication interface for information exchange between the edge server and the data acquisition nodes. ZigBee technology is well-suited for a wide range of IoT applications because of its low power requirements (Savić and Radonjić, 2018). ZigBee was selected over other low-power wide-area network technologies, such as LoRa, due to its superior data packet reliability, with a packet loss rate of approximately half that of LoRa devices (Karnjana et al., 2022). This makes it well-suited for real-time soil moisture monitoring applications (Mahbub, 2020).

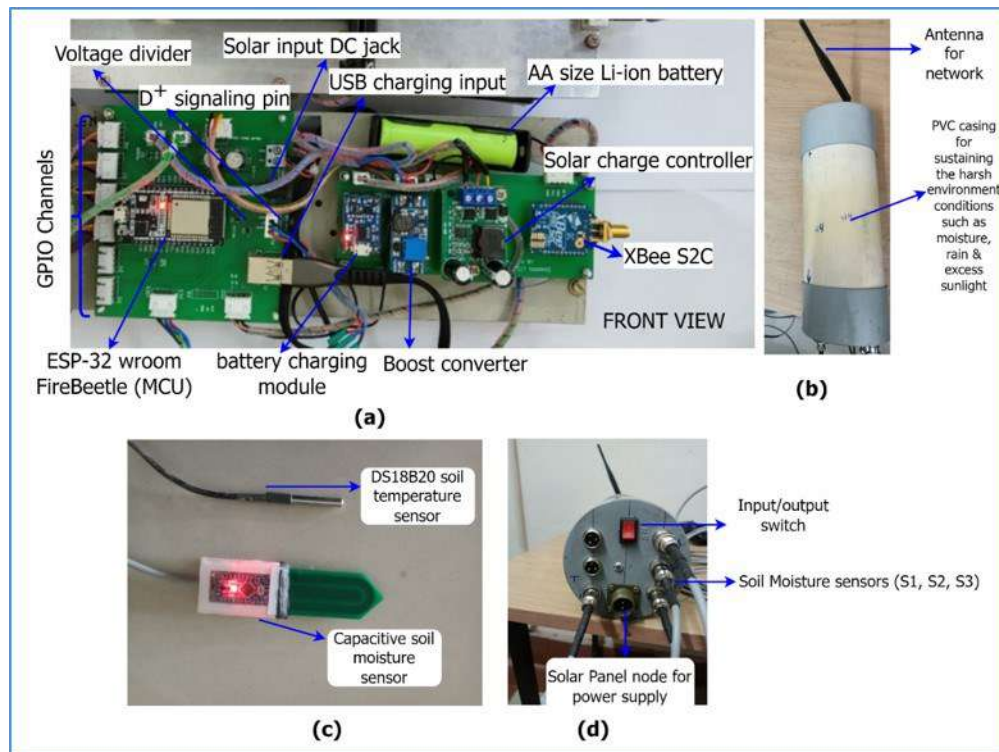


Fig. 5.11: Sensor Node (a) Front view of the designed hardware (b) PVC casing of PCB (c) Sensors (d) GPIO channels functions.

The sensor node operates on a 2600 mAh 4.2V rechargeable AA-size Li-ion battery power supply system. The battery can be charged using a solar charge controller through a USB interface. The Li-ion battery gathers solar energy from the solar panel installed at the top of the node. The voltage divider circuitry monitors the Li-ion battery's power status. There are six GPIO channels available in each node. It specifies that six sensors may be integrated simultaneously into one sensor node. The buck and boost voltage regulators are responsible for acquiring the variable power needs of each integrated module within the node. The connection of sensors and other components on the board is facilitated through plug-and-play connectors. These connectors enable fast replacement of the damaged sensors and other hardware parts when required. To detect the variation in soil moisture content, a capacitive-based moisture sensor and for monitoring soil temperature, a DS18B20 soil temperature sensor is interfaced within the node to conduct the study. A PVC pipe case has been used to secure the waterproofing of the node PCB, as seen in Fig. 5.11 (b). This PVC casing has a 90 mm diameter plastic circular pipe. The purpose of adopting PVC pipe is that it is corrosion-resistant, lightweight, and convenient for farmers or users to easily handle and install the device in agricultural applications. The complete design of the hardware, including soil moisture, soil temperature sensors, and GPIO channel functions, is shown in Fig. 5.11.

B. Software Design of Sensing Node

The designed sensor node, interfaced with three soil moisture and one soil temperature sensor, is installed at a farmer's field. It receives soil parameters every 20-minute interval from the sensors vertically installed in the irrigation field and transmits them to the edge server via a Zigbee communication module. It aims to continuously gather and transmit real-time information on soil moisture and temperature and send it to an edge device. The module software operates in active and sleep mode. These modes are specifically designed to enhance the longevity of the nodes and ensure robust integration with their environment. In the active mode, the power is ON from sleep mode to initialize all its hardware components, including the MCU. Subsequently, after the hardware components are initialized, the node proceeds to initialize the sensors and activate their power. In the active mode, the interfaced sensors collect the following data:

- 1) Using the capacitive soil moisture sensor, determine the soil moisture values.
- 2) Using the soil temperature sensor, the soil temperature values ($^{\circ}\text{C}$) are given.

After the acquisition of sensor data, the ESP-32 MCU reads the data, and the nodes activate the power supply to the XBee-S2C module. During this stage, the node also deactivates the power supply to the sensors after receiving the data. The data received is then transmitted to the edge gateway/server via the XBee-S2C communication module. The node turns off the ZigBee module and radio after the data transfer. Furthermore, the nodes monitor the voltage level of its Li-ion battery; if the voltage falls below the predefined threshold, it initiates the battery's charging process. Before entering sleep mode, the node analyzes the irrigation requirements by evaluating the acquired sensor values. It continues to awaken at regular intervals, repeating this process every 20 minutes.

5.4.2 Edge Server Layer

This layer is responsible for managing the data received from the IoT nodes (Jiaxing et al., 2018). The overall design operates as follows: When a node is powered on, it connects to the network established by the coordinator/edge server, obtains a short address, and transmits its identification to the coordinator. Additionally, nodes from the irrigation field initiate data collection at intervals of 20 minutes. The node enters sleep mode once the data packets are transmitted to the coordinator. The coordinator/edge analyzes the received packets and, based on predefined thresholds, checks whether irrigation is required or not.

A. Hardware Design of Edge Server Layer

Fig. 5.12 shows the edge layer's hardware design. In the design of the WSN system, this layer includes hardware components such as the Raspberry Pi 4 (Model B), XBee-S2C, a Solar charge controller, a 7 Ah battery, and a 20 W solar panel, as depicted in Fig. 5.12. The Raspberry Pi 4 integrates a 64-bit

quad-core Cortex-A72 ARM v8 processor with a Broadcom BCM2711 chipset, two USB 3.0 ports, two USB 2.0 ports, a gigabit Ethernet port, and a micro-SD with a speed of 1.5GHz (Gamess and Hernandez, 2022). The Raspberry Pi stores its operating system (OS) and software data on an SD card instead of its internal storage. In this design, the Raspberry Pi gathers sensor values via ZigBee wireless communication modules equipped with antennas and displays them on a webpage or PC. A USB-to-UART bridge IC is employed via USB to transmit output data to the PC. Its primary responsibilities include managing the operation and communication schedule of the entire WSN system and processing the collected data. In this system, a 7Ah battery serves as the DC power source for the edge server. A 20 W solar panel regularly charges this battery. This server stores the data in a 64 GB SD card and then transmits it to a distant computer for examination through a 4-G modem (Wi-Fi).

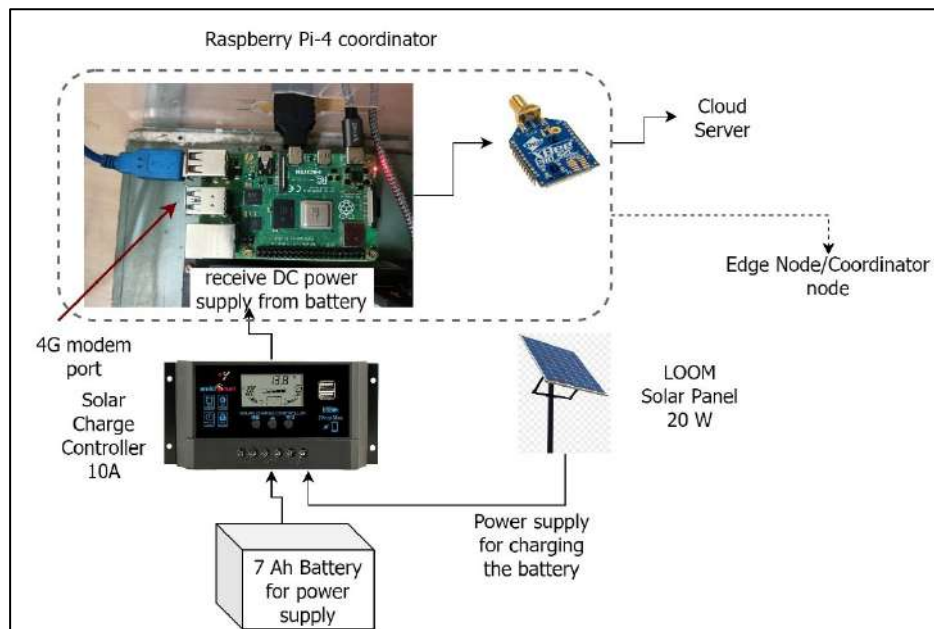


Fig. 5.12: Hardware components of edge server layer

B. Software Design of Edge Server Layer

The software design of the edge server layer is shown in Fig. 5.13. This design offers user-friendly management options for WSN, allowing configuration adjustments to optimize its performance. Subsequently, the data is recorded into a file stored on the SD card, located within an edge server, and transmitted to a cloud server via the internet. While gathering information from the numerous end nodes placed throughout the specific agricultural field, the nodes use the Zigbee-S2C communication device to send the information (soil moisture content) to the edge server node. The edge coordinator operates a small server and keeps a database of the crop's required soil moisture and temperature levels. Additionally, it can control the opening and closing of the water supply pump. A Message Queuing Telemetry Transport (MQTT) v5 broker establishes a connection between the edge devices

and the shared repository through a distributed local network. The module uses MQTT as a gateway between edge devices since the edge devices run on batteries, which lowers power usage. Furthermore, every edge device has a LoRa/ZigBee module to link the end nodes. The edge network's common repository contains the incremental data log file of soil moisture-related data relayed from end nodes. In addition to serving as an edge server, the most substantial edge device manages the shared storage.

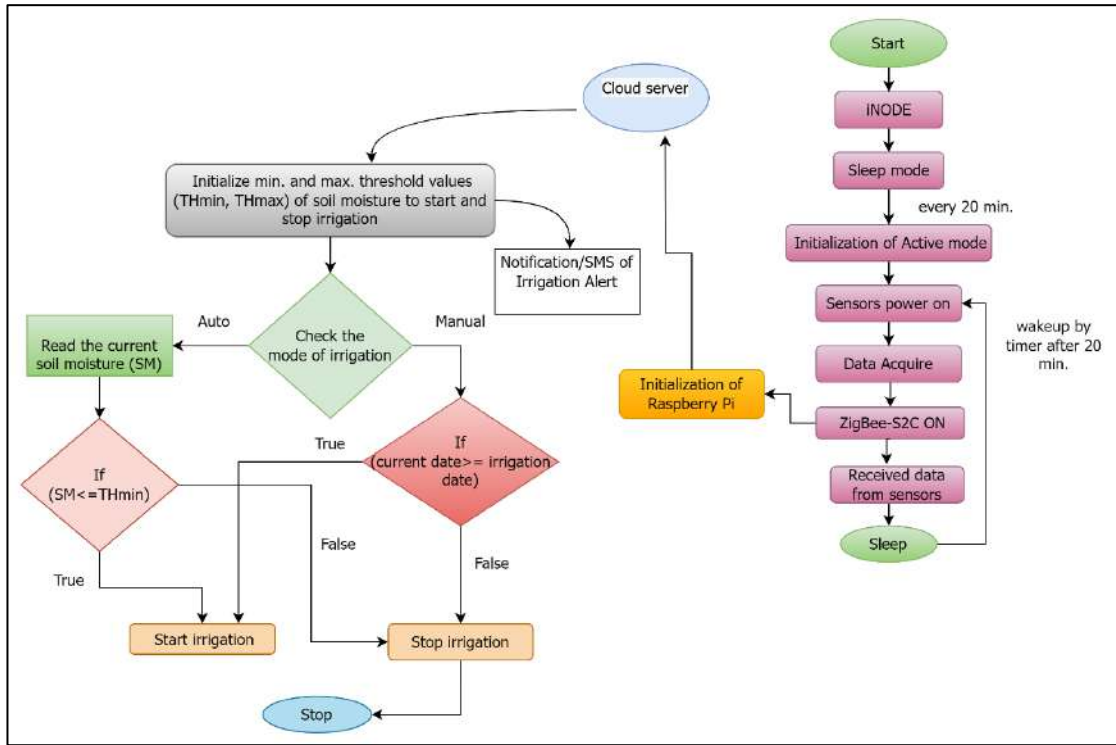


Fig. 5.13: Software workflow of the edge server layer

5.4.3 Architecture Design of Cloud/Application Layer

The cloud architecture includes a strong server that handles database management, controls data analysis algorithms, and serves as the user interface (Ghosh et al., 2016). The software workflow of cloud architecture is shown in Fig. 5.14. This layer is designed to offer application-specific services to the farmer or end-user. It serves as the central processing unit of the IoT service framework, combining cloud and edge computing capabilities (Xu et al., 2020). The cloud layer is typically used on the IoT service framework with edge computing to process data from the edge layer further, store or update essential data, and perform advanced deployment. In addition, the cloud layer can provide computing support using virtual machines when the edge layer's computing resources are insufficient (Munir et al., 2021). It handles the computational requirements of several sensor locations in the irrigation field. This framework accommodates diverse network connection pathways, like TCP/IP and MQTT, adapting to the specific connection requests from edge devices. This design utilized the MQTT protocol because it is an effective means of sending brief messages and uses low bandwidth, which

makes it ideal for Machine-to-Machine (M2M) communication (Larmo et al., 2018), particularly between connected objects. The cloud server boasts substantial memory and resource reserves when operating on a scalable Linux system. For every sensor node location, the storage web code database server is responsible for uploading historical log files and archiving incoming data. Utilizing this data offers insights through a web user interface, determining the need for irrigation in agricultural fields based on soil moisture conditions.

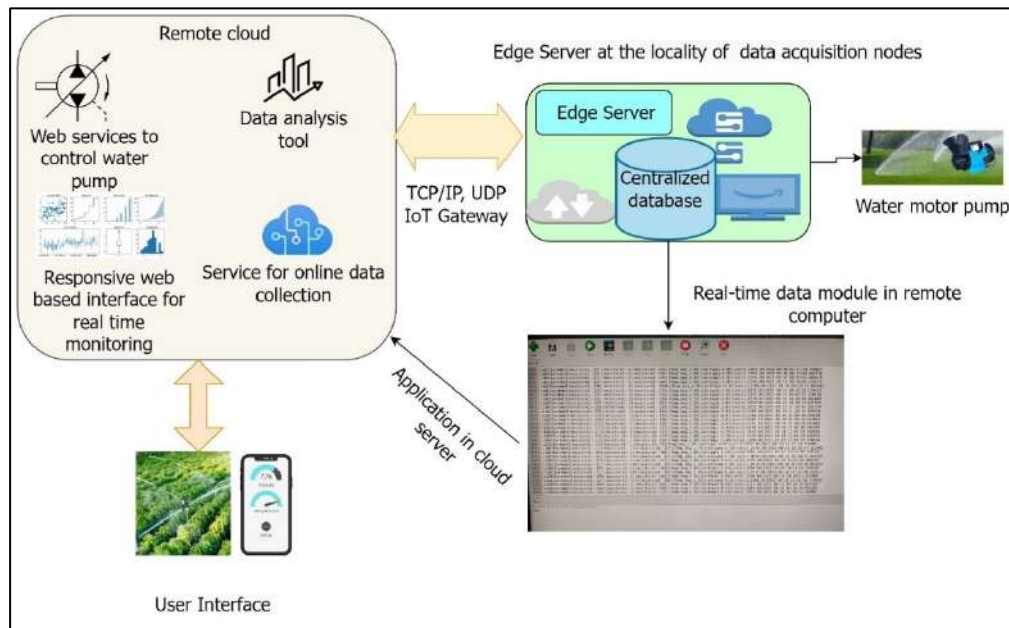


Fig. 5.14: Software workflow of cloud server layer

5.5 Experimental Validation and Results

5.5.1 Experimental Setup

In addition to lab tests, the effectiveness of the IoT-Based irrigation system is validated through a WSN network configuration installed in an experimental field. Fig. 5.15 shows the sensor's location in the field.



Fig. 5.15: Location of sensors at irrigation field (Google Earth)

The placement of sensors plays a critical role in effectively monitoring of soil moisture. When a sensor is installed in an area of soil with limited roots, it may not accurately detect changes in water content compared to another sensor installed in an area with abundant roots (Dursun and Ozden, 2017). The installation of sensors should be limited to the dispersion of roots since the soil water content is uniform across the soil when sprinkler irrigation is used. The positioning of sensors during trickle irrigation is determined by the distribution of water and roots within the wetted volume (Abioye et al., 2021). Several sensors were placed at three different soil depths, including 15, 30, and 45 cm, at 25%, 50%, and 75% of the field's length (L), respectively, to monitor soil moisture at the head, middle reach, and end reach of the basin. Table 5.4 presents the positioning of several sensors in the field at various depths.

Table 5.4: Placement of soil moisture sensors at various depths in the field

Field	Grid size (m)	Soil Moisture Sensor	Distance (m)	Depth (cm)
A	77 m×25	Sensor 1	25%L = 19.25	15
		Sensor 2	75%B = 18.75	15
		Sensor 3, 4	75% L = 57.75	30
		Sensor 5	50% L = 38.50	45
B	77 m×36	Sensor 1	25%L = 19.25	15
		Sensor 2	75%B = 27.00	15
		Sensor 3, 4	75% L = 57.75	30
		Sensor 5	50% L = 38.50	45

A wireless network module inside the data-collecting unit enables the microcontroller to send sensor data wirelessly over the internet to a cloud server. This wireless feature makes data transfer quick and

easy, enabling remote monitoring and analysis. Sensor nodes are attached to the sensors and the data logger unit, which act as a bridge between the sensors and the data logger unit. These nodes enable continuous collection and storage of the obtained data by facilitating the transmission from sensor data to the logger. The designed module data acquisition device uses this configuration to offer an affordable data transmission and gathering option in agricultural applications. The 1.2 W monocrystalline solar panel is integrated with the device to charge the lithium polymer battery daily. Fig. 5.16 shows the overall setup of the designed and developed module.



Fig. 5.16: Developed sensors placed with sensor nodes at the irrigation field

5.5.2 Interface of the Android Application with IoT Sensing Node

Blynk is an application of IoT platform for IOS or Android smartphones that is used to control Arduino, Raspberry-Pi, and Node MCU via the Internet. This application is used to create a graphical user interface (GUI) by compiling and providing the appropriate address on the available widgets. This

application can monitor and store the various types of data frames, such as soil moisture, soil temperature, relative humidity, etc., and give alert notifications according to threshold values.

In this study, the Blynk-based application monitors real-time soil moisture and temperature data through a designed IoT device. It allows the creation of interfaces of the hardware part with the Android app using various widgets. The Blynk server is responsible for all the communications between the smartphone and hardware. It is an open-source application that can easily be downloaded through the Blynk website and is able to handle thousands of devices. Fig. 5.17 shows the graphical interface of the Blynk application for irrigation purposes.

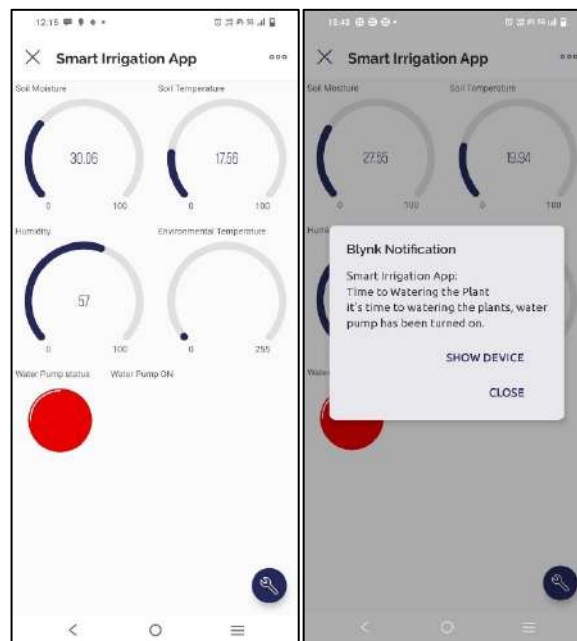


Fig. 5.17. Graphical interface of Blynk application for irrigation

After successfully designing an IoT-Based smart irrigation module, it has been integrated with the Blynk app. This application provides detailed irrigation field information (soil moisture and soil temperature) for wheat and sugarcane crops. Figure 5.18 illustrates the comprehensive system interface with the Blynk Android application in an agricultural field.

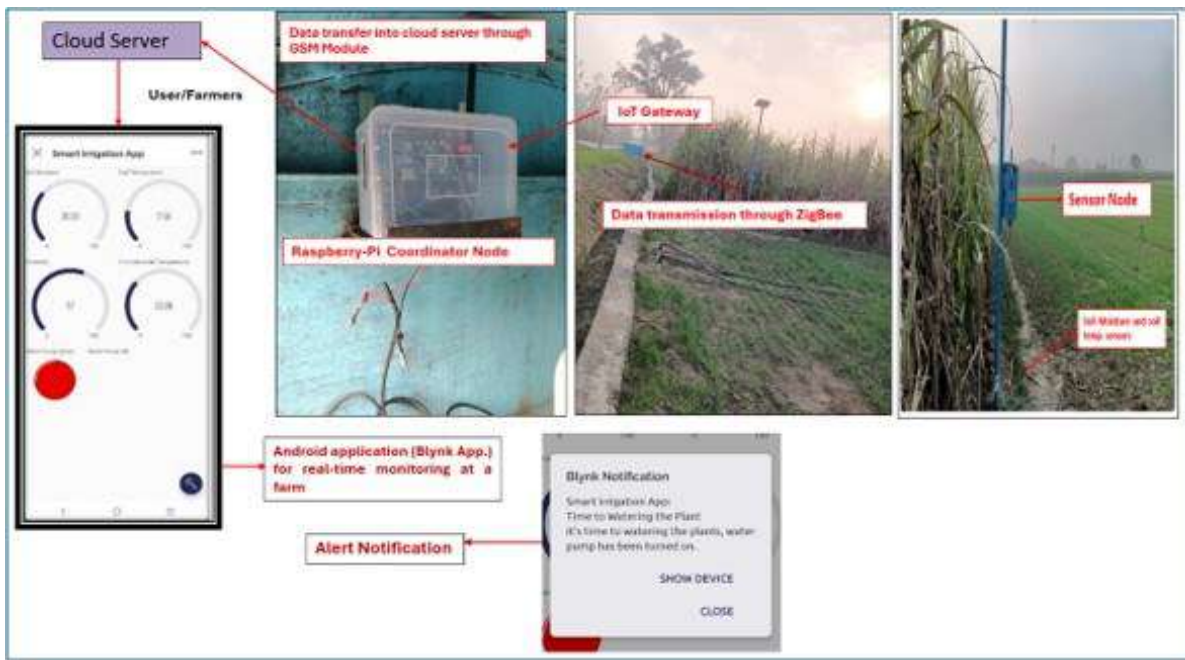


Fig. 5.18: Interface of designed module with Blynk application at field

5.6 Industrial-Based Gypsum Block Sensor

The measurements of soil moisture by gypsum block sensor involve the conversion of resistivity to soil matric potential and its conversion to volumetric soil moisture content (Ganjugunte et al., 2012; Veeranna et al., 2016). Watermark Gypsum Blocks are designed to measure soil water potential in a range from 0 to 200 kPa (or 0 to 200 centibars), which is considered as the ideal range for the soil moisture needs of most plants, particularly those that are economically significant. Optimal soil water potential typically occurs at 33 kPa (33 centibars), known as field capacity. The soil retains enough moisture for optimal plant growth without becoming waterlogged at this level. It is important to maintain soil water potential above 100 kPa for most crops, although the specific lower threshold can vary based on the crop type (such as lettuce, wheat), the stage of growth, and seasonal conditions. To conduct a comparative analysis, two gypsum block sensors were acquired from a commercial supplier to evaluate the performance differences between custom-designed IoT smart irrigation systems and established factory-made systems.

Technical Specifications:

Device Specifications:

- Manufacturer: Agrihawk Technologies Pvt. Ltd
- Dimensions: 64 cm × 14 cm × 14 cm
- Waterproof
- Weight: 2.25 kg max.

- Range of measurement: from 0 to 239 kPa
- Operating Temperature: - 10°C to – 50°C
- 4G IoT SIM
- Data Updated: once every 1 hr.
- Expected battery life: 6 months in one charge.

Soil Moisture Sensor Specifications:

- Materials: ABS plastic caps with stainless steel body over a hydrophilic fabric covered granular matrix.
- Dimensions: Diameter- 0.875 in. (22 mm) Length- 3.27 in. (83 mm)
- Weight: 0.067 kg - with 5 ft. lead

Soil Temperature Sensor Specifications:

- Sensor Type: DS18B20 digital thermometer
- Material: Stainless Steel
- Measures Temperature from -55 °C to +125 °C
- ±0.5 °C Accuracy from -10 °C to +85 °C

5.6.1 Field Installation

The gypsum block sensors were positioned at a depth of 6 inches (approximately 14.7 cm), following the guidelines specified in the manufacturer's manual. Before installation, these sensors were submerged in water for about 30 minutes to ensure proper conditioning before being embedded into the soil. These sensors were installed at wheat and sugarcane crops, as shown in Fig. 5.19. After the installation, the continuous soil moisture potential and soil temperature were received through the Android Application (Fyllo App.). Fig. 5.20 shows the snapshot of the app.



Fig. 5.19: Field Installation of gypsum block sensor in sugarcane crop

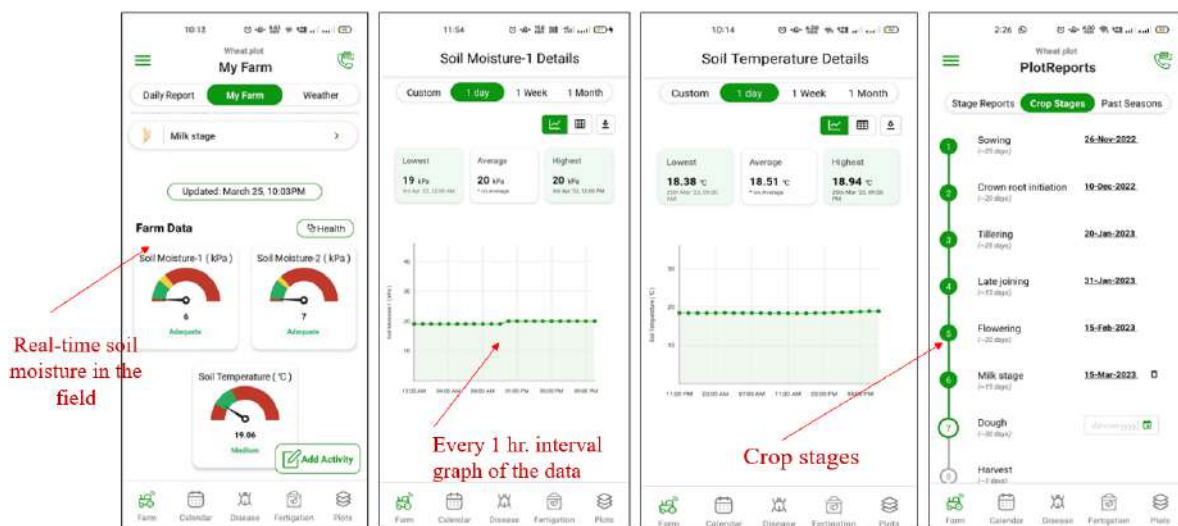


Fig. 5.20: Android App. (Fyllo) of Gypsum Block Sensor

5.6.2 Comparative Analysis of Designed and Industrial-Based IoT System

After successfully installing both Modules (Designed and Gypsum Block), various factors such as cost, accuracy, maintenance, and security were analyzed. Gypsum block sensors have some drawbacks compared to capacitive sensors in agricultural applications. As gypsum dissolves over time, these sensors become less reliable because high moisture causes errors in accuracy. Gypsum block sensors perform slow because moisture must transfer between the sample material and the block for proper measurement which makes immediate or real-time observation challenging. The field life span of gypsum block sensors is affected by frequent damage, while capacitive sensors maintain a rigid solid-

state structure for extended durability. Gypsum block sensors fail to generate accurate moisture data in saline soils since the soil's electrical conductivity is negatively affected by salt content. The measurement technique of capacitive sensors using dielectric permittivity allows them to work effectively beyond changes in soil salinity compared to traditional gypsum block sensors. The comparison of all factors is shown in Table 5.5.

Table 5.5: Comparative Analysis of Designed and Industrial-Based IoT system

S. No.	Particulars	Designed IoT-Based Irrigation System	Industrial-Based Irrigation System
1	Sensor type	Capacitive-based soil moisture sensor	Gypsum Block soil moisture sensor
2	Measurement of soil moisture	Analog value	Soil potential (kPa)
3	Measurement of soil temperature	In degree $^{\circ}\text{C}$	In degree $^{\circ}\text{C}$
4	Depth of installation	Any type of depth can be installed	Limited in 6 in. (14.7 cm)
5	Power Source	Solar Panel and rechargeable battery	rechargeable battery
6	Accuracy	$\pm 0.3\%$ for volumetric water content	Not defined for the overall system
7	Android Application	Blynk App.	Fyllo App.
8	Overall Cost of the system	Rs. 4000	Rs. 25000

5.7 Conclusion

An IoT-based smart irrigation system connects a wireless soil moisture sensor network to an Android app, enabling farmers to manage their fields remotely with minimal manual effort. This system reduces water waste, improves irrigation planning, and supports sustainable farming practices. Testing shows it enhances crop management, demonstrating the potential of IoT and web applications in precision agriculture. Integrating pH, humidity, salinity, wind speed, and rainfall sensors will provide a comprehensive soil analysis, optimizing irrigation efficiency. Future plans include using machine learning to predict soil moisture, AI for system monitoring, and blockchain for data transparency. Field trials across varied climates and soil conditions will validate the system's performance.

CHAPTER 6

FIELD STUDY OF MICRO AND CONVENTIONAL IRRIGATION FOR SUGARCANE AND WHEAT

6.1 Background

In the Gadarjudda Minor Canal command area, sugarcane is the predominant crop, covering approximately 60% of the agricultural land, while wheat accounts for 20%, with the remaining 20% allocated to other crops and activities. These crops were selected for the study due to their high-water requirements and their critical role in regional agriculture.

The traditional flood irrigation systems for wheat and sugarcane have low irrigation efficiency and suboptimal water use. Due to poor irrigation management and uneven distribution, much water is lost due to runoff, deep percolation beyond the root zone, and evaporation. Shifting from flood irrigation to a micro-irrigation system can significantly enhance irrigation efficiency. Micro-irrigation systems, which include drip and sprinkler irrigation methods, deliver water directly to the plant's root zone. This targeted water delivery minimizes losses from evaporation and runoff, thereby maximizing water use efficiency.

Appropriate scheduling is crucial in micro-irrigation systems, and this involves determining optimal irrigation timings and net irrigation tailored to the specific water requirements of the crops at different growth stages. Regular monitoring of soil moisture is a key component of effective scheduling. By frequently assessing soil moisture levels, farmers can irrigate only when necessary, which conserves water and supports plant health. Various instruments are available for measuring soil moisture, making this process quick and less cumbersome than traditional methods. These instrument capacitance probes measure the soil's dielectric constant to infer its moisture content. Other tools, like time domain reflectometry (TDR), offer high precision and can provide real-time data on soil moisture for irrigation decisions.

6.2 Design and Installation of Micro-Irrigation

The designs of sprinkler and drip irrigation systems are illustrated in this section to provide a comprehensive understanding of their implementation and benefits.

6.2.1 Design of Sprinkler Irrigation System for Wheat

In the sprinkler irrigation system, the flow of water develops the spray under pressure through small orifices or nozzles (Zakari et al. 2012). The pressure is usually obtained by pumping. With careful selection of nozzle sizes, operating pressure, and sprinkler spacing, the amount of irrigation water required to refill the crop root zone can be applied nearly uniformly at the rate to suit soil infiltration rate. The design of a sprinkler irrigation system for wheat crops is based on previous years' weather

data, soil physical properties, and some assumptions based on the FAO-24 Manual (Doorenbos et al. 1977). Primary design data are given in Table 6.1, and the design summary is in Tables 6.2 and 6.3.

Table 6.1: Data for design of Sprinkler irrigation system

S.no.	Parameter	Value
1	Soil type	Loam soil
2	Maximum Soil Moisture Holding Capacity	24.45 %
3	Crop	Wheat
4	Effective Root Zone Depth	1 m
5	Infiltration Rate	12 mm/hr
6	Reference Crop Evapotranspiration	5 mm/day
7	Desired Depletion Level	50%
8	Spacing of Row	0.2 m
9	Spacing of Plants	0.1 m
10	Emission Uniformity	98%

Table 6.2: Specification of Micro Sprinkler irrigation system

S.no.	Parameter	Value
1	Sprinkler Discharge	120 litre/hr
2	Sprinkler Spacing	4 m
3	Lateral spacing	4 m
4	Number of sprinklers per lateral	18 sprinklers
5	Number of lateral lines	6
6	Length available for lateral	77 m
7	Horsepower of Pump	2 HP

Table 6.3: Specification of Mini Sprinkler irrigation system

S.no.	Parameter	Value
1	Sprinkler Discharge	600 litre/hr
2	Sprinkler Spacing	9 m
3	Lateral spacing	9 m
4	Number of sprinklers per lateral	9
5	Number of lateral lines	2
6	Length available for lateral	77 m
7	Horsepower of Pump	2 HP

6.2.2 Design of Drip Irrigation System for Sugarcane

Data collected before the design of the drip irrigation system is shown in Table 6.4. For loam soil, the maximum moisture holding capacity is 24.45 %. Reference crop evapotranspiration was calculated using data from previous years. The value of the crop coefficient for 365 days' sugarcane crop is

calculated as per the method given in FAO 24 (Doorenbos et al. 1977). The root zone depth is considered 1.5 meters. The design summary is given in Table 6.5. Some photographs of the installation are shown in Fig. 6.1. The head unit of the micro-irrigation system installed at the experimental field is shown in Fig. 6.2.

Table 6.4: Data for design of Drip irrigation system

S.no.	Parameter	Value
1	Soil type	Loam soil
2	Maximum Soil Moisture Holding Capacity	24.45 %
3	Crop	Sugarcane
4	Effective Root Zone Depth	150 cm
5	Infiltration Rate	12 mm/hr
6	Reference Crop Evapotranspiration	8.27 mm/day
8	Spacing of Row	1.2 m
9	Spacing of Plants	1.0 m

Table 6.5: Specification of Drip irrigation system

S.no	Parameters	Value
1	Sugarcane Area	77×18 m
2	Row to Row spacing	1.2 m
3	Number of lateral lines	16
4	Total length of laterals	1232 m
5	Emitter spacing	30 cm
6	Total emitters	4106
7	Emitter capacity	2 litre/hr
8	Total discharge	8212 litre/hr
9	Wetted area for sugarcane	50%



Fig. 6.1: Installation of micro-irrigation system



Fig. 6.2: Head unit of micro-irrigation system

6.3 Performance Evolution of Micro-Irrigation System

The performance evaluation of the sprinkler and drip irrigation system is carried out. Different hydraulic performance indicators i.e., Coefficient of Uniformity, Distribution Uniformity, and Distribution Characteristic evaluated for sprinkler irrigation systems and drip irrigation systems hydraulic performance indicators Coefficient of Uniformity Distribution Uniformity Manufacturing coefficient of variation have been evaluated.

6.3.1 Hydraulic Performance Indicators

(i) Coefficient of Uniformity: One of the first and most common quantitative measures of uniformity is the Christiansen Uniformity coefficient (C_u). This was developed for evaluating sprinkler systems in 1942 and is still the most widely used and accepted measure for uniformity. It is expressed by the equation developed by Christiansen (1942)

$$C_u = 100(1.0 - \frac{\sum X}{mn}) \quad (6.1)$$

In which,

C_u = coefficient of uniformity

m = average value of all observations (average application rate), mm

n = total number of observation points

X = numerical deviation of individual observations from the average application rate, mm

A set of recommendations for the minimum requirements on uniformity coefficient is shown in Table 6.6 (Luxmini et al., 2015).

Table 6.6: Uniformity classification of sprinkler irrigation system based on UC values

S.no.	Uniformity coefficient (%)	Classification
1	Above 90%	Excellent
2	90%-80%	Good
3	80%-70%	Fair
4	70-60%	Poor
5	Below 60%	Unacceptable

The Coefficient of Uniformity for sprinkler irrigation systems is 83.84 %, which is considered good.

(ii) Distribution Uniformity (D_U): Pattern efficiency, also known as distribution uniformity (D_U), indicates the magnitude of uneven distribution and can be defined as the percentage of average application in the lowest quarter of the field. The distribution uniformity (D_U) is defined as

$$D_U = \text{Average low quarter depth of water caught} / \text{average depth of water caught}$$

A set of recommendations for the Distribution Uniformity is shown in Table 6.7 (Luxmini et al., 2015).

Table 6.7: Uniformity classification of sprinkler irrigation system based on DUC values

S.no.	Distribution uniformity, D_U (%)	Classification
1	>87	Excellent
2	75-87	Good
3	62-75	Acceptable
4	<62	Unacceptable

The Distribution Uniformity for the sprinkler irrigation system is 78 %, considered good.

(iii) Distribution Characteristic (D_c): The distribution characteristic (D_c) was calculated by using the following relationship-

$$D_c = \frac{\text{Area receiving more than average depth}}{\text{Total wetted area}} \quad (6.2)$$

The value of D_c above 40% was considered acceptable (Mane and Ayare, 2011); for the sprinkler field, the value of distribution Characteristics is 50 %, which is considered acceptable within the limit.

6.3.2 Performance evaluation of drip irrigation system

For the performance evaluation of the drip Irrigation system, the discharge of the emitter was measured by the volumetric method at the head, middle, and tail ends of the laterals. The constant pressure of 1.5 bar was maintained for performance evaluation, and the system was operated for 15 min. Immediately after the irrigation termination, the volume of water collected in cans was measured with the help of a graduated cylinder. Figure 6.3 shows the catch can and measurement in the graduated cylinder.



Figure 6.3: Catch can and measurement in the graduated cylinder

- (i) **Coefficient of Uniformity:** To determine the uniformity coefficient in drip irrigation, the depth of water in the formula (Christiansens, 1942) was replaced by the discharge rate of drip, as suggested by Wu and Gitlin (1974). The uniformity coefficient was calculated using equation 11. The Uniformity Coefficient for the system is found to be 86.78 %, which is considered excellent.
- (ii) **Distribution Uniformity (Du):** Distribution uniformity indicates the degree to which the water is applied uniformly over the area, which was determined using the relationship. $DU = \text{Average low quarter depth of water caught} / \text{average depth of water caught}$. The Distribution Uniformity for the system is 86%. A value of Du above 80% is considered acceptable.
- (iii) **Manufacturing coefficient of variation:** The emitter coefficient of manufacturing variation is used to measure the anticipated variations in discharge. It can be estimated as

$$C_v = S/q \quad (6.3)$$

Where,

C_v = Manufacturing coefficient of variation

S = Sample standard deviation

q = Average emission rate of sample

The manufacturing coefficient of variation for the system is found to be 0.17. ASCE interpretation of the Manufacturing coefficient of variation for line source emitters shows that the value between 0.10-0.20 is in average performance.

All the parameters of the performance evolution of the sprinkler and drip irrigation system were within the acceptable limit, which confirms that the overall performance parameters of the micro-irrigation system were at acceptable levels. The sprinkler and drip irrigation methods are technically feasible in the study area.

6.4 Sprinkler Irrigation in Wheat

A detailed experimental study was conducted to evaluate the effectiveness of sprinkler irrigation systems versus traditional flood irrigation for wheat farming. A plot was segmented into two distinct areas: a 1925 m² section equipped with micro sprinklers and a 1540 m² section maintained under conventional flood irrigation. Using the broadcasting method, the farmer sowed the wheat variety HD-2967 across the entire plot on December 23, 2021, where seeds are scattered broadly rather than planted in precise rows. The research team meticulously managed the micro-sprinkler area to precisely control water distribution, optimize irrigation efficiency, and closely monitor crop growth. In contrast, the flood irrigation section was left under the care of farmers who applied traditional irrigation practices. This arrangement allowed for a systematic comparison between the two irrigation methods, assessing their respective impacts on water usage, crop health, and yield, thus, providing valuable insights into the potential benefits of adopting more controlled and efficient irrigation technologies in wheat cultivation.

6.4.1 Irrigation Scheduling

Irrigation scheduling is the process of determining when to irrigate the crops and how much water to apply. Optimizing irrigation water is the key to improving the performance and sustainability of irrigation systems (Zhe Gu, 2020). Regular soil moisture monitoring at different depths with a soil moisture profiler and Time Domain Reflectometry (TDR) was carried out to determine irrigation requirements. Irrigation was supplied to fill water to the field capacity when the available soil moisture content level was below 50 %. The detailed methodology is given in Fig. 6.4. The soil moisture profiler is shown in Fig. 6.5. The net and gross irrigation requirements are calculated using equations 6.1 and 6.2. For sprinkler irrigation, the field application efficiency is 75%, as per the recommendation of FAO.

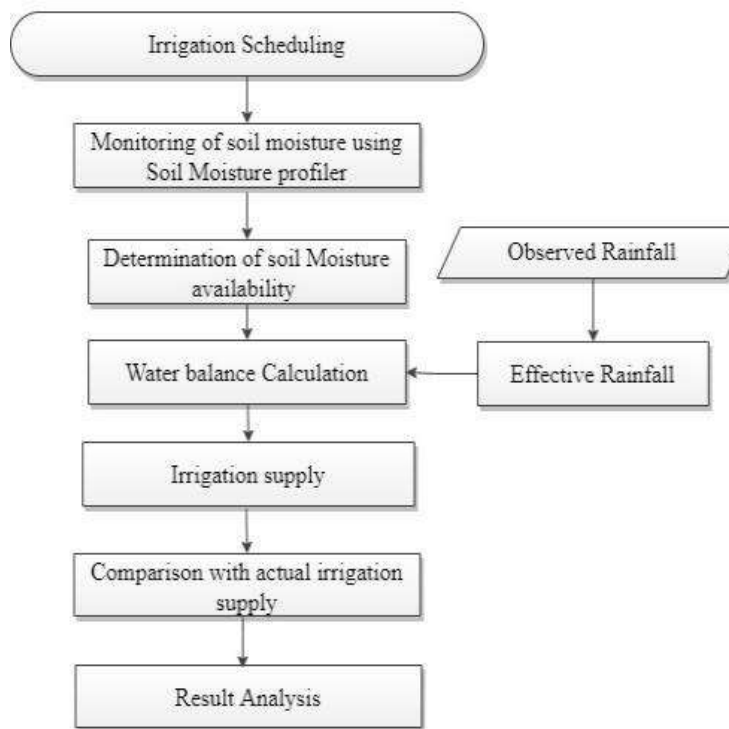


Fig.: 6.4: Irrigation scheduling

$$\text{Net Irrigation Requirement} = \frac{(M_{fc} - M_{bi})}{100} \times BD \times D \quad (6.1)$$

Where,

M_{fc} = Field capacity moisture content, percent
 M_{bi} = Moisture content before irrigation, percent
 BD = Bulk density of soil
 D = Root zone depth, cm

$$\text{Gross irrigation Requirement} = \text{NIR/Field Efficiency} \quad (6.2)$$



Fig. 6.5: Soil moisture profiler

6.4.2 Micro Sprinkler Irrigation

Knowing soil moisture, the net irrigation requirement was calculated using equations 6.1 and 6.2. The daily monitoring of soil moisture, alongside the depth of irrigation, rainfall, and changes in root zone depth throughout the crop's growing period, was meticulously recorded and is depicted in Fig. 6.6. Notably, significant rainfall occurred 15 days after sowing, leading to regular precipitation in the area, which delayed the commencement of irrigation until February. The first irrigation was required 57 days after sowing, with a net requirement of 25 mm and a gross requirement of 33 mm. Detailed irrigation data is presented in Table 6.8. Fig. 6.7 shows the sprinkler irrigation in the field. Overall, the sprinkler irrigation system's average application efficiency was 71.71%, indicating a relatively high level of water use efficiency.

Table 6.8: Irrigation details of sprinkler irrigation (Area=1925 m²)

S. No	Parameters	Irrigation					
		1 st	2 nd	3 rd	4 th	5 th	6 th
1	Date	17/02/2022	26/02/2022	06/03/2022	13/03/2022	20/03/2022	31/03/2022
2	Day after sowing	57	66	74	81	88	99
3	Irrigation source	Canal	Canal	Canal	Canal	Canal	Canal
4	Effective rainfall	132.58	0	0	0	0	0
5	Net irrigation requirement (mm)	25	23	23	25	26	25
6	Recommended field application efficiency by FAO for sprinkler irrigation	75					
7	Gross irrigation requirement	33.33	30.67	30.67	33.33	34.67	33.33
8	Average Flow rate (l/hr) of sprinkler	120					
9	Duration of irrigation (min)	312	285	285	312	321	312
10	Irrigation applied (m ³)	67.4	61.6	61.6	67.4	69.3	67.4
11	Depth of irrigation (mm)	35	32	32	35	36	35
12	Field Application Efficiency (%)	71.43	71.88	71.88	71.43	72.22	71.43

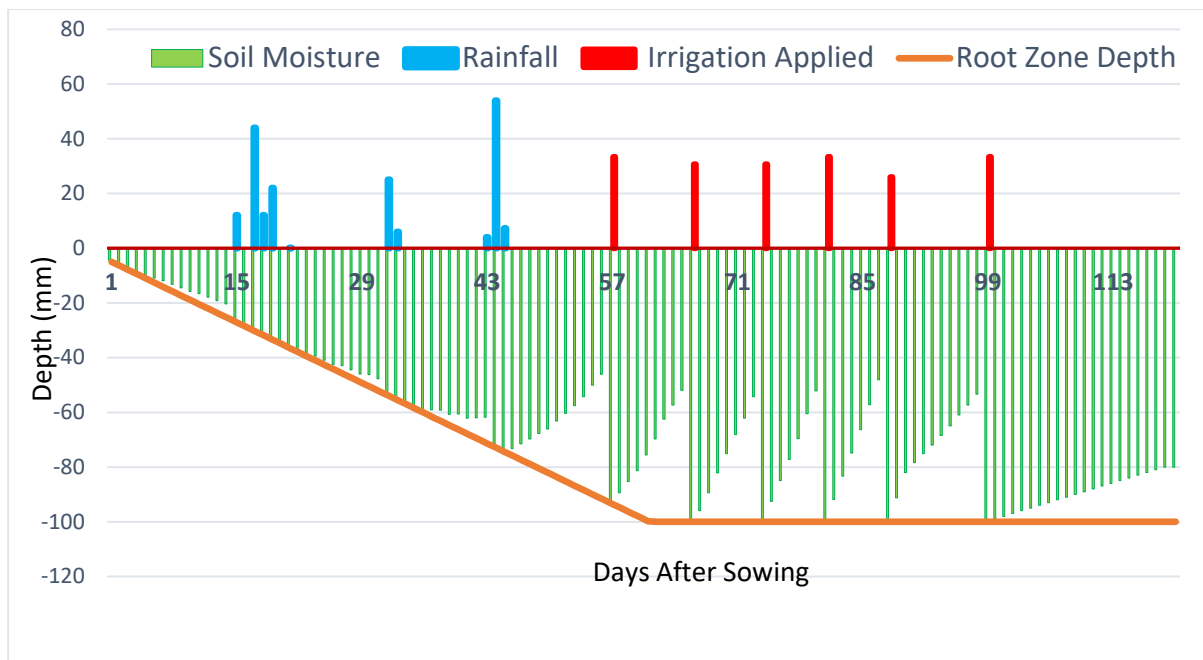


Fig. 6.6: Soil moisture, rainfall, and depth of irrigation



Fig. 6.7: Sprinkler irrigation

6.4.3 Conventional Irrigation

The farmers managed flood irrigation for the wheat crop. Throughout the growing season, three separate irrigation events were executed. The initial irrigation took place 65 days after the seeds were sown, with canal water sourced from the head reach of the watercourse being used to irrigate the crops. However, during each irrigation season, the farmers tended to apply a greater volume of water than what was ideally needed by the crop. This over-irrigation led to excessive deep percolation, where water seeped deeper into the soil beyond the root zone, resulting in significant water losses. The details of these irrigation practices and their outcomes are documented in Table 6.9. Due to the excessive water application, the overall field application efficiency, which measures how much water the crop

uses and does not go to waste, was only 46.33%. This lower efficiency highlights the challenges and inefficiencies in flood irrigation practices without precise control.

The daily soil moisture, along with the depth of irrigation water supplied, rainfall data, and changes in the root zone depth during the wheat's growth period, were carefully recorded and are illustrated in Fig. 6.8. Additional visuals of the irrigated wheat field are provided in Figs. 6.9 & 6.10.

Table 6.9: Flood irrigation details of wheat crop (Area=1540 m²)

S.no.	Parameters	Irrigation		
		1 st	2 nd	3 rd
1	Date	25/02/2022	11/03/2022	28/03/2022
2	Day after sowing	65	79	96
3	Irrigation source	Canal	Canal	Canal
4	Effective rainfall	134.32	0.00	0.00
5	Net irrigation requirement (mm)	32.14	41.00	60.80
6	Recommended field application efficiency by FAO	60		
7	Gross irrigation requirement	53.57	68.33	101.33
8	Flow rate (l/s) diverted from source	29.00	25.00	23.00
9	Flow rate delivered to the field	27.55	24.00	22.08
10	Conveyance Efficiency (%)	95.00	96.00	96.00
11	Duration of irrigation (min)	70	100	135
12	Irrigation applied (m ³)	116	144	179
13	Depth of irrigation (mm)	75.14	93.51	116.14
14	Field Application Efficiency (%)	42.78	43.85	52.35
15	Irrigation efficiency (%)	40.64	42.09	50.26

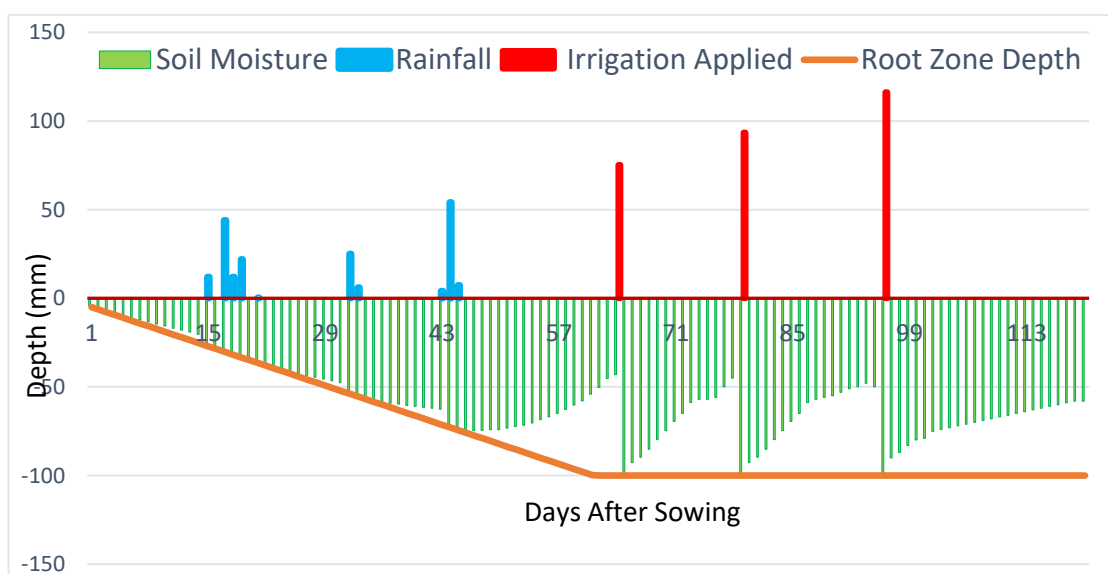


Fig. 6.8: Soil moisture, rainfall, and depth of irrigation for flood-irrigated wheat



Fig. 6.9: Flood irrigated field



Fig. 6.10: Canal water diverted to the field

6.5 Comparison of Flood and Sprinkler Irrigation

The data presented in Table 6.10 and in Fig. 6.11 highlighted a notable advantage of sprinkler irrigation systems over traditional flood irrigation methods, particularly regarding water conservation. The findings showed that sprinkler irrigation resulted in a significant 28% reduction in water usage when compared to flood irrigation. This efficiency is particularly critical in canal command areas, where water distribution can often be less controlled and thus more wasteful. Sprinkler systems distribute water more uniformly and directly to the plant's root zone, minimizing losses. This method not only ensures that water is conserved but also that it is used more effectively to meet the precise needs of the crop without over-saturation.

Table 6.10: Comparison of sprinkler and flood irrigation

S.No.	Parameters	Flood irrigation	Sprinkler irrigation
1	Irrigation Required (m^3/ha)	1340	1340
2	Effective Rainfall (mm)	134	134
3	Irrigation Applied (m^3/ha)	2848	2050
4	Avg. Conveyance Efficiency	90%	95%
5	Avg. Application Efficiency	47.05%	65.37%
6	Irrigation Efficiency	42.35%	62.10%
7	Water Saving	28%	

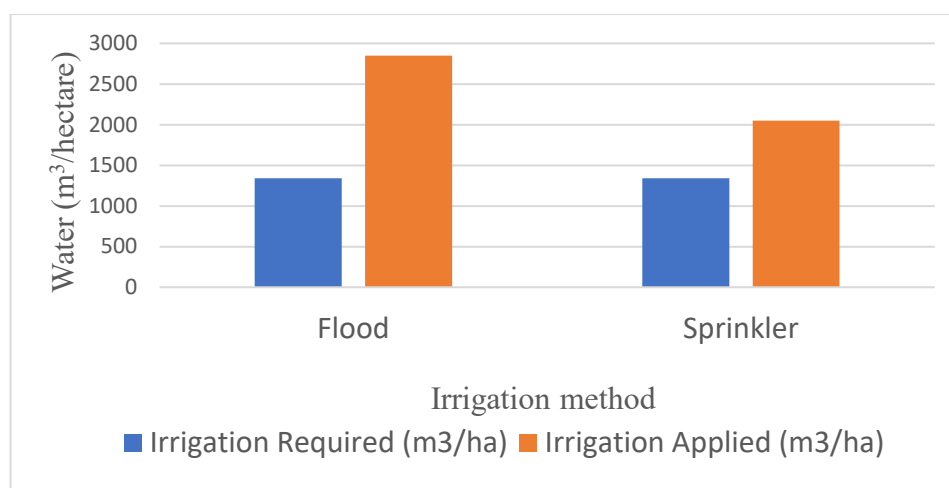


Fig. 6.11: Comparison of sprinkler and flood irrigation

6.5.1 Yield and Yield Attribute

At the time of wheat harvesting, a random sample of $10\text{m} \times 10\text{m}$ was taken from both fields to determine yields from the whole area of the experimental unit and then converted to yield per hectare. The crop water use efficiency, field water use efficiency, and water productivity have been calculated using the equations given in the previous section. Data tabulated in Table 6.11 revealed that grain yield was 5% more in sprinkler irrigation than in the flood-irrigated wheat. The overall yield was less in both fields than the average yield (53.10 q/ha) because of the late sowing of wheat and heavy rainfall in the initial stage. The water productivity of sprinkler and flood irrigation systems is 1.18 and 0.91 kg/m^3 , respectively. Fig. 6.12 shows the harvesting and threshing practice in the field.

Table 6.11: Yield attributes of sprinkler and flood irrigation system

S. No.	Parameters	Flood Irrigation	Sprinkler Irrigation
1.	Area (m ²)	1540	1925
2.	Yield (quintal/hectare)	38	40
3.	Crop ET (mm)	214	214
4.	Effective Rainfall (mm)	134.32	134.32
5.	Irrigation Applied (mm)	285	205
6.	Crop Water Use Efficiency (kg/hectare/mm)	17.76	18.69
7.	Field Water Use Efficiency (kg/hectare/mm)	9.06	11.79
8.	Water Productivity (kg/m ³)	0.91	1.18



Fig. 6.12: Harvesting and threshing of wheat

6.6 Mini Sprinkler in Wheat Crop

In the previous growing rabi season of 2021-22, micro sprinklers were used to irrigate wheat crops, and the broadcasting method was utilized to sow the seeds. This traditional broadcasting method involved scattering seeds over the surface of the field, a technique that, while straightforward, can lead to uneven seed distribution and potentially less efficient water usage. Recognizing the need for improvement in both sowing and irrigation techniques, significant changes have been made for the

2022-23 wheat season. In the second season of the wheat crop, the irrigation system was upgraded to mini sprinklers. Compared to micro sprinklers, mini sprinklers can offer better water coverage and more efficient water use, which is crucial for achieving optimal growth conditions and conserving water. Additionally, shifted from broadcasting to using a seed drill for planting. The seed drill allows for more precise sowing of seeds at uniform depths and spacing. This method improves the wheat's germination rates and growth uniformity and maximizes the use of available land and resources. These upgrades in our farming practices aim to enhance wheat crop productivity and reduce water usage.

On November 18th, 2022, farmers sowed the wheat variety HD-2967 using a seed drill to ensure precise seed placement and optimal soil contact. The plot designated for this purpose was divided into two distinct sections, each spanning 1386 square meters. One part was outfitted with mini sprinklers and managed using proper irrigation scheduling. The other part was maintained using conventional flood irrigation methods managed by the farmers. Regular monitoring of soil moisture was conducted using a soil moisture profiler. By performing this side-by-side comparison of two different irrigation approaches on identically sized plots, our goal was to evaluate and demonstrate the effectiveness and efficiency of modern irrigation technology compared to traditional practices, particularly in terms of water usage and crop yield. Fig. 6.13 illustrates the sowing of the wheat crop with the seed drill.



Fig. 6.13: Sowing of the wheat crop with the seed drill

6.6.1 Irrigation in Wheat Crop

Soil moisture was monitored, and the depth of irrigation required was calculated. Daily soil moisture, irrigation depth, rainfall, and root zone changes are meticulously recorded and displayed in Fig. 6.14. The irrigation details are given in Table 6.12, and field photos of sprinkler irrigation are shown in Fig. 6.16. The mini sprinkler system achieved an average application efficiency of 74%, indicating high water use efficiency. Conversely, flood irrigation was managed by farmers, who applied irrigation four times during the growing season. The first irrigation was applied 28 days after sowing by farmers, using canal water from the head reach of the watercourse, ensuring better water availability but leading

to over-irrigation and substantial deep percolation losses noted in every season. Flood irrigation details are shown in Table 6.13, and soil moisture, irrigation depth, rainfall, and root zone changes are illustrated in Fig. 6.15. The overall field application efficiency in flood irrigation is only 46%. This contrasts sharply with the more controlled and efficient sprinkler irrigation, which underscores the need for better water management in flood-irrigated fields to minimize waste and improve efficiency.

Table 6.12: Sprinkler irrigation (Area=1386 m²)

S.No	Parameters	Irrigation					
		1 st	2 nd	3 rd	4 th	5 th	6 th
1	Date	11/12/2022	12/01/2023	01/02/2023	14/02/2023	25/02/2023	06/03/2023
2	Day after sowing	24	56	76	89	100	109
3	Irrigation source	Canal	Canal	Canal	Canal	Canal	Canal
4	Effective rainfall (mm)	0	0	0	0	0	0
5	Net irrigation requirement (mm)	24	26	26	26.5	28	29
6	Recommended field application efficiency by FAO for sprinkler irrigation	75					
7	Gross irrigation requirement	32.00	34.67	34.67	35.33	37.33	38.67
8	Average Flow rate (l/hr) of sprinkler	600					
9	Duration of irrigation (min)	254	270	270	277	293	300
10	Irrigation Applied (m ³)	45.7	48.5	48.5	49.9	52.7	54.1
11	Depth of irrigation (mm)	33	35	35	36	38	39
12	Field Application Efficiency (%)	72.73	74.29	74.29	73.61	73.68	74.36

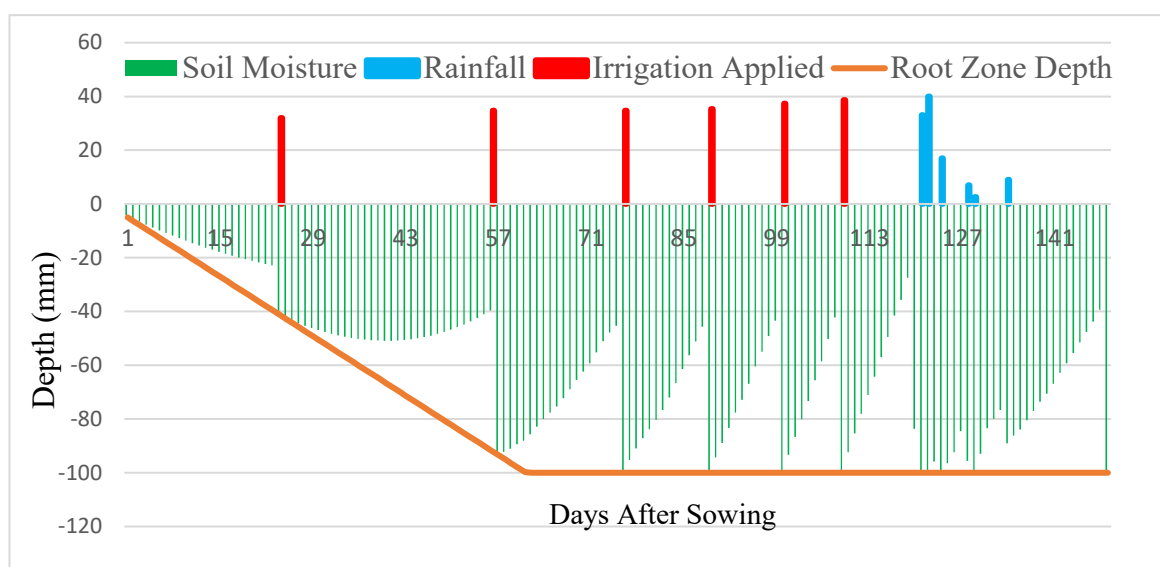


Fig. 6.14: Soil moisture, rainfall, and depth of irrigation for mini sprinkler irrigated wheat

Table 6.13: Flood irrigation details (Area=1386 m²)

S.no.	Parameters	Irrigation			
		1 st	2 nd	3 rd	4 th
1	Date	15/12/2022	27/01/2023	19/02/2023	04/03/2023
2	Day after sowing	28	71	91	107
3	Irrigation source	Canal	Canal	Canal	Canal
4	Effective rainfall	0.00	0.00	0.00	0.00
5	Net irrigation requirement (mm)	24.9	36.20	35.20	45.70
6	Recommended field application efficiency by FAO	60			
7	Gross irrigation requirement (mm)	41.50	60.33	58.67	76.17
8	Flow rate (l/s) diverted from source	25.00	27.00	30.00	28.00
9	Flow rate (l/s) delivered to field	23.00	25.50	28.50	27.00
10	Conveyance Efficiency (%)	92.00	94.44	95.00	96.43
11	Duration of irrigation (min)	55	70	63	85
12	Irrigation supplied (m ³)	75.90	107.10	107.73	137.70
13	Depth of irrigation (mm)	54.76	77.27	77.73	99.35
14	Field Application Efficiency (%)	45.47	46.85	45.29	46.00
15	Irrigation efficiency (%)	41.83	44.24	43.02	44.36

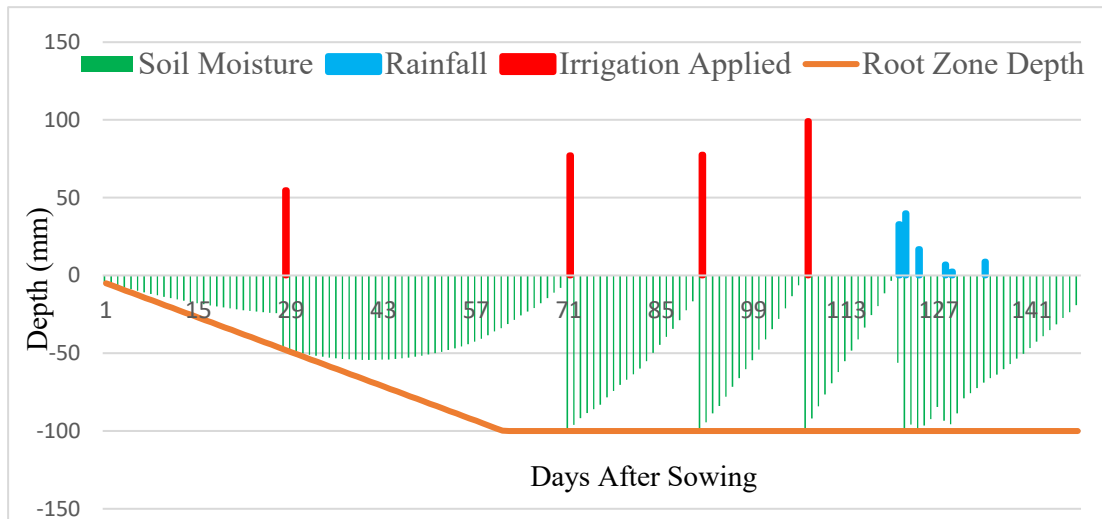


Fig. 6.15: Soil moisture, rainfall, and depth of irrigation for flood irrigated wheat



Fig. 6.16: Mini sprinkler irrigation

6.6.2 Comparison of Flood and Sprinkler Irrigation

The data presented in Table 6.14 illustrates the performance of mini sprinkler irrigation systems over traditional flood irrigation techniques, especially regarding water conservation, showcasing a notable 30% decrease in water usage. Mini sprinkler systems stand out as they provide greater efficiency than micro irrigation systems. In terms of agricultural outputs, during wheat harvesting, samples were taken from a 10m ×10m area of both fields to estimate yields per hectare. The findings, detailed in Table 6.13, show that water productivity was estimated to be 1.75 kg/m³ for sprinkler irrigation and 1.09 kg/m³ for flood irrigation, underscoring the efficiency of sprinkler systems. This comprehensive analysis highlights the critical role of efficient irrigation methods in improving yield and water productivity in agricultural practices.

Table 6.14: Comparison of sprinkler and flood irrigation

S.No.	Parameters	Flood irrigation	Sprinkler irrigation
1	Irrigation Required (m ³ /ha)	1600	1600
2	Effective Rainfall (mm)	76	76
3	Irrigation Applied (m ³ /ha)	3090	2160
4	Avg. Conveyance Efficiency	94%	95%
5	Avg. Application Efficiency	46.00%	74.00%
6	Irrigation Efficiency	43.24%	70.70%
7	Water Saving	30%	

Table 6.15: Yield attributes of sprinkler and flood irrigation system

S. No.	Parameters	Flood Irrigation	Sprinkler Irrigation
1	Area (m ²)	1386	1386
2	Yield (quintal/hectare)	42	51
3	Crop ET (mm)	250.52	250.52
4	Effective Rainfall (mm)	76	76
5	Irrigation Applied (mm)	309	216
6	Crop Water Use Efficiency (kg/hectare/mm)	16.77	20.36
7	Field Water Use Efficiency (kg/hectare/mm)	10.91	17.47
8	Water Productivity (kg/m ³)	1.09	1.75

6.7 Drip Irrigation in Sugarcane

To evaluate the effectiveness of drip irrigation for sugarcane cultivation, a comparative study has been set up where a sugarcane field is split into two equal sections, each covering an area of 1386 m². One section is designated for the application of drip irrigation managed by the research team. In contrast, the other section is managed by farmers of identical size and is maintained under traditional flood irrigation practices. This setup directly compares the two irrigation methods under the same agricultural conditions. Drip irrigation, known for its precision and efficiency, delivers water directly to the plant's root zone through a network of valves, tubes, and emitters. This method is controlled and monitored by us to ensure optimal scheduling based on the specific water needs of the sugarcane at various stages of its growth cycle. Conversely, the farmers manage the flood irrigation section using conventional methods of irrigation.

Sugarcane harvested in the previous season can regrow through ratooning, also known as stubble cropping, which is a critical agricultural practice in sugarcane cultivation where a new crop is grown from the regrowth of stubble left behind from the previous harvest. This method eliminates the need for replanting, utilizing the remaining roots and base of the old plants to sprout new shoots. Raising

one to two ratoons in India is customary, making it a cost-effective and labor-saving technique, as it bypasses the initial stages of crop establishment. In this year's experimental field, ratoon sugarcane cultivation combined with drip irrigation was chosen for the study.

6.7.1 Irrigation

Sugarcane crops under a drip irrigation system were irrigated as per crop water requirement, which is given once every three days based on the soil moisture of the crop field. The Source of water is the canal; however, sometimes the canal is not in operation, so the irrigation gap may be more. A total of 1232 m length of lateral lines are placed in the field. The emitter spacing is 30 cm, and the total emitters in the area are 4106. The flow rate of each emitter is 2 liter/hr. All specifications of the drip irrigation system are given in Table 6.16. The net irrigation and gross irrigation requirements are calculated using equations given in the previous section. The wetted area for sugarcane is considered 50%. Irrigation details of drip-irrigated sugarcane are given in Table 6.17, and flood irrigation details are given in Table 6.18. Table 6.19 shows the comparison between drip and flood irrigation. The comparison indicates that the water required for drip irrigation is 40 % less than the water used for flood irrigation. Fig. 6.17 shows the drip irrigation in the field.

Table 6.16: Specifications of drip irrigation system

S.no	Parameters	Value
1	Sugarcane Area	77×18 m
2	Row to Row spacing	1.2 m
3	Total Rows	16
4	Total length of laterals	1232 m
5	Emitter spacing	30 cm
6	Total emitters	4106
7	Emitter capacity	2 litre/hr
8	Total discharge	8212 litre/hr

Table 6.17: Irrigation details of drip irrigated sugarcane (Area =1386 m²)

Irrigation	Date	DAS	Net Irrigation (mm)	Gross Irrigation (mm)	Duration of irrigation (min)	Irrigation Applied (m ³)	Depth of irrigation applied (mm)
1	27-01-22	3	7.01	7.79	44	6	8
2	30-01-22	6	1.82	2.03	15	2	3
3	02-02-22	9	1.77	1.97	15	2	2
4	08-02-22	15	2.42	2.69	19	3	3
5	11-02-22	18	2.64	2.93	20	3	3
6	14-02-22	21	2.87	3.19	21	3	4
7	17-02-22	24	3.53	3.92	25	3	4
8	20-02-22	27	3.65	4.06	26	4	5
9	23-02-22	30	4.52	5.02	30	4	6
10	26-02-22	33	3.59	3.99	25	3	4
11	01-03-22	36	4.38	4.87	30	4	5
12	04-03-22	39	5.06	5.62	34	5	6
13	07-03-22	42	10.96	12.18	67	9	13
14	10-03-22	45	6.41	7.13	41	6	8
15	13-03-22	48	7.69	8.55	48	7	9
16	16-03-22	51	7.76	8.62	49	7	9
17	19-03-22	54	8.73	9.7	54	7	10
18	22-03-22	57	9.07	10.08	56	8	11
19	25-03-22	60	9.82	10.91	60	8	11
20	28-03-22	63	11.1	12.33	68	9	13
21	31-03-22	66	11.8	13.11	71	10	14
22	03-04-22	69	11.92	13.24	72	10	14
23	06-04-22	72	11.78	13.09	71	10	14
24	09-04-22	75	13.37	14.85	80	11	15
25	12-04-22	78	14.44	16.04	86	12	17
26	15-04-22	81	15.61	17.34	93	13	18
27	18-04-22	84	14.4	16	86	12	16
28	21-04-22	87	16.25	18.06	96	13	19
29	24-04-22	90	15.56	17.29	93	13	18
30	27-04-22	93	19.08	21.2	112	15	22
31	30-04-22	96	18.57	20.63	110	15	21
32	03-05-22	99	18.93	21.03	112	15	22
33	06-05-22	102	19.07	21.19	112	15	22
34	09-05-22	105	18.89	20.99	111	15	21
35	12-05-22	108	17.96	19.96	106	15	20
36	15-05-22	111	19.14	21.27	113	15	22
37	18-05-22	114	18.94	21.05	112	15	22
38	21-05-22	117	17.91	19.91	106	14	20
39	24-05-22	120	14.65	16.27	87	12	17
40	27-05-22	123	17.29	19.21	102	14	20
41	30-05-22	126	19.51	21.68	115	16	22
42	02-06-22	129	19.72	21.91	116	16	22
43	05-06-22	132	21.72	24.13	127	17	25
44	08-06-22	135	20.69	22.99	121	17	23
45	11-06-22	138	20.83	23.14	122	17	24
46	14-06-22	141	22.19	24.66	130	18	25
47	18-06-22	145	16.56	18.40	98	13	19
48	21-06-22	148	11.76	13.07	71	10	14
49	24-06-22	151	18.36	20.40	108	15	21
50	27-06-22	154	17.57	19.52	104	14	20
51	30-06-22	157	13.77	15.30	83	11	16
52	03-07-22	160	11.81	13.12	72	10	14

Irrigation	Date	DAS	Net Irrigation (mm)	Gross Irrigation (mm)	Duration of irrigation (min)	Irrigation Applied (m ³)	Depth of irrigation applied (mm)
53	06-07-22	163	17.00	18.89	101	14	19
54	09-07-22	166	17.42	19.00	101	14	20
55	13-07-22	170	17.06	18.95	101	14	19
56	16-07-22	173	13.37	14.86	80	11	15
57	24-07-22	181	16.28	18.09	97	13	19
58	27-07-22	184	18.64	20.71	110	15	21
59	30-07-22	187	10.15	11.28	62	9	12
60	02-08-22	190	11.26	12.51	68	9	13
61	10-08-22	198	17.96	19.96	106	15	20
62	13-08-22	201	14.89	16.54	89	12	17
63	16-08-22	204	12.35	13.73	75	10	14
64	19-08-22	207	16.68	18.53	99	14	19
65	22-08-22	210	12.39	13.77	75	10	14
66	25-08-22	213	16.12	17.91	96	13	18
67	28-08-22	216	15.04	16.71	90	12	17
68	31-08-22	219	12.76	14.18	77	11	14
69	03-09-22	222	12.79	14.21	77	11	14
70	06-09-22	225	15.75	17.50	94	13	18
71	09-09-22	228	11.50	12.78	70	10	13



Fig. 6.17: Drip irrigation in sugarcane

Table 6.18: Flood irrigation details of Ratoon sugarcane (Area =1386 m²)

Irrigation	Date	DAS	Net irrigation requirement (mm)	Gross irrigation requirement (mm)	Flow rate (l/s) diverted from source	Flow rate (l/s) delivered to field	Conveyance Efficiency (%)	Duration of irrigation (min)	Irrigation supplied (m ³)	Depth of irrigation (mm)	Field Application Efficiency (%)	Irrigation efficiency (%)
1	19-03-22	54	55	93.54	27	26	97	109	173	125	44.17	43.06
2	05-04-22	71	62	105.44	30	28	94	115	196	141	43.92	41.51
3	17-04-22	83	58	98.64	25	24	96	129	186	134	43.14	41.42
4	30-04-22	96	75	127.55	26	25	95	137	205	148	50.82	48.28
5	12-05-22	108	76	129.25	28	27	95	133	214	155	49.11	46.65
6	19-05-22	115	35	59.52	27	26	95	72	112	81	43.39	41.22
7	02-06-22	129	63	107.14	25	24	94	122	176	127	49.61	46.88
8	09-06-22	136	50	85.03	25	24	94	93	135	97	51.50	48.58
9	16-06-22	143	51	86.73	24	24	93	101	143	103	49.57	46.10
10	23-06-22	150	34	57.82	32	31	96	58	106	76	44.46	42.68
11	07-07-22	164	47	79.93	34	33	97	72	143	103	45.56	44.42
12	14-07-22	171	39	66.33	25	24	97	79	115	83	46.98	45.57
13	28-07-22	185	35	59.52	24	23	96	72	99	72	48.81	46.86
14	18-08-22	207	51	86.73	26	25	97	101	152	110	46.41	45.02
15	25-08-22	213	34	57.82	25	24	95	72	102	74	46.00	43.70
16	01-09-22	220	38	64.63	26	24	93	79	115	83	45.91	42.69
17	08-09-22	227	34	57.82	28	27	97	65	105	76	44.70	43.35

6.7.2 Comparison of Flood and Drip Irrigation

The information provided in Table 6.19 demonstrates the advantages of using drip irrigation systems over conventional flood irrigation methods, with a particular focus on water efficiency. This table shows that drip irrigation leads to a significant 40% reduction in water consumption. Additionally, in exploring agricultural productivity, data from sugarcane fields were analyzed by taking samples from a standardized area measuring 10 meters by 10 meters in both drip-irrigated and flood-irrigated plots to project yields per hectare. According to Table 6.20, the water productivity is 6.75 kg/m³ for drip irrigated plots and 4.46 kg/m³ for flood irrigated sugarcane, which highlights the superior efficiency of drip irrigation systems. Comparison underlines the pivotal role that efficient irrigation techniques play in enhancing both yield and water productivity in sugarcane cultivation.

Table 6.19: Comparison of drip and flood irrigation

S.No.	Parameters	Flood Irrigation	Drip Irrigation
1	Irrigation Required (m ³ /ha)	8370	8370
2	Effective Rainfall (mm)	479	479
3	Irrigation Supplied (m ³ /ha)	17870	10750
4	Avg. Conveyance Efficiency	90%	95%
5	Avg. Application Efficiency	42.16%	77.86%
6	Irrigation Efficiency	37.95%	73.97%
7	Water Saving	40%	

Table 6.20: Yield attributes of drip and flood irrigation system

S. No.	Parameters	Flood Irrigation	Drip Irrigation
1	Area (m ²)	1386	1386
2	Yield (tons/hectare)	101	105
3	Crop ET (mm)	1100	1100
4	Effective Rainfall (mm)	479	479
5	Irrigation Applied (mm)	1787	1070
6	Crop Water Use Efficiency (kg/hectare/mm)	91.83	95.11
7	Field Water Use Efficiency (kg/hectare/mm)	44.58	67.54
8	Water Productivity (kg/m ³)	4.46	6.75

6.8 Conclusions

In this study, the effectiveness of micro-irrigation methods was evaluated. The following conclusions are drawn from the present study-

- (1) Precision irrigation methods significantly improve water efficiency and productivity. Using a micro-sprinkler system for wheat reduced water usage by 28% and increased water productivity from 0.91 to 1.18 kg/m³. Mini sprinklers further enhanced efficiency, saving 30% more water and boosting productivity to 1.75 kg/m³ compared to 1.09 kg/m³ with flood irrigation. In sugarcane cultivation, drip irrigation conserved up to 40% more water, raising water productivity to 6.75 kg/m³ from 4.46 kg/m³ under traditional flood irrigation.
- (2) The broader implications for regions with limited water resources are significant. In the Gadarjudda Minor Canal command area, sugarcane and wheat are the primary crops cultivated and are well-suited to the region's climate and soil. Adopting sprinkler irrigation for wheat can save up to 30% of water, allowing for the irrigation of an additional 43% of the land with the same water allocation. Similarly, drip irrigation for sugarcane can reduce water consumption by 40%, enabling the irrigation of an additional 67% of the land. These points have been elaborated upon in the revised report to emphasize the potential of micro-irrigation as a sustainable solution for water conservation in regions with limited water availability.

CHAPTER 7

SOIL MOISTURE ESTIMATION USING REMOTE SENSING

7.1 Introduction

The amount of water present in the pores space of the topmost soil layer (0-5 cm) is known as surface soil moisture (SSM), a crucial parameter for agricultural and atmospheric studies (Lei et al. 2022). It is mainly affected by climatic variables (rainfall and temperature), human intervention (irrigation), and soil's physical properties (Pandey et al. 2021). In agricultural studies, soil moisture plays a key role and has various applications, such as irrigation scheduling, crop yield estimation, evapotranspiration estimation, and drought monitoring (Dave et al., 2021). Hence, monitoring soil moisture at a regional scale for proper irrigation planning and management is essential. Numerous conventional techniques, such as the oven-dry method, time domain reflectometry (TDR), neutron probe, frequency domain reflectometry (FDR), and tensiometers, are used to measure soil moisture. These instruments have several advantages, such as being easy to install and maintain, being portable, measuring at the desired depth, and providing direct and reliable accurate measurements (Ochsner et al. 2013; Susha et al. 2014). In contrast, these have a considerable disadvantage; they have limited spatial representation, with a maximum of up to a few squares (Babaeian et al. 2019). Therefore, monitoring soil moisture on a regional scale using traditional techniques is very costly and time-consuming.

Over the last few decades, several SAR-based algorithms have been developed to estimate soil moisture, classified as theoretical, empirical, and semi-empirical models. Dubois model (Dubois et al. 1995), the Oh model (Oh, 2004), the Small perturbation model (SPM), and the Integral equation model (IEM) (Fung et al. 1992) are a few examples of semi-empirical models. All these models were applied over the bare soil for estimating SM, but they cannot be used directly over the vegetated area. As soil and vegetation contribute to the total backscattering signal, separating the backscattered signal from the entire backscattered signal is necessary to estimate the soil moisture. Therefore, the water cloud model (WCM) (Ulaby et al. 1984; Attema and Ulaby 1978) is most popular in the research community. It is used to estimate soil moisture over the vegetated area because it needs prior information and is easy to implement. In WCM, vegetation water content is one of the most crucial parameters; therefore, researchers used biophysical factors to remove its effect on assessing soil moisture. The biophysical factors are mainly estimated using optical-based vegetative descriptors, namely, normalized difference vegetation index (NDVI) (Rouse et al. 1973), Leaf area index (LAI) (Gong et al. 2003), normalized difference moisture index (NDMI) (Gao 1996), and Enhanced Vegetation Index (EVI) (Huete et al. 1997). Similarly, the radar vegetation index (RVI) (Trudel et al. 2012), depolarization ratio, backscatter intensity ratio, and VH polarization (Vertical characteristics signal sent by radar/sensor,

horizontal characteristics signal received by radar/sensor) are the SAR-based vegetative descriptors for estimating the vegetation water content. Several researchers (Bao et. 2018; Yadav et al. 2021; Wang et al. 2021; Chaudhary et al. 2021; Zhang et al. 2021; Lei et al. 2022) incorporated the above-mentioned vegetative descriptors in their studies to improve the accuracy of WCM, but those studies were mainly applied over larger size plots. Selecting suitable vegetative descriptors to estimate soil moisture over small-width fields ranging between 25m-35m is very challenging. Therefore, further work must be conducted to choose suitable vegetative descriptors to improve the accuracy of WCM over a plot of smaller size.

This study develops a technique to retrieve the surface soil moisture over the wheat crop using the modified water cloud model (MWCM). The sentinel-1 (SAR) and sentinel-2 (optical) data-based vegetative descriptors were used in MWCM to eliminate the effect of vegetation water content on SSM estimation. The main focus of the study is on investigating the implications of different descriptors, namely Radar Vegetation Index (RVI), depolarization ratio, Backscatter Intensity Ratio, and NDMI, on the performance of MWCM to estimate SSM over the wheat plot of widths ranging between 25m-35 m.

7.2 Remote Sensing Data

The SAR (Sentinel-1) and Optical (Sentinel-2) images were acquired from the European Space Agency (ESA) Copernicus Open Hub (<https://scihub.copernicus.eu/>). The sentinel-1 and sentinel-2 are freely accessible, with a temporal resolution of 12 and 10 days, respectively. The frequency of the SAR sensor is 5.405 GHz (C-band) with a spatial resolution of 10m. Sentinel-1 operates at four imaging modes, i.e., Strip map model (SM), Interferometric wide swath (IW), extra-wide swath (EW), and Wave mode (WM) (Fig. 7.1). The product types available from Sentinel-1 are ground range detection (GRD) and single look complex (SLC). The processed GRD product provides the backscatter coefficient at a 10 m resolution. On the other hand, the processed SLC product offers data in slant range geometry, including amplitude and phase information. This study used ground range detected product (GRD) with IW imaging modes due to their enhanced image quality and swath width (250 km). The Sentinel-2 multispectral satellite data consists of 13 spectral bands, with four bands at 10 m, six bands at 20 m, and the remaining three at 60 m resolution (Drusch et al. 2012). Its orbital swath coverage is about 290 km. Users get data products of two types, Level-1C and Level-2A. Level-2A products present data in the Bottom of reflectance, whereas Level-1 contains pixel information in the Top of Atmosphere radiances as described in Fig. 7.1. A total of 12 Sentinel-2 images were acquired with less than 10% cloud cover, with dates close to the sentinel-1 acquisition date, which is summarized in Table 7.1.

Sentinel-2 products are used for this work due to their fine temporal and spectral resolution compared to Landsat-8 satellite data products, with a temporal resolution of 16 days and a spectra resolution of 30m. Since Sentinel 2 data can be downloaded at 5- or 10-day intervals, it was possible to compute vegetation indices as required for the entire growth period of the wheat crop.

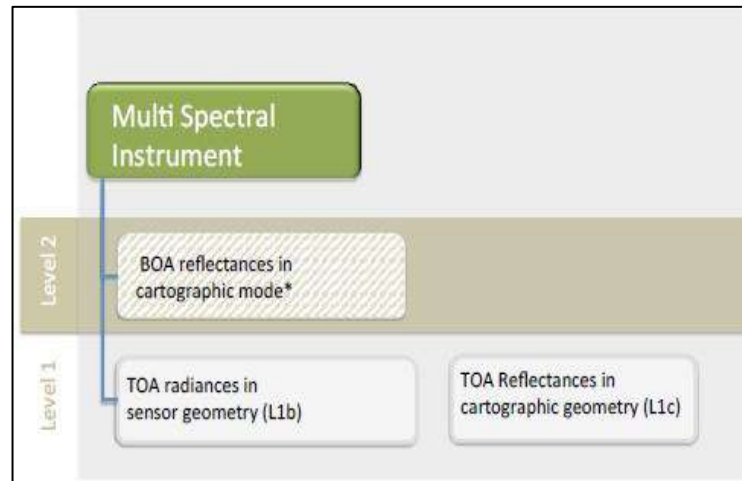


Fig.7.1 Graphical Representation of Sentinel-2 Core Products
(Source: <https://sentinel.esa.int/web/sentinel/missions/sentinel-1/data-products>)

Table 7.1: List of satellite and in-situ soil moisture data acquired over the study area

Sl. No.	Acquisition Date		
	Sentinel-1	Sentinel-2	In-situ soil moisture collection
1	30 th November 2021	30 th November 2021	30 th November 2021
2	05 th December 2021	05 th December 2021	05 th December 2021
3	13 th December 2021	10 th December 2021	13 th December 2021
4	17 th December 2021	15 th December 2021	17 th December 2021
5	21 st December 2021	20 th December 2021	21 st December 2021
6	24 th December 2021	25 th December 2021	24 th December 2021
7	29 th December 2021	30 th December 2021	29 th December 2021
8	10 th February 2022	08 th February 2022	10 th February 2022
9	22 nd February 2022	18 th February 2022	22 nd February 2022
10	11 th March 2022	15 th March 2022	11 th March 2022
11	23 rd March 2022	25 th March 2022	23 rd March 2022
12	30 th March 2022	30 th March 2022	30 th March 2022

7.3 Soil Moisture Data Collection

Field soil moisture data is also needed to calibrate and validate the model for the soil moisture estimation. So, it is necessary to use a reliable field method of soil moisture that gives accurate results, and it should not be time-consuming. The Oven Dry method is the most accurate but time-consuming and laborious. Therefore, the Time Domain Reflectometry (TDR) instrument was used for field data measurement as it is quick and quite accurate. The in-situ surface (0-5 cm) soil moisture data were collected during the Sentinel-1 satellite overpasses using a TDR for developing the soil moisture content model over wheat crops for the entire growth cycle. Detailed information about the in-situ soil moisture data collection in the experimental sites is summarized in Table 7.1. The soil moisture data were collected using the calibrated TDR with random sampling techniques. 480 in situ soil moisture measurements were obtained during the twelve field visits from 30th November 2021 to 30th March 2022 . Field soil moisture data is given in Annexure-A.

7.4 Methodology

In the present era, Microwave remote sensing is one of the most extensively used techniques in estimating soil moisture. Its backscattering signal is dependent on the dielectric constant of soil. As a result, the microwave signal is utilized to retrieve soil moisture. Therefore, the SAR data were used in this study to retrieve soil moisture from the wheat crop. Fig. 7.2 depicts the procedure for developing the wheat crop's surface soil moisture (SSM) estimation methodology. It primarily includes preprocessing, i.e., orbit correction, geocoding, radiometric calibration, geometric correction (Range-Doppler terrain correction), thermal noise removal,

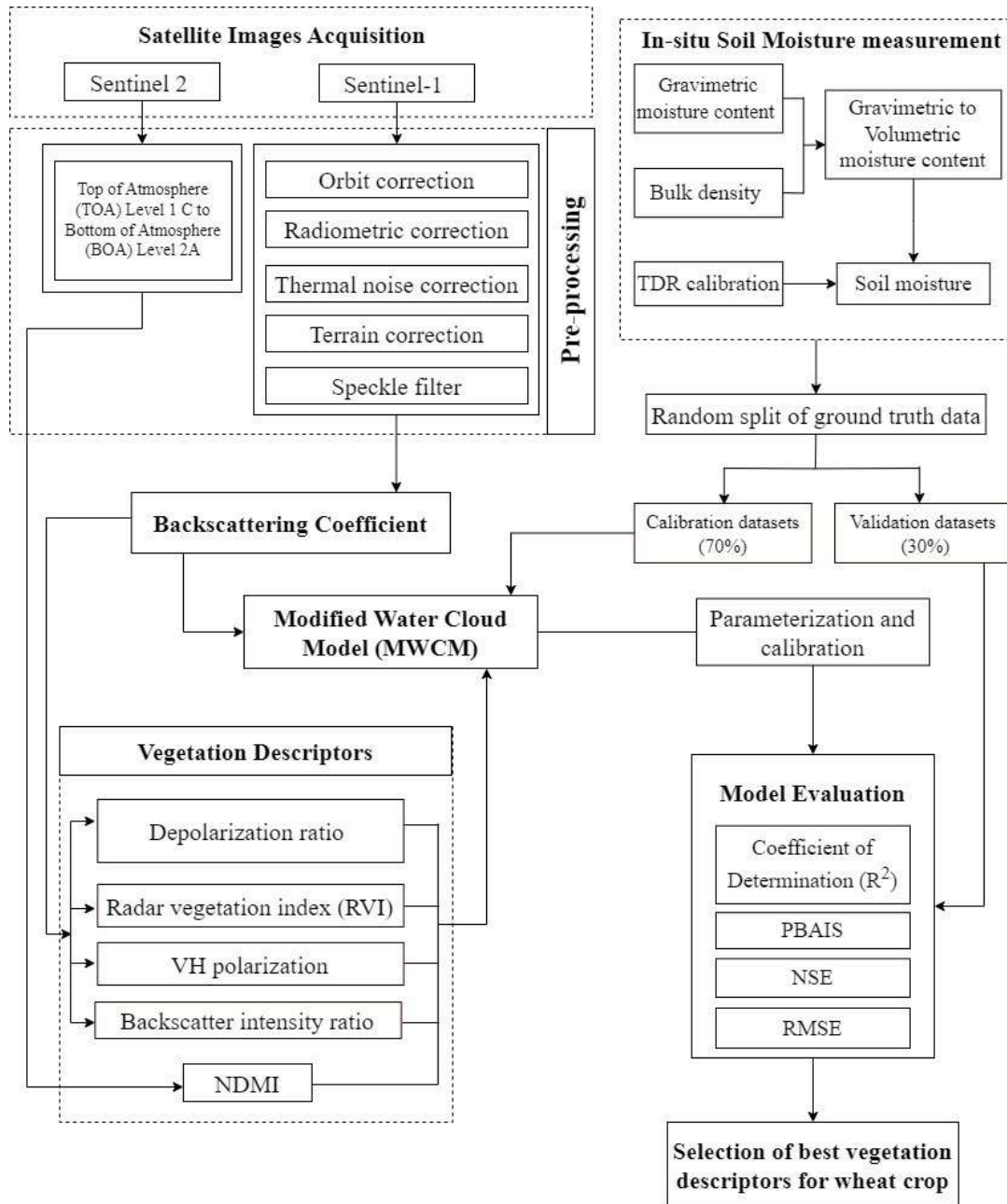


Fig. 7.2 Methodology flowchart for estimation of soil moisture over the wheat field

speckle filtering (Lee filter), and re-projection (WGS 1884 Universal Transverse Mercator coordinates) of Sentinel-1 SAR data using Sentinel Application Platforms (SNAP) tools to transform the backscattered radar signal (in linear/digital number format) into backscattering coefficient (σ°) in dB unit (Fig. 7.3). These backscattering coefficient values (σ_{VV}^0 & σ_{VH}^0) were used to calculate SAR-based vegetative descriptors to estimate the vegetation water content (VWC). In addition, sentinel-2 images were preprocessed, such as radiometric and atmospheric corrections, in the SNAP tool. Furthermore, the preprocessed Sentinel-2 images were used to obtain normalized difference moisture index (NDMI) vegetation maps covering the experimental areas' geographical extent. The

backscattering coefficient, SAR-based vegetative descriptors, and NDMI of each sample were extracted using latitude and longitude coordinates of TDR sample points.

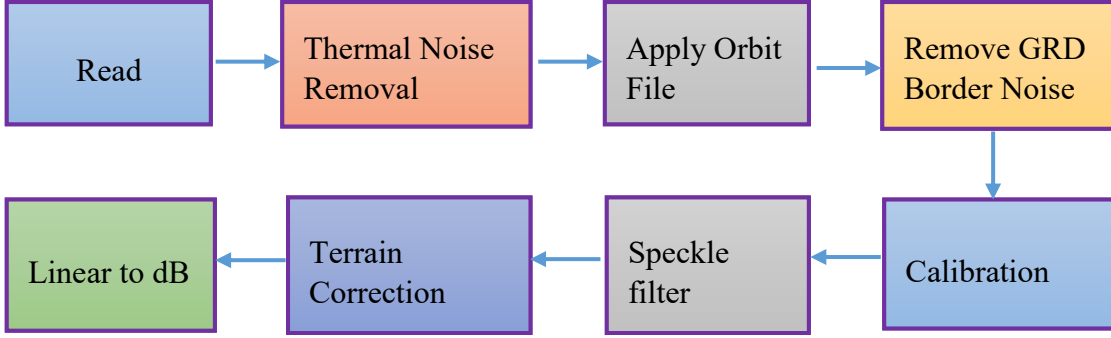


Fig. 7.3 Flow diagram for Pre-processing steps of Sentinel-1A GRD images in SNAP

The water-cloud model (WCM) was employed to develop a semi-empirical model for estimating surface soil moisture (SSM). The WCM includes two crucial parameters, i.e., vegetation water content (VWC) which can be obtained from vegetative descriptors, and soil backscattering coefficient; it may be concisely explained using a linear correlation with SSM. The RVI, depolarization ratio, and backscatter intensity ratio were employed as SAR-based vegetative descriptors, and the NDMI was used as an optical descriptor to estimate VWC. Further, the database has been prepared for model calibration and validation. A random sampling of situ soil moisture data points were segregated into calibration (70%; 340 data points) and validation (30%; 140 data points). After that, a comparison of the performance of different vegetative descriptors in WCM for SM retrieval was made using various statistical indicators.

7.4.1 Water Cloud Model (WCM)

The canopy backscattering model is widely used to investigate the relationship between the backscattering coefficient and soil moisture. The water-cloud model proposed by Attema and Ulaby (1978) was used in this present research to better represent the backscattering of soil and vegetation in vegetation-covered areas. WCM assumed that the vegetation canopy should be uniform horizontal clouds to avoid numerous scattering effects. In WCM, the total backscattering in the dominating vegetation area is the summation of scattering reflected directly from the vegetation canopy and backscattering from the soil (Kumar et al., 2015). WCM is a relatively simple and practical result; it is commonly used to estimate soil moisture over crop-covered areas (Pierdicca et al., 2013). The WCM is mathematically expressed as follows:

$$\sigma_T^0 = \sigma_{veg}^0 + \tau^2 \sigma_{soil}^0 \quad (7.1)$$

$$\sigma_{veg}^0 = A \cdot M_v \cdot \cos\theta \cdot (1 - \tau^2) \quad (7.2)$$

$$\tau^2 = \exp(-2BM_v \sec\theta) \quad (7.3)$$

Where, σ_T^0 represent the total backscattering coefficient (dB); σ_{veg}^0 is the backscattered radar signal from the vegetation canopy (dB); σ_{soil}^0 denotes the backscattering response from bare soil surfaces (dB); τ^2 represents the double attenuation factor through vegetation-soil interfaces; M_v is the vegetation water content (kg/m²); θ is the incident angle (°); A and B are constants related to the vegetation type.

7.4.2 Estimation of Vegetation Water Content (M_v) Using Remote Sensing Data

Vegetation water content is one of the vital parameters in WCM. So, it is necessary to remove the influence of vegetation water content on soil moisture estimation. According to scientific literature, vegetation indices derived from remotely sensed data can be used to estimate vegetation water content (Kim et al. 2012; Qiu et al. 2019). NDVI (Prakash et al. 2012), EVI (Bai et al. 2016), LAI (Chaudhary et al. 2021), and NDMI (Zheng et al. 2014) are some of the most commonly used vegetation indices for estimating vegetation water content using optical remote sensing data. Similarly, SAR-based vegetation indices widely used in assessing vegetation water content are the radar vegetation index (RVI), depolarization ratio, backscatter intensity ratio, and VH polarization. For this study, RVI, depolarization Ratio, backscatter intensity ratio, and NDMI were selected to estimate vegetation water content (Table 7.2).

Table 7.2: List of remote sensing vegetative descriptors

Sl .No	Vegetative descriptors	Formulae
1	Radar Vegetation Index (RVI)	$RVI = 4\sigma_{VH}^0 / (\sigma_{VV}^0 + \sigma_{VH}^0)$
2	Depolarization Ratio	$\sigma_{VH}^0 - \sigma_{VV}^0$
3	Backscatter intensity ratio	$\sigma_{VH}^0 / \sigma_{VV}^0$
4	Normalized difference moisture index (NDMI)	$(NIR - SWIR1) / (NIR + SWIR1)$

Note: σ_{VH}^0 = cross polarization backscattering coefficient; σ_{VV}^0 = co-polarization backscattering coefficient; NIR = reflectivity at the near-infrared band; SWIR1 = reflectivity at the near Shortwave infrared.

Various researchers have shown that the relationship between the vegetation water content and vegetation indices is linear, one-variable quadratic, and exponential. For this study, one-variable quadratic was considered because of its accuracy and simplicity.

$$M_v = aVI^2 + bVI + C \quad (7.4)$$

7.4.3 Soil moisture estimation model

Existing research has found a strong linear relationship between the soil backscattering coefficient and SSM (Zribi and Dechambre 2003; Mattia et al. 2006). As a result, soil volumetric moisture SSM can be used to characterize the soil backscattering coefficient soil.

$$\sigma_{soil}^o = C \times SSM + D \quad (7.5)$$

Bao et al. (2018) developed a semi-empirical model for soil water content estimation. For which they first expand the $\exp(-2BM_v \sec \theta)$ term using the Taylor approximation, and then they substituted the equations (4) and (5) in the water cloud model to develop the soil moisture estimation model. The final developed equation is as follows:

$$\begin{aligned} SSM \\ = & K_1 + K_2\sigma^o + K_3VI + K_4VI^2 + K_5VI^3 + K_6VI^4 + K_7\sigma^o \sec \theta + K_8\sigma^o VI \sec \theta \\ & + K_9\sigma^o VI^2 \sec \theta \end{aligned} \quad (7.6)$$

Where SSM is the surface soil moisture (cm^3/cm^3); σ^o is the VV or VH backscattering coefficient (dB); $K_1 \sim K_9$ is the regression coefficient.

7.4.4 Statistical Analysis

The various statistical indicators, namely Coefficient of determination (R^2), Percent Bias (PBIAS), Nash Sutcliffe Efficiency (NSE), and Root mean square error (RMSE), were used in this study to evaluate the performance of WCM, which shown Table 7.3.

Table 7.3: List of statistical indicators with the mathematical equation

Sl. No	Statistical indicators	Mathematical Equation	Range	Significance
1	Coefficient of determination	$R^2 = 1 - \frac{\sum_{i=1}^n (\theta_i^{\text{sim}} - \theta^{\text{mean}})^2}{\sum_{i=1}^n (\theta_i^{\text{obs}} - \theta^{\text{mean}})^2}$	0-1	Measured the agreement between the observed and simulated
2	Percent Bias	$\text{PBIAS} = \frac{\sum_{i=1}^n (\theta_i^{\text{obs}} - \theta_i^{\text{sim}}) \times 100}{\sum_{i=1}^n \theta_i^{\text{obs}}}$	0-100	Shows whether the model is over-predicting or under predicting
3	Nash Sutcliffe Efficiency	$\text{NSE} = 1 - \frac{\sum_{i=1}^n (\theta_i^{\text{obs}} - \theta_i^{\text{sim}})^2}{\sum_{i=1}^n (\theta_i^{\text{obs}} - \theta_i^{\text{mean}})^2}$	$-\infty$ to 1	Measured the residuals variation between the observed and simulated
4	Root mean square error	$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (\theta_i^{\text{obs}} - \theta_i^{\text{sim}})^2}{N}}$	0 to ∞	Measured the robustness of the model

Note: θ_i^{sim} = ith simulated volumetric moisture content; θ_i^{obs} = ith observed volumetric moisture content; θ^{mean} = mean of observed volumetric content; N = number of observations;

7.5 Results and Discussion

7.5.1 Field Measurements

For the development of the soil moisture model, the in-situ Soil moisture was collected over the wheat plots using the TDR for each date of the sentinel -1 pass, which is summarized in Table 7.4. The measured soil moisture shows that the maximum, minimum, and mean soil moisture varies from 40.3 to 27.9 (m³/m³), 2.5 to 19.2 (m³/m³), and 13.06 to 28.48 (m³/m³), respectively. The soil moisture observation for January is missing due to rainfall. In the study area, the farmers mainly sow the wheat crop in the 1st to 2nd week of November and harvest it by the last week of April. The observation shows that the average moisture content in the wheat plot during the crown root initiation (CRI) and the tillering stage is minimal; however, it is maximum during the flowering (Anthesis) stage and the grain filling stage. The different stages of wheat crop production are shown in Fig. 7.4.

Table 7.4: Statistics of measured volumetric moisture content

Sl no.	Measurement date	Volumetric moisture content (m ³ /m ³)		
		Maximum	Mean	Minimum
1	30 th November 2021	35.1	13.06	6.3
2	05 th December 2021	35.9	15.04	5.4
3	13 th December 2021	38.6	16.3	2.5
4	17 th December 2021	38.6	13.91	4.1
5	21 st December 2021	34	17.30	4.9
6	24 th December 2021	36.3	20.56	3.9
7	29 th December 2021	27.9	14.74	3.5
8	10 th February 2022	36	28.48	19.2
9	22 nd February 2022	33.1	19.25	10.5
10	11 th March 2022	40.3	24.12	10.6
11	23 rd March 2022	31.6	21.48	10.6
12	30 th March 2022	29.9	14.7	7.5



Vegetation stage



Tillering stage



Crown root initiation stage



Flowering stage



Grain filling stage



Maturity Stage



Harvesting stage

Fig. 7.4 Different crop stages of wheat crop

7.5.2 Soil Moisture Estimation Models

This research developed soil moisture estimation models using in-situ soil moisture measurement and SAR data based on localized and generalized concepts. If the relationship or model were established using only one date of the data points, it would be referred to as a localized model. In contrast, a generalized model would be developed utilizing all dates of the data points.

7.5.2.1 Localized Models

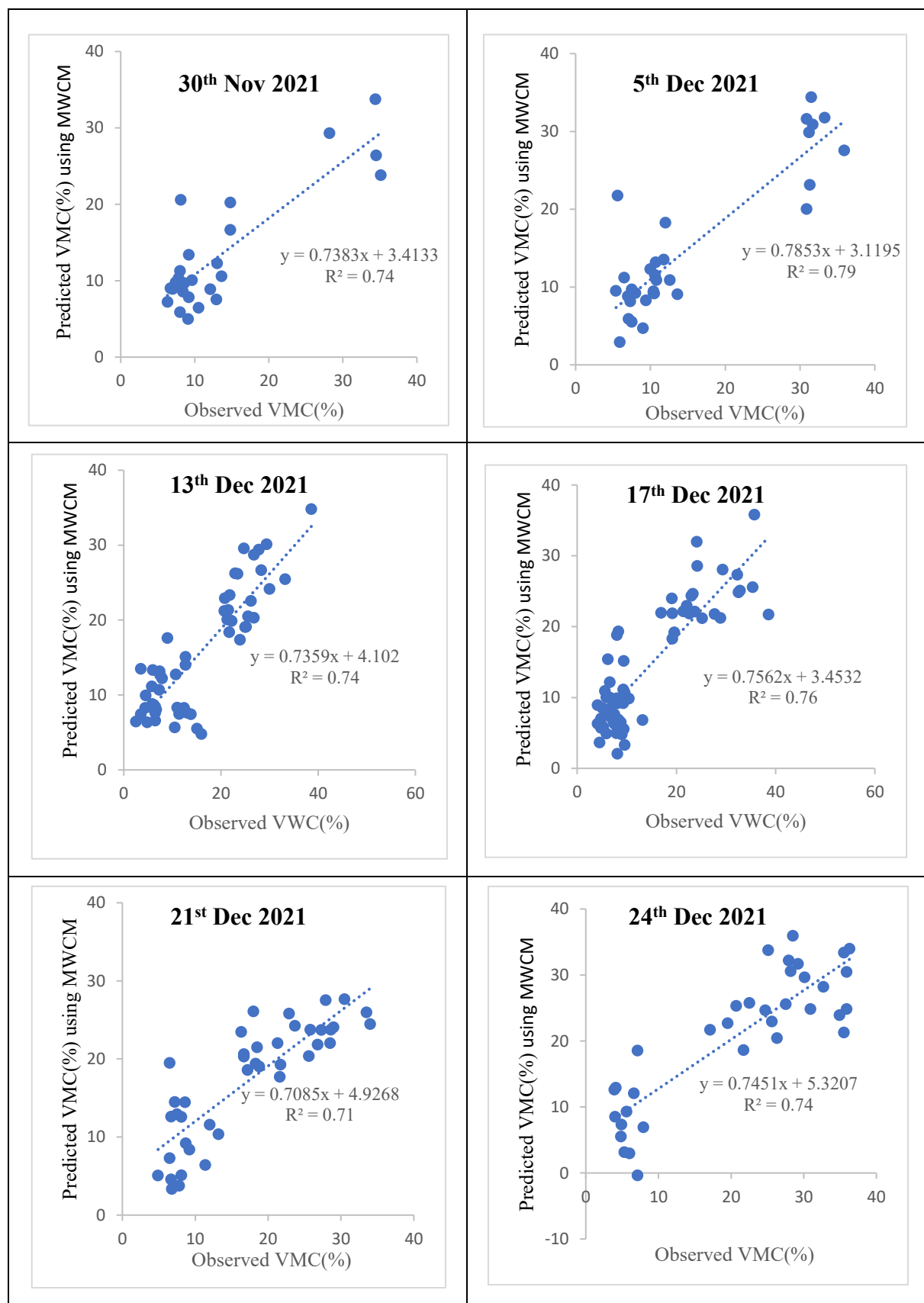
A total of twelve localized WCM models were developed using different vegetative descriptors. The first three localized models are SAR-based vegetative descriptors: RVI, depolarization ratio, and backscatter intensity ratio, and the last one is NDMI, which is optically based. The coefficient of determination and RMSE between the estimated and measured soil moisture based on the different vegetation descriptors are highlighted in Table 7.5. The coefficient of determination of localized developed models using different vegetation descriptors varies from 0.68 to 0.44, 0.67 to 0.49, 0.67 to 0.45, and 0.82 to 0.53 for VH polarization, Radar Vegetation Index (RVI), Depolarization, backscatter intensity ratio and Normalized difference moisture index (NDMI) respectively. The results show that the accuracy of the soil moisture retrieval model varies with the crop's growth stage. Based on statistical indicators R^2 and RMSE, it is evident that the WCM with NDMI as a vegetation descriptor outperformed as compared to the other three vegetation descriptors in estimating soil moisture over the wheat crop. This finding can be highlighted by the fact that the SWIR channel is typically more sensitive to water present in the vegetation (Ceccato et al. 2002 a,b). Since the SWIR band can collect more precise vegetation water content (Chuvieco et al. 2002), it can reduce the influence of vegetation on SSM estimation more efficiently. It is also clear that both RVI and backscatter intensity ratios show almost similar results.

Localized scatter plots between observed soil moisture and estimated SSM using NDMI as vegetative descriptors in MWCM are shown in Fig. 7.6. The scatter plots show that the data points along the best-fit line vary with the crop's growth stage. It is evident from the localized scatter plot that during the CRI and Tillering stage (i.e., for dates namely, 30th November 2021, 05th December 2021, and 13th December 2021) as well as for the jointing stage (i.e., for dates namely, 17th December 2021, 21st December 2021, 24th December 2021 and 29th December 2021), the developed model is underestimating the lower values (< 12 %). The developed model was furthermore overestimating the higher values (>35%) for the jointing stage (i.e., for dates, namely, 17th December 2021, 24th December 2021, and 29th December 2021). In addition, the scatter plots for the grain filling (i.e., for dates, namely, 10th February 2022 and 22nd February 2022) and ripening stage (i.e., for dates, namely, 11th March 2022, 23rd March 2022, and 30th March 2022) show that the data points are along the goodness of line.

The scatterplot Fig.7.5 reveals that the developed model outperformed during the grain filling and ripening stages compared to other growth stages (i.e., CRI, Tillering, and jointing stages). The overall outcome of the study illustrates that the MWCM using NDMI as vegetative descriptors performed well with good agreement with measured moisture content. Therefore, NDMI is used as a vegetative descriptor in MWCM to establish the generalized model to retrieve the SSM for the wheat crop.

Table 7.5: Comparison of agreement between measured and estimated soil moisture for MWCM using different vegetative descriptors

Day no.	Acquisition Date	Vegetation Descriptors			
		Radar Vegetation Index (RVI)	Depolarization Ratio	Backscatter Intensity Ratio	NDMI
		Coefficient of Determination (R^2)			
1	30 th November 2021	0.63	0.1	0.63	0.74
2	05 th December 2021	0.42	0.5	0.45	0.79
3	13 th December 2021	0.57	0.36	0.57	0.74
4	17 th December 2021	0.52	0.58	0.56	0.76
5	21 st December 2021	0.56	0.64	0.59	0.71
6	24 th December 2021	0.59	0.21	0.57	0.74
7	29 th December 2021	0.53	0.53	0.54	0.82
8	10 th February 2020	0.65	0.55	0.67	0.67
9	22 nd February 2022	0.5	0.50	0.61	0.66
10	11 th March 2022	0.42	0.49	0.45	0.79
11	23 rd March 2022	0.56	0.61	0.60	0.63
12	30 th March 2022	0.45	0.62	0.67	0.53



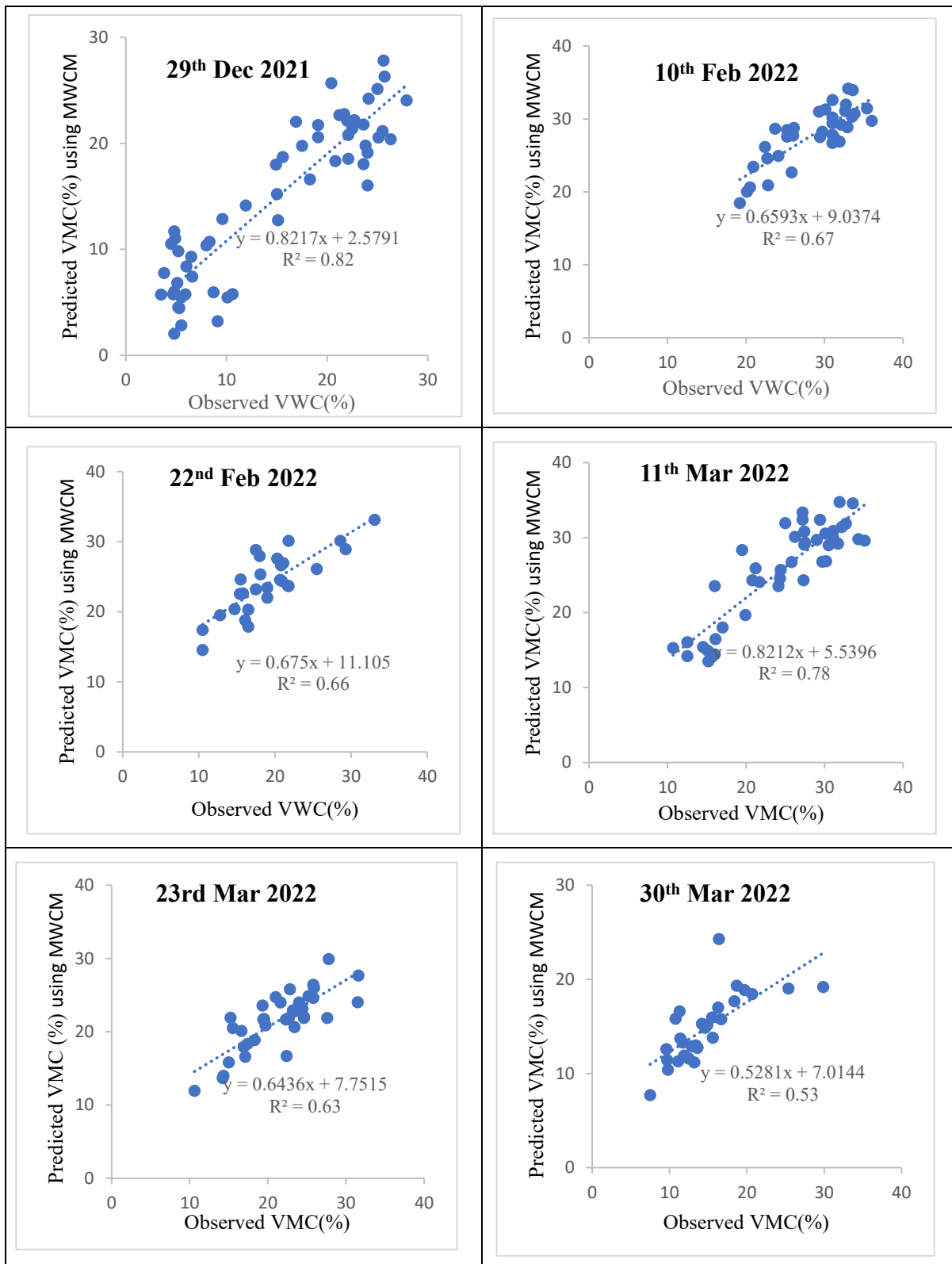


Fig. 7.5: Localized relationship between observed soil moisture and predicted soil moisture from MWCM using NDMI vegetative descriptors

7.5.2.2 Generalized Relationships

In this study, generalized models were developed to explore the effect of the crop's growth stage on the efficacy of WCM in estimating soil moisture. Based on localized results, it can be concluded that NDMI obtained from sentinel -2 satellite data performed better than other SAR-based vegetative descriptors. Therefore, NDMI was selected to develop a generalized model using Eq. (7.6). Furthermore, using the best fitting technique, the coefficients, i.e., $k_1 \sim k_9$ of Eq. (7.6), were obtained based on calibration 340 datasets. The final developed model using VV polarization backscattering (σ_{VV}°) and NDMI for SSM estimation is shown in Eq. (7.7).

$$SSM = 27.48 + 2.605\sigma_{VV}^\circ \sigma^\circ + 106.5NDMI - 42.9NDMI^2 - 513NDMI^3 + 447NDMI^4 - 0.777\sigma_{VV}^\circ \sec \theta + 4.54\sigma_{VV}^\circ NDMI \sec \theta - 11.34\sigma_{VV}^\circ VI^2 \sec \theta \quad (7.7)$$

The obtained coefficients ($k_1 \sim k_9$) are shown in Eq. (7.7). The estimated SSM using the developed model was evaluated using statistical indicators, namely, R^2 , NSE, PBIAS, and RMSE. Based on statistical indicators values for calibration, i.e., ($R^2 = 0.61$, NSE = 0.61, PBIAS = 0.06, and RMSE = 5.84) and validation ($R^2 = 0.55$, NSE = 0.55, PBIAS = 1.31, and RMSE = 6.36) respectively, it can be concluded that developed model performed satisfactorily for both calibration and validation (Table 7.6).

Table 7.6 Statistical indicators values for calibration and validation periods

Period	R^2	PBIAS	RMSE	NSE
Calibration	0.61	0.06	5.84	0.61
Validation	0.55	1.31	6.36	0.55

The scatter plot for calibration and validation is shown in Fig. 7.7. It is quite evident from Fig.7.7 that during calibration, the estimated SSM is underestimated for lower values ($< 12\%$) and higher values ($> 35\%$) whereas overestimated for moderate soil moisture range values (15-30 %). Likewise, during validation, the developed model underestimates lower values ($< 15\%$) and overestimates over moderate moisture values (15-25 %). In addition, Fig.7.6 indicates that the model underestimates some higher values and overestimates others. The scatterplot illustrates that the developed model data points are almost along the goodness of fit line during calibration and validation.

The developed semi-empirical SSM estimation model (MWCM) was used to retrieve surface soil moisture over wheat crops using synergetic satellite data, i.e., Sentinel-1 and Sentinel-2, under cloud-

free conditions. The results of estimated soil moisture using the developed model show considerable consistency with measured soil moisture. Therefore, it can be concluded that the developed MWCM model using NDMI vegetative descriptors is applicable for estimating the surface soil moisture over wheat crops on the regional scale.

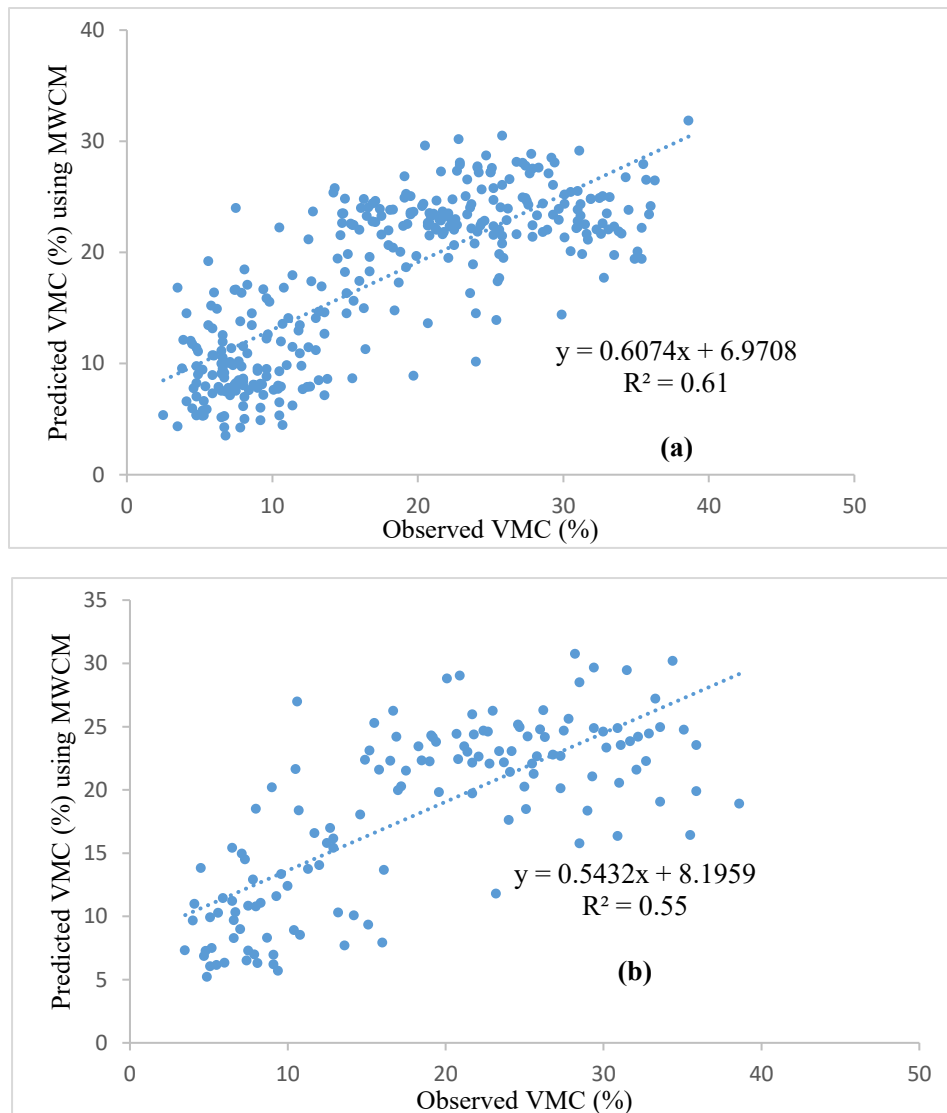


Fig. 7.6: Developed generalized relationship between observed soil moisture and Predicted Soil Moisture using MWCM for (a) calibration and (b) validation

7.6 Conclusion

The Spatio-temporal soil moisture maps derived from microwave remote sensing data allow for real-time assessment of soil moisture conditions, which are not affected by the weather. It supports efficient irrigation scheduling and helps to develop mitigation measures in response to extreme climate events like drought. The present study aims to estimate soil moisture accurately using the MWCM model over the wheat plot. Over vegetation region, SSM estimation seems to be more challenging than in a bare soil region. As a result, removing the vegetation layer's effect on the radar's backscattering coefficient, establishing a realistic vegetation scattering model, and providing a model with acceptable accuracy are critical in monitoring soil moisture remotely. The vegetation water content is one of the important parameters of the MWCM model that can be estimated from vegetative descriptors. It is challenging to select vegetative descriptors over the smaller wheat plot of widths ranging between 25m-35 m because the pixel is distributed in the adjacent fields, which partially captures the features. To overcome the above-said problem, three SAR-based vegetative descriptors (RVI, Depolarization Ratio, and backscatter intensity ratio) and one optical-based (NDMI) were selected to accurately estimate the vegetation water content.

According to the proposed methodology, the backscattering coefficient of VH and VV polarization were extracted with latitude and longitude sample points using preprocessed imagery of sentinel-1. Then, different vegetative descriptors were calculated for each soil moisture sample geographical location using preprocessed SAR and optical images. The soil moisture was estimated over the study using different vegetative descriptors. Based on localized results, it can be illustrated that the NDMI outperformed the other vegetation descriptors. The study concluded that the MWCM model results with NDMI as vegetative descriptors showed an acceptable performance, i.e., the statistical indicators viz., R^2 , PBIAS, RMSE, and NSE were obtained to be 0.61, 0.06, 5.84, and 0.61 for the calibration period and 0.55, 1.31, 6.36 and 0.55 for the validation period, respectively. The study revealed a decrease in the accuracy of MWCM with crop growth stages.

CHAPTER 8

FARMERS SURVEY TO DETERMINE FARMERS' PERSPECTIVES

8.1 Background

A comprehensive survey was conducted to assess farmers' perspectives on adopting improved on-farm water management techniques in the minor command area. Farmers from the head, middle, and tail reaches were questioned about the canal system and their perception of micro-irrigation adoption. A random sampling method ensured unbiased representation of different field conditions and farming practices.

The questionnaire was designed to capture as much relevant information as possible. The interview schedule consists of five major components. First, the respondents' general information is recorded. The second part discusses the cropping and irrigation status of the minor. Third, the techno-economic feasibility of micro-irrigation in the command area is assessed. Fourth, WUA's role is studied. At last, the challenges they encounter with the current irrigation system and when adopting new irrigation technologies are included. The Osarabandi (or Warabandi) schedule, which is the allocation and scheduling of irrigation water among land holdings based on a set rotation, was also examined. Diagnostic analytics of the Gadarjudda minor were performed by postgraduate students from IIT Roorkee, who evaluated various parameters affecting irrigation efficiency also studied. Interactions with farmers during field visits and discussions held in awareness workshops added further depth to this analysis. A farmer's survey aims to understand farmers' mindset regarding micro-irrigation in canal command. A total of 132 farmers were interviewed in their fields and homes. Fig. 8.1 shows the interaction with farmers during the survey.



Fig. 8.1: Interaction with farmers during survey

8.2 Social Survey

The primary data was collected from the respondent farmers through structured interviews to collect relevant information from the farmers. The farmers were interviewed face-to-face in their farm fields and houses. Prior to the start of the interview, the farmers were explained about the study's purpose. The collected information was classified and tabulated, and findings were derived after analysis. The findings are elaborated in this section.

8.2.1 Age Group

The age group of the 132 farmers interviewed is shown in Fig. 8.2. The respondents' age group showed that the majority of farmers, i.e., 55%, were in the middle age group from 36 to 50. The percentage of young farmers below the age of 35 is the lowest, having only 12% of the farmers surveyed. On the other hand, old-age farmers account for 33% of the respondents who are older than 50 years.

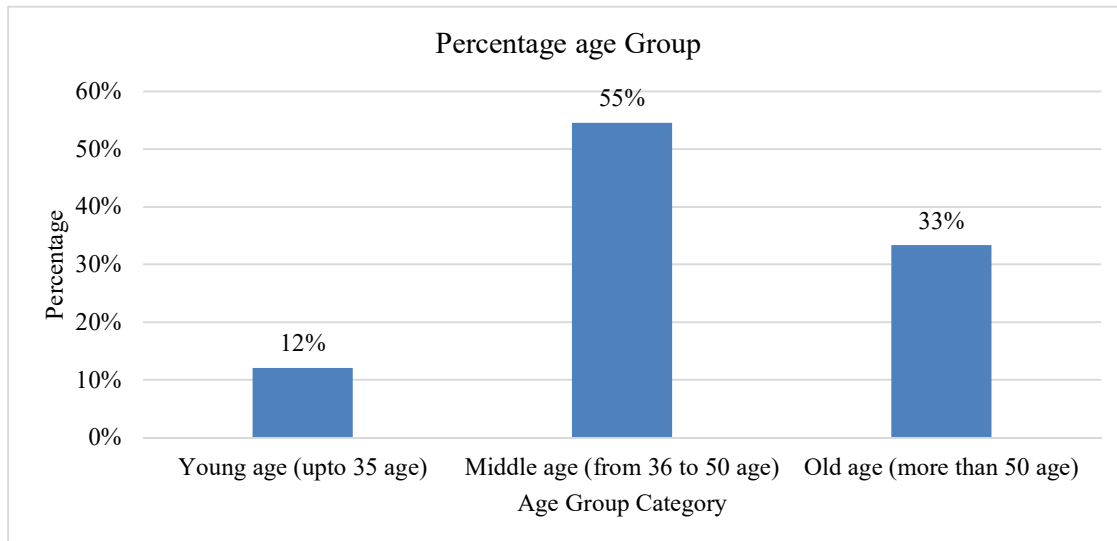


Fig. 8.2: Distribution of farmers by the age group

The farmers' age group also indicates the farmer's acceptance level towards new technology. Young groups are more interested in adopting advanced technology in the farm fields whereas, old age farmer tend to follow their traditional agricultural practices, showing reluctance to change.

8.2.2 Education

The education level of the responding farmers of the minor command is categorized from illiterate, literate, secondary level, higher secondary, under graduate (UG), and post-graduate (PG). Education is an important factor influencing the farmers' perceptions, behavior and attitude. Farmers with higher levels of education tend to have access to information and resources relating to adopting new

technology in their farm fields. Conversely, farmers with lower education levels may resist unfamiliar technologies mentioning high initial cost and technical complexity. About 55% of the respondents have education level of 10th standard, followed by 15% each by 12th standard level (higher secondary) and undergrad level. The percentage of PG was found to be 12% of the total number of farmers interviewed. None of the respondents were illiterate. The result is illustrated in Fig. 8.3.

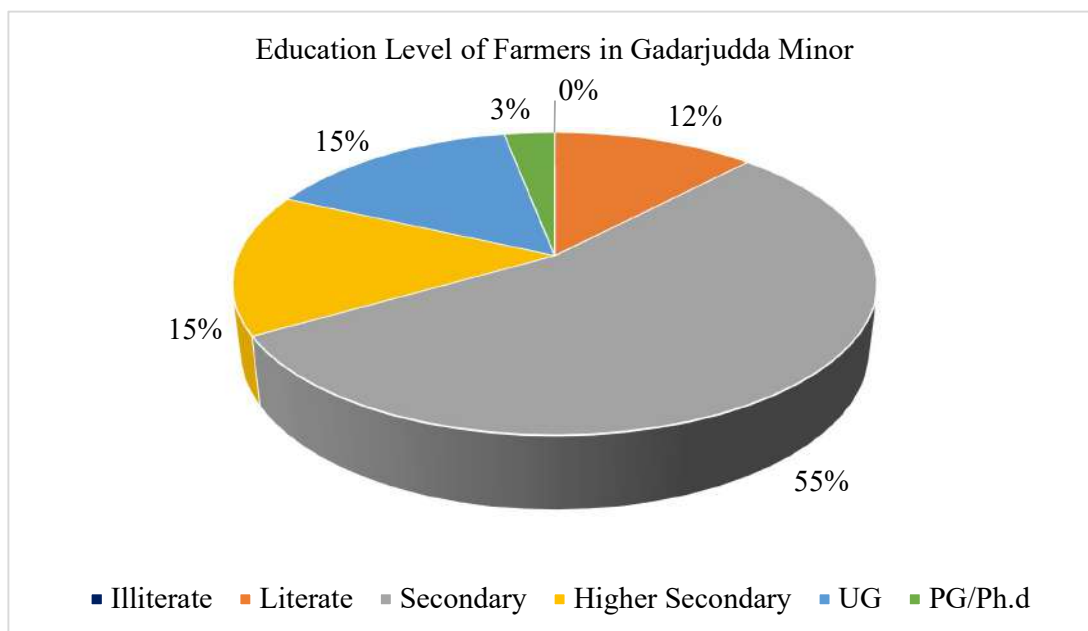


Fig. 8.3: Education level of farmers of Gadarjudda minor

8.2.3 Occupation

The people living in the Gadarjudda command area represent most respondents, about 79% are full-time farmers. 9% are involved in the service sector (government & private jobs), and 12% of the farmers are observed as business owners. More people involved in farming as the main profession indicates the need to refine agricultural practices and upgrade irrigation technology to improve the agricultural productivity of the study area. Fig. 8.4 depicts the occupational background of the farmers in the study area.

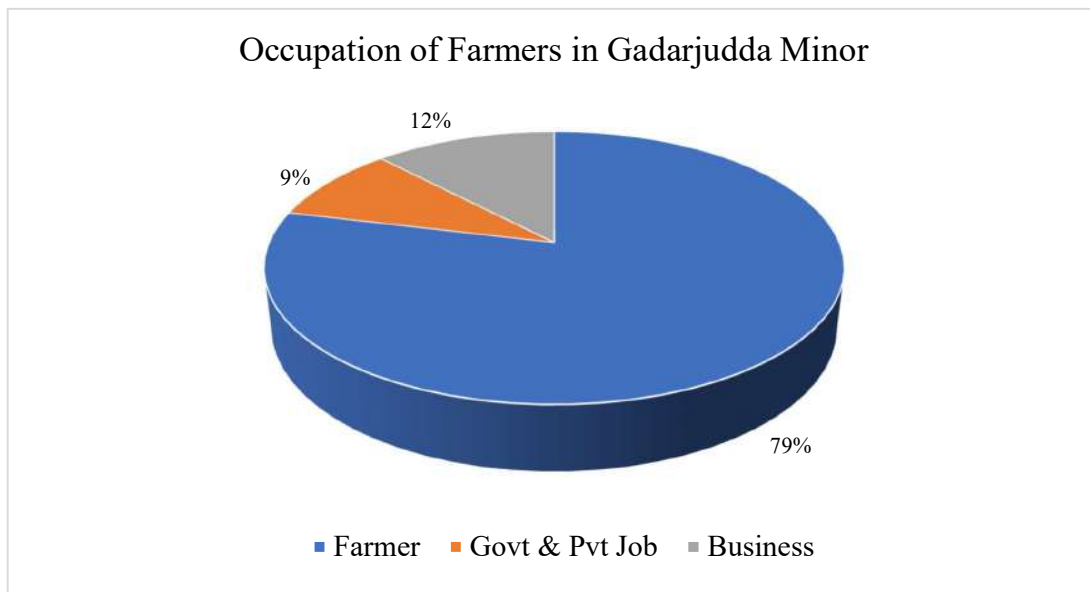


Fig. 8.4: Occupation of farmers in Gadarjudda minor

8.2.4 Cropping Pattern

The cropping pattern of the study area shows dominant crops such as sugarcane, wheat, and paddy. Many farmers have planted poplar trees in their fields. In the rabi season, farmers plant mustard by intermixing with other crops. Fodder and vegetables are grown for domestic consumption. The cropping percentage of these crops is shown in Fig. 8.5. Detailed crop pattern with plantation and harvest is shown in Fig. 8.6.

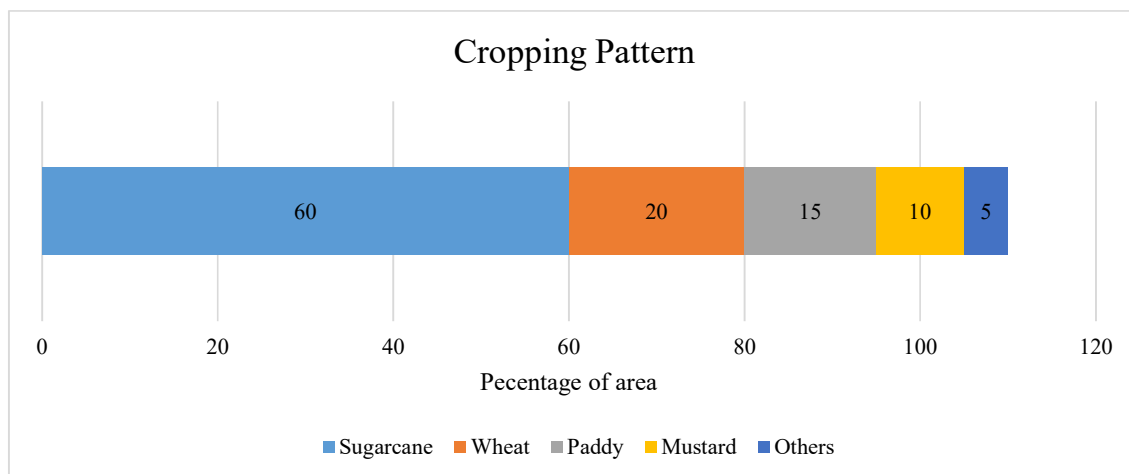


Fig. 8.5: Cropping pattern of the Gadarjudda minor command area

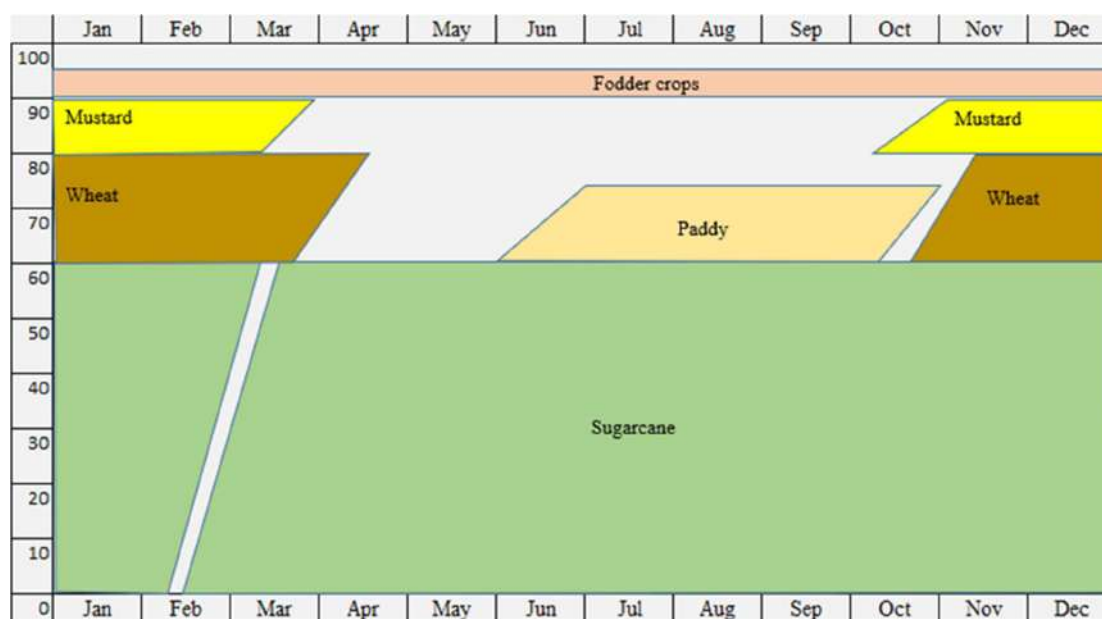


Fig. 8.6: Cropping pattern with plantation and harvest of the crops

8.2.5 Land Holding

The classification of farmers based on the size of their land holdings offers a clear picture of the farming community's structure. In the Gadarjudda command area, 40% are marginal farmers with land holding less than 1 ha, followed by 36% small farmers with an area of 1 to 2 ha. Medium farmers, who own 2 to 4 hectares, represent 18% of the total, and those with more than 4 hectares comprise only 6 % of the total. The sum of the marginal and small farmers dominate the overall land holding of the minor command area. Large and medium farmers tend to have more resources and access to information than small and marginal farmers. Small and marginal farmers tend to have less involvement in irrigation decisions in the command area. The result shows the necessity of support

programs of subsidy and agricultural extension intervention of micro-irrigation technology targeting small and marginal farmers. The farmer's land holding is illustrated in Fig. 8.7.

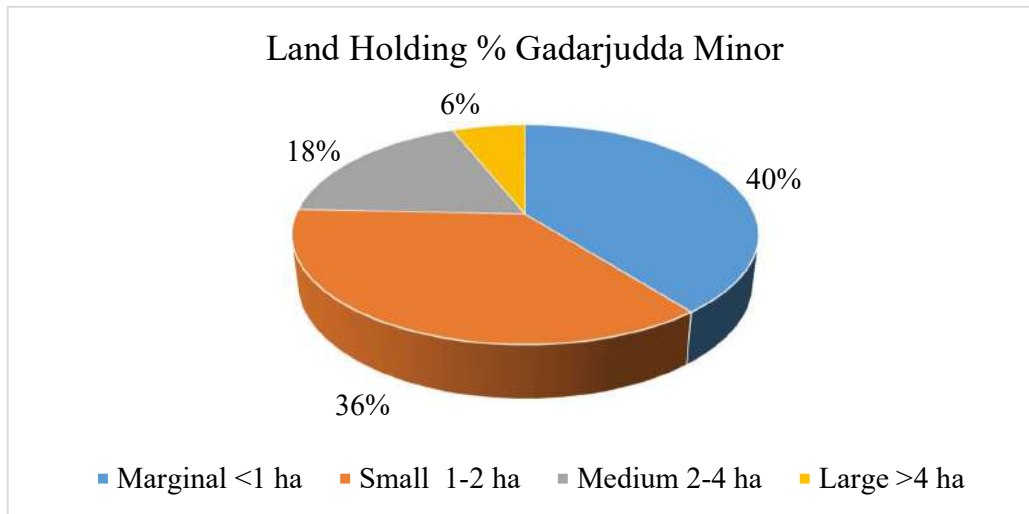


Fig. 8.7: Distribution of land holding among farmers of Gadarjudda minor

8.2.6 Irrigation Source

The irrigation source of the Gadarjudda minor is studied through the questionnaire with the farmers. The result is shown in Fig. 8.8. In head reach 80% of irrigation is performed by minor canal and 20% by groundwater tubewell. Similarly, in the middle reach 44% canal and 56% groundwater. The unavailability of water in the time of requirement in the tail reach compels farmers to use more groundwater than in other reaches. Groundwater use is 72% in tail reach, and canal water is 28%. This trend shows the need to improve canal water conveyance efficiency and efficient water distribution for equity and reliability of irrigation.

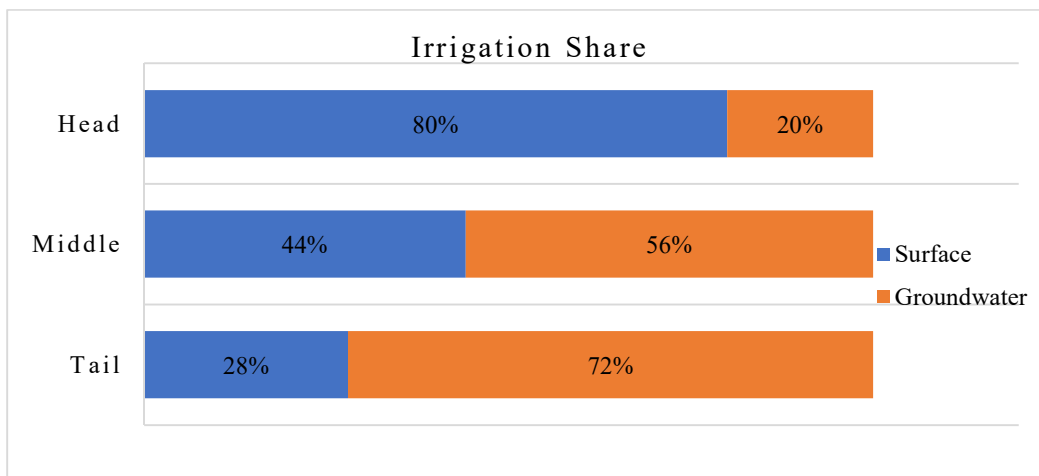


Fig. 8.8: Irrigation source in head, middle and tail end of Gadarjudda minor

8.3 Techno-Economic Feasibility

Feasibility of micro-irrigation in canal command is carried out by using techno-economic feasibility assessment, this method analyzes different characters of farmer like, awareness about the micro-irrigation, knowledge of the system, attitude towards implementation of micro-irrigation, willingness to adopt in their own land and lastly the purchasing capacity denoting the ability of farmer to invest are marked in a Likert scale of score attributes from 0-3, starting from nil (0), low (1), medium (2), and high (3). nil represents negligible agreement to the factor assigned, low denotes minimal agreement to the factor, medium shows moderate level of satisfaction or agreement to the factor, whereas high mean the highest level of agreement or satisfaction by the respondent. Every respondent is given choice to choose on the scale. Descriptive statistics are performed to analyze the data.

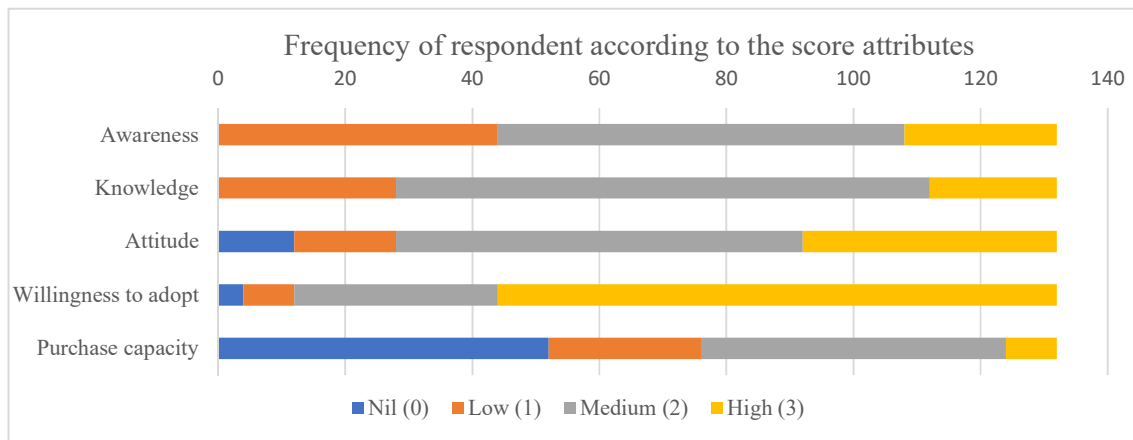


Fig. 8.9: Frequency of respondent according to the socre attributes

For overall evaluation of the different five factors, attributes are given upper and lower limit as shown in Table 8.1. The mean for each factors are determined to classify them in the predefined class of attributes.

Table 8.1: Assignment of lower and upper limit to the attributes

Attributes	Score	Lower limit	Upper limit
Nil	0	0	0.5
Low	1	0.51	1.5
Medium	2	1.51	2.5
High	3	2.51	3

The number of respondents giving response to the respective factors are shown in Table 8.2. Arithmetic mean of each factor is carried out. The factors are then classified on the basis of mean score given by farmers according to Table 8.1.

Table 8.2: Interpretation of the mean score for each factor

Factors	Nil	Low	Medium	High	Mean	Interpretation
Awareness	0	44	64	24	1.85	Medium
Knowledge	0	28	84	20	1.94	Medium
Attitude	12	16	64	40	2.00	Medium
Willingness to adopt	4	8	32	88	2.55	High
Purchase capacity	52	24	48	8	1.09	Low

Table 8.2 shows the high level of willingness of the farmers to adopt micro-irrigation in their fields but with very low purchasing capacity. The awareness, knowledge, and attitude seem to be medium. The overall percentage score of the techno-economic feasibility is presented in Fig. 8.10.

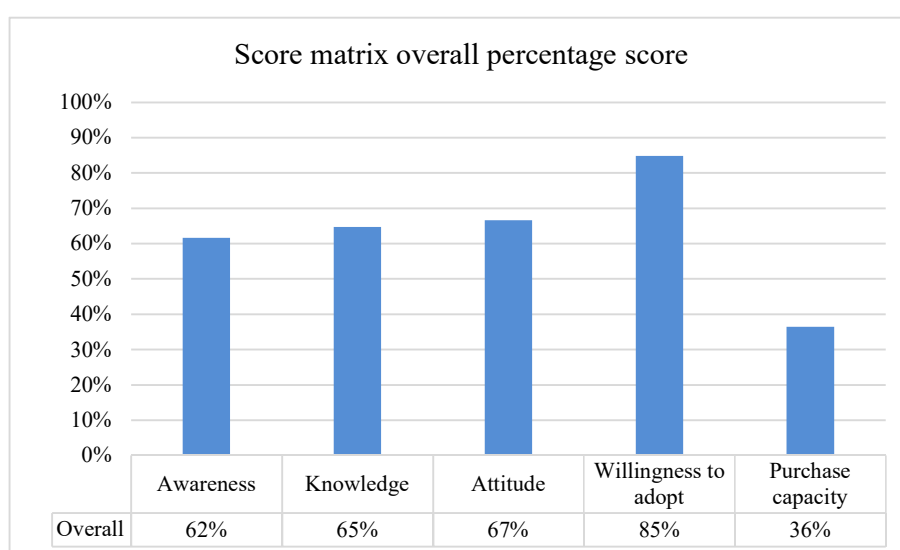


Fig. 8.10: Overall percentage of the score matrix with respect to factors

Overall percentage of the score matrix shows high level of willingness by the farmers to adopt micro-irrigation in their field. Attitude, knowledge and awareness are all increasing from 62 to 67%, which shows the need for technical training and extension services required for successful implementation. The detrimental factor for the adoption of micro-irrigation in canal command of Gadarjudda minor observed in Table 8.2 and Figures 8.9 & 8.10 is low purchasing capacity. Although farmers are ready to adopt the system but they don't have the financial capability. Farmers expect subsidies to be provided to them. This condition is depicted as a challenge to the feasibility of micro-irrigation in canal command, because, even in the government schemes the farmer has to invest 25 to 50% of the scheme cost. Hence, subsidy schemes should focus more on targeted marginal and small land holdings with more incentives and technical training.

8.4 Water User Association (WUA)

Within the Gadarjudda canal command area, no registered Water User Association (WUA) has been established. Consequently, farmers facing issues related to canal irrigation must address these concerns individually, often seeking resolution by directly approaching higher authorities or intermediating through the Gram Pradhan. This one-on-one approach to problem-solving indicates a lack of collective action, which can be pivotal for advocating for farmers' interests and ensuring efficient operation and maintenance of the irrigation system. The absence of a participatory irrigation management (PIM) framework means that issues may take longer to resolve, as there is no structured group representation to streamline communication and decision-making processes. PIM, characterized by joint management and cooperative strategies among users, typically leads to more sustainable and equitable water distribution. Forming a water user association is essential to address the challenges that hinder efficient irrigation practices. Such an association would act as a collective platform for farmers to address common issues related to water management collaboratively. Forming a Water Use Consortium provides a holistic approach to solving farmers' diverse constraints, promoting solidarity, cooperation, and effective resource management within the farming community. Due to absence of WUA farmers faced following challenges-

1. **Water Scarcity at Tail Reach of The Canal:** Farmers at the downstream end of the canal experience water scarcity, especially during peak demand periods, which affects their crop irrigation schedules and overall agricultural productivity.
2. **Improper Distribution of Canal Water:** Uneven water distribution along the canal often leads to conflicts among farmers, as those located closer to the water source tend to receive more water than those further away.
3. **Unexpected Canal Closures:** The closure of minor canals without prior notification disrupts farming activities, leaving farmers unprepared and unable to irrigate their crops adequately.
4. **Irregular Maintenance of the Canal:** Inconsistent upkeep of the canal infrastructure leads to inefficiencies in water flow and delivery, compounding water scarcity and distribution issues.
5. **Lack of Farmer Involvement in Water Distribution Planning:** Farmers are not involved in planning the water distribution roster (Osarabandi), leading to schedules that do not align with their actual water needs and cultivation patterns.

6. **Water Logging in Rainy Season:** During the rainy season, water logging in low-lying agricultural lands impedes farming operations, damages crops, and reduces soil fertility.
7. **Significant Breakages in Water Courses:** Large breakages in the water course infrastructure cause significant water loss, further exacerbating water scarcity and distribution issues.
8. **Water Quality Issues:** Problems with water quality, including contamination and sedimentation, affect crop health and yield, posing additional challenges for farmers striving for efficient and productive agriculture.
9. **Lack of Training for Irrigation Management:** Farmers have not received training in irrigation management, limiting their exposure to improved practices and techniques for efficient water use.
10. **Lack of Awareness About Government Schemes:** There is a shortfall in farmers' awareness of government agricultural schemes, which could lead to underutilization of available resources and support.

Establishing a Water User Association (WUA) could effectively address the challenges in the Gadarjudda canal command area. As a collective body, a WUA would ensure equitable water distribution, particularly to farmers at the tail end, reducing conflicts and promoting cooperation. It would oversee regular maintenance of the canal infrastructure, enhancing water flow and efficiency, and coordinate water distribution planning to meet the actual needs of various crops. Additionally, a WUA could manage infrastructure repairs, improve water quality, and provide training in irrigation management. It could also serve as a link to government agricultural schemes, ensuring farmers have the necessary information and access to these resources. A WUA would be crucial for improving irrigation management, fostering community involvement, and boosting agricultural productivity.

8.5 Challenges in Adaption of Micro-Irrigation

When engaging with farmers to discuss the challenges they face in adopting micro-irrigation, the following key issues are commonly highlighted-

1. **High Installation Cost:** The majority of farmers, about 76 %, are marginal or small in the Gadarjudda canal command area. Their lack of awareness about government subsidies and the high initial costs of micro-irrigation systems pose significant barriers to adoption.
2. **Protection from Animals:** In the study area, agricultural fields are open and susceptible to damage from groups of Nilgai roaming and destroying farms. There is a constant concern over the security of expensive irrigation equipment due to the risk of vandalism.

3. **Electricity Connection and Availability:** In the command area, most farms are located away from the farmers' houses and lack access to electricity, which hinders the use of micro-irrigation systems.
4. **Restrictions from Irrigation Rosters:** The allocation of water through irrigation rosters often limits the timing and frequency of irrigation, posing challenges for effectively using micro-irrigation systems that require precise irrigation scheduling.
5. **Canal Water Quality:** The water quality from canals is sometimes unsuitable for micro-irrigation systems due to high sediment levels or contaminants that can clog or damage the system.
6. **Maintenance of the System:** Farmers lack the skills required for regular maintenance to keep micro-irrigation systems operational, which poses a challenge for some to manage effectively.
7. **Low Water Flow Issues:** Occasionally, in the minor canal, the water flow is too low to be effectively distributed through micro-irrigation systems, compromising their efficiency and the uniformity of water delivery to crops.
8. **Fragmented Farmer Plots:** The scattered nature of farmers' plots complicates the installation and management of micro-irrigation systems.
9. **Cultural Practices:** Traditional farming methods are deeply ingrained in agricultural communities. Shifting to a new irrigation method requires changing these established practices, which is a significant cultural and behavioral challenge.

Numerous challenges hinder the adoption of micro-irrigation in the Gadarjudda canal command area. To overcome the above barriers, raising awareness about government subsidies to help cover installation costs, secure fields against wildlife, provide reliable electricity, and offer training programs to improve farmers' maintenance skills is essential. Additionally, gradually integrating new practices can help shift traditional farming methods towards improved on-farm water management techniques, facilitating the transition to micro-irrigation systems and enhancing agricultural sustainability.

8.6 Conclusions

In the Gadarjudda canal command area, a significant amount of agricultural land is used for sugarcane and wheat, suggesting that these focused farming practices could benefit from specific interventions. The demographic composition of the area's farmers, predominantly marginal and small-scale, indicates that these individuals might not have extensive financial resources at their disposal, yet they are educated enough to benefit significantly from specialized training programs. Training in on-farm water management could be particularly advantageous. Since around 80% of the local population is directly engaged in agriculture, enhancing water management skills could substantially improve crop yield and resource efficiency. The need for consistent water availability is acute throughout the cropping period and is particularly critical in the tail reaches of the canal command area, where water distribution is likely less efficient. To address these challenges comprehensively, the formation of Participatory Irrigation Management (PIM) groups or Water Users Associations (WUA) is recommended. These organizations empower farmers by involving them directly in the management and decision-making processes related to irrigation practices. Such collective management structures can enhance accountability, improve resource allocation, and facilitate equitable water distribution.

The adoption of micro-irrigation systems is seen as a necessary advance for the region; however, it requires a holistic approach rather than piecemeal or individual efforts. Micro-irrigation can significantly increase water efficiency by organizing into PIMs or WUAs. Farmers can share the burden of managing these systems, reduce individual costs, and improve overall effectiveness. This collective approach simplifies the logistical aspects of micro-irrigation and fosters a community-based solution to broader agricultural challenges.

CHAPTER 9

FARMERS AWARENESS PROGRAMMS FOR DISSEMINATION OF PROJECT OUTPUT

To encourage farmers, several awareness activities have been organized. These initiatives aim to illustrate the benefits of micro-irrigation in the farmers' field where micro irrigation was installed and used. Additionally, these efforts support the formation of water user associations, which help in managing irrigation resources more effectively and sustainably. Through these activities, farmers are provided with demonstrations and educational resources, empowering them to make informed decisions about their irrigation practices.

9.1 Kisan Chaupal

At the beginning of the project on date December 27, 2020, a kisan chaupal was held in Nagla Aimad village to facilitate direct interaction with farmers. This program served as a crucial platform where not only local farmers from Nagla Aimad but also progressive farmers from neighboring villages participated. During the chaupal, discussions about the project's objectives, planning, and execution took place. Farmers engaged enthusiastically in conversations about irrigation methods and agricultural practices. This initial workshop established a solid foundation for fostering farmer cooperation throughout the project. A photograph of Kisan Chaupal is shown in Fig. 9.1.



Fig. 9.1: Kisan Chaupal at Nagla Aimad village

9.2 Farmers Awareness Workshop-I

A farmer awareness workshop was organized at Village Nagla Aimad, Narsan Block, District Haridwar on 15th March 2023. The main objective of the workshop was to share the progress made so far in the project and to increase awareness among farmers about the importance of water management in agriculture. This workshop served as a useful platform for the farmers to interact with experts, share

their experiences and gain knowledge about modern technologies in irrigation water management. The importance of micro-irrigation, water conservation and water user associations were discussed in the workshop. Attendees were encouraged to ask questions and share their thoughts and experiences related to the topic. One hundred sixty-one stakeholders from villages including Nagla Aimad, Jhibran, Kurdi, Thaska, Harjoli, Libhareedi, Kumrada, Alawalpur, Munder, Bawakhedi and Roorkee participated in the workshop. The chief guest in the program was Mr. Anuj Kanwal, Commissioner, Command Area Development and Water Management (CADWM) and Bureau of Water Use Efficiency (BWUE). Farmers and guests present at the workshop visited the experimental field, where they shared their experiences. Photographs of farmers awareness programme are shown in Fig. 9.2.



Fig. 9.2: Farmer awareness workshop at Nagla Aimad Village

9.3 Kisan Chaupal

A kisan Chaupal was organized on September 1, 2023, in Nagla Aimad village. The chief guest of the program was Padmashree Umashankar Pandey, who received the Padmashree award for his contributions to water harvesting and conservation. During his interaction with farmers, Shri Pandey shared how the dire water level situation in his native village in Bundelkhand, Uttar Pradesh, motivated him to champion water harvesting and management. He shared his numerous initiatives and 'Paani ke Pehredaar' model to improve groundwater levels. He urged everyone to commit to water conservation.

Farmers engaged enthusiastically in conversations with Shri Pandey, who later visited the experimental field and shared his insights. Photographs of programme are shown in Fig. 9.3.



Fig. 9.3: Kisan Chaupal at Village Nagla Aimad and Experimental field visit

9.4 Awareness Workshop-II

An awareness workshop took place at the IIT Roorkee, as part of the project. This programme aimed to disseminate project activities, observations, analysis and results among farmers, students, and scholars. It covered topics such as micro-irrigation, water conservation, IoT applications in irrigation, and the role of water user associations. The session facilitated engaging discussions with experts and the release of a booklet titled “परियोजना के कार्यकलाप, अवलोकन, विश्लेषण और परिणाम” (Project Activities, Observations, Analysis and Results) detailing project findings to educate rural stakeholders and students. Dr. R.P. Pandey, Member Secretary of the Indian National Committee on Climate Change, served as the chief guest. He discussed the significance of the Upper Ganga Canal and its role in

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9.5 Awareness Booklet

A booklet titled “परियोजना के कार्यकलाप, अवलोकन, विश्लेषण और परिणाम” (Project Activities, Observations, Analysis and Results) has been published in Hindi language to share the activities, observations, analyses, and results obtained from the project. The primary objective of this booklet is to raise awareness among rural stakeholders about innovations in water management. By introducing these stakeholders to new techniques and strategies in the field, the booklet aims to inform and educate farmers about the potential benefits and innovations can bring to their agricultural practices. This booklet released on 9th March 2024. Fig 9.5 shows the front page of booklet and release of booklet in Awareness Workshop-II, held at IIT Roorkee on dated March 9, 2024.

9.6 Experimental Field Visit by Farmers and Students

Farmers and students regularly visit the experimental field to observe firsthand the effectiveness of micro-irrigation in the canal command area and the application of IoT in irrigation management. These visits provide practical insights into the advanced technologies and strategies implemented for water conservation in agriculture. This exposure has motivated both farmers and students to adopt similar water conservation strategies and technologies in their practices. The primary objective of these visits is to equip them with the necessary skills and knowledge to effectively address contemporary challenges in water resources management and agricultural sustainability. Some photographs of visits are shown in Fig. 9.6.



Fig. 9.6: Experimental field visit of students and farmer

9.7: Outcomes of the Awareness programmes

The following key outcomes were achieved through different awareness activities:

- (i)** Kisan Chaupal (December 27, 2020, Nagla Aimad Village): This event fostered direct engagement with farmers, discussing project objectives and irrigation practices. Farmers actively participated, laying the foundation for collaboration throughout the project.
- (ii)** Farmers Awareness Workshop-I (March 15, 2023, Nagla Aimad Village): Attended by 161 stakeholders, this workshop focused on water management, micro-irrigation, and the role of Water User Associations (WUAs). Farmers interacted with experts emphasized efficient irrigation practices.
- (iii)** Kisan Chaupal (September 1, 2023, Nagla Aimad Village): Padmashree Umashankar Pandey shared insights on water conservation, discussing his 'Paani ke Pehredaar' model. Farmers engaged in discussions and gained practical knowledge from his experiences in groundwater management.
- (iv)** Awareness Workshop-II (IIT Roorkee): Focused on micro-irrigation, IoT in irrigation, and water conservation. A booklet summarizing project findings was released to educate stakeholders.

To ensure sustained farmer engagement and effective adoption of innovations, the program will integrate local partnerships with agricultural departments, NGOs, and financial institutions to expand training and provide resources for micro-irrigation. Outreach will be increased through digital platforms like social media, apps, and webinars, creating a space for sharing best practices and offering real-time support. Follow-up training, on-field demonstrations, and a helpline or WhatsApp group will reinforce learning and address concerns. These strategies, outlined in the revised report, aim to ensure long-term impact and sustainability

CHAPTER 10

SUMMARY AND CONCLUSIONS

10.1 Summary

The National Water Mission (NWM), Department of Water Resources (DoWR), River Development and Ganga Rejuvenation (RD&GR), Ministry of Jal Shakti, Government of India has sanctioned a research project entitled “Irrigation Efficiency Improvement Through On-Farm Water Management” with the following specific objectives:

- I. To enhance water use efficiency at the farm level through various measures of minimizing the water losses in the watercourse and in the irrigated field.
- II. To study the efficacy of various micro-irrigation methods such as sprinkler and drip and, evaluate the water savings as well as enhanced water use efficiency at farm level due to adoption of these methods over the prevailing method of flood irrigation.
- III. To evolve irrigation scheduling considering the crops, soil moisture and prevailing climatic conditions using Internet of Things (IoT).
- IV. To identify various factors which would help to promote adoption of the improved OFWM practices by the farmers, and various constraints which discourage the farmers for adopting those practices.
- V. To review the role of existing Water Use Associations (WUA) and suggest suitable modifications for encouraging better OFWM practices and equitable water distribution among the farmers and online demonstration and organization of workshops on OFWM practices.

The study area for the above-mentioned objectives is the Gadarjudda minor canal command area, it is the part of Upper Ganga Canal (UGC). Experiments were conducted in a farmer's field located in the village of Nagla Aimad in the Narsan block of Haridwar district, within the command area, Uttarakhand, situated at 29°46'53.9"N latitude, 77°50'9.4"E longitude, and 261 m above mean sea level. The area of the experimental field is 1.14 acres. The selected field, where farmers carry out their agricultural practices, provides a practical setting for the application and observation of the study's objectives. Both drip and sprinkler irrigation systems have been implemented to study the efficacy of various micro-irrigation methods in the canal command area. An IoT-based smart irrigation system has been employed in the experimental field to optimize water, use and assess soil moisture levels. By implementing these modern irrigation systems in the field, the study aims to evaluate their potential impact on water conservation and agricultural output.

10.2 Awareness Activities

1. At the beginning of the project, an important workshop promoting direct interaction with farmers was held in Nagla Aimad Village. This program served as an important platform in which the farmers living in Nagla Aimad and the progressive farmers from the neighboring villages participated.
2. To share the progress of the project, a farmer's awareness workshop titled "Irrigation Efficiency Improvement Through On-Farm Water Management" was organized on March 15, 2023, in the village Nagla Aimad, Narsan Block, District Haridwar. The chief guest for the program was Er. Anuj Kanwal, Commissioner of Command Area Development and Water Management, and Bureau of Water Use Efficiency, Ministry of Jal Shakti, Government of India.
3. On September 1, 2023, in the village Nagla Aimad, a Kisan Chaupal, an interactive gathering for farmers, was organized to promote awareness about water conservation. The event was graced by Padmashri Uma Shankar Pandey, a distinguished personality known for contributing to agriculture and rural development. This Kisan Chaupal served as a platform to educate and engage local farmers on the importance of sustainable water use and innovative water management practices.
4. To disseminate the project activities, observations, analyses, and results, an awareness workshop was organized on March 9, 2024, at the Indian Institute of Technology Roorkee. The event targeted farmers, students, and academics. This workshop served as a platform to bridge the gap between practical agricultural practices and academic research, enhancing collaboration and knowledge transfer among participants.
5. To facilitate better understanding and engagement among students and farmers, a booklet titled “परियोजना के कार्यकलाप, अवलोकन, विश्लेषण और परिणाम” (Project Activities, Observations, Analysis, and Results) was published in Hindi. This publication aims to provide comprehensive insights into the project's scope and findings in a language accessible to the local community. The booklet covers detailed descriptions of the methodologies employed, the data gathered, and the conclusions drawn from the analyses.
6. Farmers and students regularly visited the experimental field, where they gained firsthand experience with water management techniques through practical demonstrations. These visits expose them to various irrigation methods, water conservation strategies, and agricultural technologies.

10.3 Conclusions

1. The cleaning and maintenance of the watercourse, which involved removing silt and weeds with the active support of farmers, significantly enhanced its water-carrying capacity by 26.36%.
2. With irrigation scheduling based on soil moisture monitoring, farmers can achieve significant water savings. Specifically, this method can lead to a 21% reduction in water usage for wheat crops and a 17% reduction for sugarcane crops. This approach facilitates more precise water application, ensuring that crops receive the optimal amount of water at precisely the right times.
3. An IoT-based smart irrigation system has been developed, providing real-time data collection from sensors, which is transmitted to cloud storage and accessible via an Android app, allowing farmers to remotely monitor soil moisture, temperature, and humidity to control the irrigation system with alerts based on moisture thresholds. The system includes a sensor node, three soil moisture sensors, and a temperature sensor. It offers a cost-effective, highly accurate soil moisture (98.56%) solution that enhances usability and ensures timely interventions whenever necessary.
4. The comparison of micro-irrigation and traditional methods in divided sections of a farmer's field revealed that the micro-sprinkler system managed with precise irrigation schedules and soil moisture monitoring, reduced water usage by 28%. Additionally, water productivity was higher with micro-sprinkler irrigation (1.18 kg/m^3) compared to flood irrigation (0.91 kg/m^3).
5. Implementing mini sprinkler systems in wheat fields has proven highly effective, enabling a 30% water saving compared to conventional irrigation methods. The utilization of mini sprinkler irrigation has led to increased water productivity, achieving 1.75 kilograms of wheat per cubic meter of water, which is notably higher than the 1.09 kg/m^3 achieved through traditional flood irrigation.
6. Adopting drip irrigation in sugarcane cultivation significantly increased water efficiency, saving up to 40% of water compared to traditional flood irrigation and enhancing productivity from 4.46 kg/m^3 to 6.75 kg/m^3 . Results demonstrate drip irrigation's effectiveness in improving sugarcane crop water usage.
7. For the determination of soil moisture using Remote Sensing indices, the accuracy of the soil moisture retrieval model fluctuates with the growth stages of the crop. The Water Cloud Model (WCM), utilizing the Normalized Difference Moisture Index (NDMI) as a vegetation descriptor, has proven to be superior to other descriptors such as RVI, Depolarization Ratio, and Backscatter Intensity Ratio. The MWCM model incorporating NDMI demonstrated

acceptable performance across both calibration and validation periods, affirming its effectiveness in estimating regional surface soil moisture for wheat crops.

8. The Farmer questionnaire survey highlighted numerous obstacles while adopting new irrigation methods in the Gadarjudda minor canal area. Key challenges include the absence of a registered Water User Association, limited awareness of government schemes, and security concerns in open fields. Additionally, irregular power supply, restricted irrigation times, animal disturbances, poor irrigation system maintenance, inadequate canal water flow, and fragmented land ownership complicate effective water management.
9. Several awareness activities have been organized to motivate farmers to adopt improved on-farm water management techniques. These initiatives aim to demonstrate the benefits of micro-irrigation in the farmers' fields where micro-irrigation was installed and used. Additionally, these efforts support the formation of water user associations, which help in managing irrigation resources more effectively and sustainably.

10.4 Recommendations

1. Creation of a Water User Association (WUA): It is highly recommended that a Water User Association (WUA) be established, managed by local farmers and relevant authorities, to facilitate the regular maintenance of canals in the area. The WUA would be responsible for upgrading conventional irrigation to micro-irrigation by organizing training and awareness programmes.

2. Adopt Sprinkler Irrigation for Wheat Cultivation: It is recommended that farmers switch from conventional irrigation methods to sprinkler irrigation in the command areas, particularly in the Gadarjudda minor canal command area. This change is expected to yield a 30% savings in water usage due to the enhanced efficiency of sprinkler systems. The water conserved through this method can then be effectively used to irrigate an additional 43% of the land, thereby expanding agricultural productivity within the same water budget.

3. Implement Drip Irrigation for Sugarcane Cultivation: Transitioning to drip irrigation in the Gadarjudda canal command area is recommended. Drip irrigation can reduce water usage by 40%, substantially conserving resources. The water saved by this method can be utilized to irrigate an additional 67 % of the land. This shift optimizes water usage and extends the irrigated area significantly, enhancing overall crop output and improving water use efficiency.

4. Adoption of IoT-Based Smart Irrigation Systems: Farmers are encouraged to adopt the cost-effective IoT-based smart irrigation system. This system allows for real-time monitoring and control of soil moisture. It facilitates efficient water management through timely alerts and enhances resource use and agricultural productivity.

5. Regular Awareness Programmes: Farmers often hesitate to adopt new technologies due to a lack of familiarity and confidence in potential benefits. To address this, it is essential to implement awareness programs and hands-on demonstrations. These initiatives should aim to train farmers comprehensively, equipping them with the necessary skills and knowledge to utilize advanced agricultural techniques effectively.

10.5 Limitations and Future Research Scope

- (1) This project experimented in one farmer's field. It could be expanded to include multiple farmers' fields to enhance the study and improve its generalizability. This broader scope would allow for a more comprehensive analysis of varying conditions and practices across different agricultural practices, potentially providing more robust conclusions.
- (2) There is significant potential to enhance the effectiveness and reliability of the IoT irrigation system, given its current limitations. The system's range is restricted to one-kilometer radius, limiting its use in larger fields, and it faces power backup issues during the winter, impacting its continuous operation. Additionally, security vulnerabilities have been identified, underscoring the need for improved protective measures to mitigate potential threats.
- (3) In this study, soil moisture assessment using remote sensing indices is limited to wheat crops. However, there is potential to expand this methodology to encompass all types of crops. By integrating machine learning algorithms with remote sensing indices, it is possible to enhance the accuracy of soil moisture estimations. This approach could offer a more comprehensive and precise understanding of soil moisture across various agricultural contexts.
- (4) Further research is required to conduct a comprehensive feasibility and sustainability assessment of canal water-fed pressurized irrigation systems across the canal command area. This study would evaluate the practicality and long-term viability of implementing such systems. Analyzing these aspects will help determine the potential for scaling up pressurized irrigation systems, which could lead to improved water management practices and sustainability in agricultural irrigation.

PUBLICATIONS

Publications in refereed International Journals

1. Chourasia, S. K., Chhetri, S. K., & Pandey, A. (2024). Evaluating the need and feasibility of micro-irrigation systems for sustainable irrigation. *Environmental Monitoring and Assessment*, 196(10), 957.
2. Kushwaha, Y. K., Joshi, A., Panigrahi, R. K., & Pandey, A. (2024). Development of a smart irrigation monitoring system employing the wireless sensor network for agricultural water management. *Journal of Hydroinformatics*, 26(12), 3224-3243.
3. Das, D. P., & Pandey, A. (2025). Soil moisture retrieval from dual-polarized Sentinel-1 SAR data over agricultural regions using a water cloud model. *Environmental Monitoring and Assessment*, 197(1), 1-22.
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Paper/Poster Presentation in Conferences/Workshops

5. Chourasia, S., & Pandey, A. (2024). Irrigation efficiency improvement through on farm water management [Poster presentation]. Institute Research Day 2024, IIT Roorkee, March 13-14, 2024.
6. Kushwaha, Y. K., & Pandey, A. (2024). Smart Agriculture Management System using IoT-Based Modules [Poster presentation]. Institute Research Day 2024, IIT Roorkee, March 13-14, 2024.
7. Chourasia, S., & Pandey, A. (2024). Enhancing Water Use Efficiency in Canal Command Areas for Sustainable Agriculture. In *International Conference on Future Water Resources (ICFWR 2024)*. IWRS and IIT Roorkee, January 18-20, 2024.
8. Das, D. P., & Pandey, A. (2024). Soil Moisture Retrieval from Dual-Polarized Sentinel-1 SAR Data over Agricultural Regions Using a Water Cloud Model. In *International Conference on Future Water Resources (ICFWR 2024)*. IWRS and IIT Roorkee, January 18-20, 2024.
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12. Kushwaha, Y. K., & Pandey, A. (2024). Irrigation Scheduling in Wheat Crops using Wireless Sensor Networks. Paper presented at International Conference RWC 2024.

13. Chourasia, S., & Pandey, A. (2023). Improving Physical Crop Water Productivity Using Micro-Irrigation in Canal Command Areas [Poster presentation]. 25th International Congress, International Commission on Irrigation and Drainage (ICID), November 01-08, 2023, Visakhapatnam.
14. Kushwaha, Y. K., & Pandey, A. (2023). Smart Agriculture Management System using IoT-Based Modules [Paper presentation]. 25th International Congress, International Commission on Irrigation and Drainage (ICID), November 01-08, 2023, Visakhapatnam.
15. Kushwaha, Y. K., & Pandey, A. (2023). Smart Agriculture Irrigation Model using IoT-Based Architecture for Wheat Crops [Poster presentation]. AGU Fall Meeting 2023.
16. Chourasia, S., & Pandey, A. (2023). Assessment of Variability in Reference Evapotranspiration Estimation Methods for Improving Water Use Efficiency [Poster presentation]. AGU Fall Meeting 2023.
17. Chourasia, S., & Pandey, A. (2023). Irrigation Efficiency Improvement through on-farm Water Management [Poster presentation]. National Workshop on “On-Farm Water Management for Future Water Security,” Indian Water Resources Society (IWRS), New Delhi, March 20, 2023.
18. Kushwaha, Y. K., & Pandey, A. (2023). IoT-Based Smart Irrigation through Machine Learning Techniques [Poster presentation]. National Workshop on “On-Farm Water Management for Future Water Security,” Indian Water Resources Society (IWRS), New Delhi, March 20, 2023.
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Annexure-A

Field data Collection Records of TDR Spectrum 350 Instrument

(1) Date: 30/11/2021_5cm depth

Sr. No.	Time	VWC%	Temp_Soil (°C)	Temp_Soil (F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	30-11-2021 10:31	7	21.1	69.9	29.78083	77.83847	14	T	S	V
2	30-11-2021 10:32	9.6	21.3	70.4	29.78071	77.8388	14	T	S	V
3	30-11-2021 10:38	12.1	22.1	71.8	29.78387	77.83467	12	T	S	V
4	30-11-2021 10:40	7.4	22.5	72.6	29.78416	77.83487	12	T	S	V
5	30-11-2021 10:46	8.6	23.4	74.2	29.78436	77.83315	13	T	S	V
6	30-11-2021 10:47	7.8	23.6	74.5	29.78397	77.83282	14	T	S	V
7	30-11-2021 10:53	12.9	24.8	76.7	29.78484	77.83099	12	T	S	V
8	30-11-2021 11:08	8.1	25.2	77.5	29.7831	77.82818	14	T	S	V
9	30-11-2021 11:12	13.6	25.6	78.1	29.78275	77.82564	12	T	S	V
10	30-11-2021 11:13	13	25.7	78.3	29.78258	77.82601	13	T	S	V
11	30-11-2021 11:14	7.8	25.8	78.4	29.78243	77.82642	14	T	S	V
12	30-11-2021 11:20	14.8	26.8	80.3	29.78216	77.82476	13	T	S	V
13	30-11-2021 11:23	14.8	26.9	80.4	29.78124	77.82564	12	T	S	V
14	30-11-2021 11:27	9.2	26.9	80.5	29.78033	77.82783	13	T	S	V
15	30-11-2021 11:29	7.7	27	80.7	29.78009	77.82817	12	T	S	V
16	30-11-2021 11:30	9.1	27.1	80.8	29.78007	77.82847	13	T	S	V
17	30-11-2021 11:43	8	26.5	79.7	29.77552	77.8384	12	T	S	V
18	30-11-2021 11:44	8	26.9	80.5	29.77567	77.83916	11	T	S	V
19	30-11-2021 11:46	10.5	27.2	81	29.77553	77.8394	13	T	S	V
20	30-11-2021 11:48	9.2	28.4	83.1	29.77663	77.8399	12	T	S	V
21	30-11-2021 11:49	6.3	28.5	83.3	29.77653	77.84015	14	T	S	V
22	30-11-2021 11:55	6.7	28.6	83.5	29.77383	77.84283	12	T	S	V
23	30-11-2021 12:00	8.4	28.1	82.6	29.77367	77.8429	13	T	S	V
24	30-11-2021 12:06	35.1	27.9	82.3	29.7804	77.83629	12	T	S	V
25	30-11-2021 12:07	34.4	27.5	81.6	29.78028	77.83653	14	T	S	V

(2) Date: 05/12/2021_5cm depth

Sr. No.	Time	VWC%	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	05-12-2021 00:00	31.7	23.4	74.2	29.78343	77.85028	0	T	S	V
2	05-12-2021 00:00	6.5	24	75.2	29.78355	77.84699	4	T	S	V
3	05-12-2021 00:00	8	24.4	75.9	29.78396	77.84718	6	T	S	V
4	05-12-2021 00:00	35.9	25.1	77.2	29.78132	77.83855	7	T	S	V
5	05-12-2021 00:00	30.9	23.9	75	29.78022	77.83788	8	T	S	V
6	05-12-2021 00:00	10.7	23.9	75	29.78028	77.83775	8	T	S	V
7	05-12-2021 00:00	9	25	77.1	29.78279	77.83628	8	T	S	V
8	05-12-2021 00:00	12	26.1	79.1	29.78393	77.83461	9	T	S	V
9	05-12-2021 00:00	5.6	26.3	79.4	29.7842	77.83484	9	T	S	V
10	05-12-2021 00:00	9.4	26.4	79.5	29.78792	77.83169	10	T	S	V
11	05-12-2021 00:00	10.5	26	78.9	29.78601	77.83019	11	T	S	V
12	05-12-2021 00:00	10	26	78.8	29.78674	77.82894	11	T	S	V
13	05-12-2021 00:00	10.4	25.9	78.6	29.78553	77.82713	9	T	S	V
14	05-12-2021 00:00	5.4	25.8	78.5	29.78528	77.8274	12	T	S	V
15	05-12-2021 00:00	7.5	25.8	78.5	29.7848	77.82701	9	T	S	V
16	05-12-2021 00:00	13.6	25.7	78.3	29.78258	77.82569	10	T	S	V
17	05-12-2021 00:00	7	25.7	78.3	29.7824	77.82627	10	T	S	V
18	05-12-2021 00:00	5.9	25.7	78.3	29.78214	77.82681	9	T	S	V
19	05-12-2021 00:00	10.8	25.6	78.1	29.78195	77.82736	10	T	S	V
20	05-12-2021 00:00	10.4	25.7	78.4	29.78203	77.82535	10	T	S	V
21	05-12-2021 00:00	11.8	25.9	78.6	29.78037	77.82766	10	T	S	V
22	05-12-2021 00:00	12.6	24.5	76.2	29.77967	77.82916	11	T	S	V
23	05-12-2021 00:00	31.3	23.9	75.1	29.78039	77.83614	9	T	S	V
24	05-12-2021 00:00	30.9	24.3	75.7	29.78122	77.83599	11	T	S	V
25	05-12-2021 00:00	31.2	24.5	76.2	29.78134	77.83545	9	T	S	V
26	05-12-2021 00:00	33.3	24.5	76.1	29.78091	77.83571	10	T	S	V
27	05-12-2021 00:00	31.5	24.5	76.1	29.78104	77.83582	11	T	S	V
28	05-12-2021 00:00	10.6	24.8	76.7	29.77645	77.83608	12	T	S	V
29	05-12-2021 00:00	7.5	26.1	79.1	29.77559	77.83917	9	T	S	V
30	05-12-2021 00:00	7.3	26.6	79.9	29.77375	77.84271	13	T	S	V

(3) Date: 13/12/2021_5cm depth

Sr. No.	Time	VWC %	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	13-12-2021 10:25	2.5	17.8	64	29.7836	77.84735	10	T	S	V
2	13-12-2021 10:29	3.5	18.1	64.6	29.78247	77.84657	10	T	S	V
3	13-12-2021 12:06	3.5	22.6	72.8	29.7775	77.83128	11	T	S	V
4	13-12-2021 10:26	4.4	17.9	64.2	29.78401	77.84734	9	T	S	V
5	13-12-2021 10:48	4.5	19	66.3	29.78403	77.83367	10	T	S	V
6	13-12-2021 11:13	4.8	21.1	69.9	29.78836	77.83073	12	T	S	V
7	13-12-2021 10:23	5.8	17.7	63.9	29.78347	77.84944	6	T	S	V
8	13-12-2021 11:32	5.9	20.6	69.1	29.78477	77.82705	13	T	S	V
9	13-12-2021 10:39	6	18.4	65.2	29.78037	77.83783	10	T	S	V
10	13-12-2021 11:20	6.5	20.3	68.6	29.78772	77.83144	14	T	S	V
11	13-12-2021 11:31	6.5	20.7	69.2	29.78549	77.82711	11	T	S	V
12	13-12-2021 11:52	6.5	20.6	69.2	29.78038	77.82836	11	T	S	V
13	13-12-2021 11:16	6.7	20.4	68.8	29.78859	77.83011	14	T	S	V
14	13-12-2021 11:24	7.3	20.6	69.2	29.78597	77.83011	12	T	S	V
15	13-12-2021 11:58	7.4	22	71.7	29.78029	77.82956	10	T	S	V
16	13-12-2021 11:04	7.5	21.8	71.2	29.7848	77.8314	9	T	S	V
17	13-12-2021 12:18	7.9	21.8	71.3	29.78011	77.8361	10	T	S	V
18	13-12-2021 11:56	9	21.8	71.3	29.77973	77.82919	9	T	S	V
19	13-12-2021 11:01	10.5	21.1	70.1	29.78484	77.83238	11	T	S	V
20	13-12-2021 11:42	10.7	20.3	68.6	29.78206	77.82535	12	T	S	V
21	13-12-2021 11:40	11	20.3	68.6	29.78319	77.82585	10	T	S	V
22	13-12-2021 10:42	11.4	18.6	65.4	29.77994	77.83795	8	T	S	V
23	13-12-2021 11:03	12.4	21.7	71.1	29.78515	77.83164	11	T	S	V
24	13-12-2021 11:26	12.7	20.8	69.5	29.78658	77.8298	14	T	S	V
25	13-12-2021 11:45	12.7	20.4	68.7	29.78105	77.82568	11	T	S	V
26	13-12-2021 10:52	13	19.1	66.4	29.78472	77.83365	10	T	S	V
27	13-12-2021 11:47	13.8	20.4	68.8	29.78059	77.8259	11	T	S	V
28	13-12-2021 11:05	15.1	21.9	71.4	29.78482	77.83116	9	T	S	V
29	13-12-2021 11:54	16	21.1	70	29.77986	77.82795	8	T	S	V
30	13-12-2021 12:19	20.7	21.8	71.3	29.78039	77.83619	10	T	S	V
31	13-12-2021 11:28	20.8	20.8	69.5	29.78668	77.82892	12	T	S	V
32	13-12-2021 10:20	21.3	17.8	64.1	29.78345	77.85023	5	T	S	V
33	13-12-2021 12:26	21.5	20.6	69.2	29.781	77.83581	10	T	S	V

(4) Date: 17/12/2021_5cm depth

Sr. No.	Time	VWC%	Temp_S oil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	17-12-2021 10:05	23.3	14.6	58.3	29.7838	77.85148	0	T	S	V
2	17-12-2021 10:06	24.1	14.8	58.6	29.78395	77.85126	0	T	S	V
3	17-12-2021 10:11	27.7	14.5	58.1	29.78381	77.85201	10	T	S	V
4	17-12-2021 10:14	10.4	15.2	59.5	29.78464	77.85061	10	T	S	V
5	17-12-2021 10:15	22.1	15.3	59.5	29.78458	77.85088	12	T	S	V
6	17-12-2021 10:18	6.7	15.8	60.5	29.78482	77.85152	12	T	S	V
7	17-12-2021 10:19	8	16	60.9	29.78454	77.85207	12	T	S	V
8	17-12-2021 10:23	19.2	16.7	62.2	29.78381	77.85057	13	T	S	V
9	17-12-2021 10:26	5.9	17	62.7	29.784	77.84739	12	T	S	V
10	17-12-2021 10:29	6.8	17.2	62.9	29.78243	77.84663	11	T	S	V
11	17-12-2021 10:30	16.9	17.2	63	29.78229	77.8465	12	T	S	V
12	17-12-2021 10:33	24.2	17	62.6	29.78152	77.84669	12	T	S	V
13	17-12-2021 10:41	19.1	17.1	62.8	29.78144	77.83833	10	T	S	V
14	17-12-2021 10:41	21.4	16.9	62.5	29.7813	77.83862	13	T	S	V
15	17-12-2021 10:45	5.6	16.8	62.2	29.78039	77.83781	14	T	S	V
16	17-12-2021 10:45	22.6	16.8	62.2	29.78025	77.83792	13	T	S	V
17	17-12-2021 10:46	9.3	16.8	62.3	29.77994	77.83796	14	T	S	V
18	17-12-2021 10:47	9.4	16.9	62.4	29.77978	77.83786	13	T	S	V
19	17-12-2021 10:48	8.3	16.9	62.4	29.77974	77.83837	13	T	S	V
20	17-12-2021 10:52	25.2	16.8	62.3	29.78026	77.83833	12	T	S	V
21	17-12-2021 11:00	29.3	18.1	64.5	29.78288	77.83618	15	T	S	V
22	17-12-2021 11:03	35.4	18	64.5	29.78389	77.83453	16	T	S	V
23	17-12-2021 11:04	38.6	18.2	64.7	29.78408	77.8348	17	T	S	V
24	17-12-2021 11:07	6.2	18	64.4	29.78399	77.83371	13	T	S	V
25	17-12-2021 11:07	32.8	18	64.5	29.78396	77.83376	16	T	S	V
26	17-12-2021 11:09	23.7	18	64.5	29.78431	77.83324	14	T	S	V
27	17-12-2021 11:10	5.1	18	64.4	29.78462	77.83361	15	T	S	V
28	17-12-2021 11:10	9.6	18	64.5	29.78464	77.83344	14	T	S	V
29	17-12-2021 11:11	9.3	18.1	64.7	29.78477	77.83355	14	T	S	V
30	17-12-2021 11:12	7.7	18.2	64.8	29.78505	77.83372	15	T	S	V
31	17-12-2021 11:13	8.8	18.3	64.9	29.78523	77.83389	15	T	S	V
32	17-12-2021 11:15	6.6	18.4	65.1	29.78485	77.83242	14	T	S	V
33	17-12-2021 11:21	8.1	19.7	67.5	29.78511	77.83164	14	T	S	V

(5) Date: 21/12/2021_5cm depth

Sr. No.	Time	VWC%	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	21-12-2021 00:00	18	15.9	60.7	29.78413	77.85101	9	T	S	V
2	21-12-2021 00:00	23.7	16.1	60.9	29.7841	77.85124	9	T	S	V
3	21-12-2021 00:00	21.3	16.2	61.2	29.78386	77.8516	10	T	S	V
4	21-12-2021 00:00	21.6	15.4	59.8	29.78392	77.852	13	T	S	V
5	21-12-2021 00:00	12	17.5	63.5	29.78422	77.85243	14	T	S	V
6	21-12-2021 00:00	7.8	17.7	63.9	29.78452	77.85212	14	T	S	V
7	21-12-2021 00:00	9.2	18	64.4	29.78469	77.85184	13	T	S	V
8	21-12-2021 00:00	8.1	18.2	64.8	29.78462	77.85152	13	T	S	V
9	21-12-2021 00:00	7.2	18.7	65.6	29.78465	77.85073	13	T	S	V
10	21-12-2021 00:00	27.3	19.3	66.7	29.7835	77.84953	13	T	S	V
11	21-12-2021 00:00	27.9	19.4	66.9	29.78341	77.84752	14	T	S	V
12	21-12-2021 00:00	28.5	19.3	66.8	29.78359	77.84742	13	T	S	V
13	21-12-2021 00:00	8.7	18.6	65.6	29.78217	77.84726	12	T	S	V
14	21-12-2021 00:00	16.7	18.6	65.5	29.78192	77.84705	12	T	S	V
15	21-12-2021 00:00	25.8	18.8	65.9	29.78162	77.84708	11	T	S	V
16	21-12-2021 00:00	26.8	18.9	66	29.78145	77.84673	10	T	S	V
17	21-12-2021 00:00	22.9	18.9	66.1	29.78131	77.84883	11	T	S	V
18	21-12-2021 00:00	16.3	18.2	64.8	29.78124	77.83829	11	T	S	V
19	21-12-2021 00:00	18.3	18.1	64.7	29.7812	77.83851	11	T	S	V
20	21-12-2021 00:00	18.5	18	64.5	29.78103	77.83841	11	T	S	V
21	21-12-2021 00:00	6.5	18.2	64.8	29.78036	77.83786	11	T	S	V
22	21-12-2021 00:00	18.8	18.4	65.1	29.78024	77.83788	11	T	S	V
23	21-12-2021 00:00	16.7	18.5	65.4	29.78017	77.83804	11	T	S	V
24	21-12-2021 00:00	6.7	18.7	65.7	29.77995	77.83794	10	T	S	V
25	21-12-2021 00:00	25.6	20.9	69.7	29.78276	77.8364	11	T	S	V
26	21-12-2021 00:00	33.5	21.4	70.6	29.78388	77.83451	11	T	S	V
27	21-12-2021 00:00	29	21.5	70.7	29.78414	77.83471	11	T	S	V
28	21-12-2021 00:00	28.6	25.2	77.3	29.78401	77.83381	9	T	S	V
29	21-12-2021 00:00	6.7	24.7	76.5	29.78458	77.83356	9	T	S	V
30	21-12-2021 00:00	6.8	24.7	76.5	29.78469	77.83349	9	T	S	V
31	21-12-2021 00:00	11.4	24.3	75.8	29.78444	77.83219	9	T	S	V
32	21-12-2021 00:00	4.9	24.3	75.8	29.78469	77.83222	8	T	S	V
33	21-12-2021 00:00	13.2	24.3	75.9	29.78523	77.83177	9	T	S	V

(6) Date: 24/12/2021_5cm depth

Sr. No.	Time	VWC%	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	24-12-2021 10:11	32.7	19.4	66.9	29.79152	77.854	4	T	S	V
2	24-12-2021 10:15	35.5	20.1	68.2	29.79195	77.85063	5	T	S	V
3	24-12-2021 10:16	34.9	20.1	68.2	29.79148	77.85013	5	T	S	V
4	24-12-2021 10:18	36.3	20.5	68.9	29.79177	77.8497	7	T	S	V
5	24-12-2021 10:22	4.8	21.2	70.2	29.79271	77.85104	7	T	S	V
6	24-12-2021 10:27	35.5	21.9	71.4	29.79477	77.8477	9	T	S	V
7	24-12-2021 10:28	27.5	21.6	70.9	29.79488	77.8474	8	T	S	V
8	24-12-2021 10:30	3.9	21.1	70	29.7958	77.84799	11	T	S	V
9	24-12-2021 10:32	30.9	21	69.9	29.79524	77.848	11	T	S	V
10	24-12-2021 10:36	21.7	22.1	71.8	29.79395	77.84441	9	T	S	V
11	24-12-2021 10:38	35.9	22	71.7	29.79433	77.84471	11	T	S	V
12	24-12-2021 10:42	30.1	21.4	70.6	29.79468	77.84246	12	T	S	V
13	24-12-2021 10:55	7.1	22.8	73	29.78804	77.83976	11	T	S	V
14	24-12-2021 11:03	5.6	25	77	29.78755	77.83774	13	T	S	V
15	24-12-2021 11:04	4	25.3	77.6	29.78768	77.83749	12	T	S	V
16	24-12-2021 11:05	6	25.3	77.6	29.78735	77.83707	12	T	S	V
17	24-12-2021 11:10	4.9	24.5	76.2	29.78618	77.83825	9	T	S	V
18	24-12-2021 11:11	22.5	24.6	76.4	29.78634	77.83849	10	T	S	V
19	24-12-2021 11:15	25.1	24	75.3	29.78607	77.83949	10	T	S	V
20	24-12-2021 11:16	4.1	23.8	74.9	29.78569	77.83992	8	T	S	V
21	24-12-2021 11:23	29.2	24.5	76.1	29.78279	77.83635	9	T	S	V
22	24-12-2021 11:26	25.6	24.1	75.3	29.78389	77.83457	9	T	S	V
23	24-12-2021 11:27	28.2	24.2	75.5	29.78418	77.83481	9	T	S	V
24	24-12-2021 11:32	27.9	24.3	75.7	29.78384	77.83382	9	T	S	V
25	24-12-2021 11:34	24.7	24.3	75.8	29.78435	77.83328	10	T	S	V
26	24-12-2021 11:35	7.1	24.2	75.5	29.78455	77.83357	10	T	S	V
27	24-12-2021 11:36	6.6	24.5	76.1	29.78482	77.83244	10	T	S	V
28	24-12-2021 11:38	7.9	24.8	76.7	29.7851	77.83163	9	T	S	V
29	24-12-2021 11:49	35.9	26.8	80.3	29.78243	77.83415	9	T	S	V
30	24-12-2021 11:51	28.5	26.2	79.3	29.78194	77.83479	9	T	S	V
31	24-12-2021 11:52	19.5	25.6	78.2	29.78127	77.83537	9	T	S	V
32	24-12-2021 11:54	17.1	25.3	77.6	29.78082	77.83571	9	T	S	V
33	24-12-2021 11:54	20.7	25.2	77.4	29.78097	77.83577	9	T	S	V

(7) Date: 29/12/2021_5cm depth

Sr. No.	Time	VWC%	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	29-12-2021 09:46	20.4	16.4	61.6	29.784	77.85129	7	T	S	V
2	29-12-2021 09:47	19.1	16.5	61.8	29.78382	77.85159	9	T	S	V
3	29-12-2021 09:49	26.3	16.6	62	29.78384	77.85199	8	T	S	V
4	29-12-2021 09:51	24	16.9	62.5	29.78452	77.85104	9	T	S	V
5	29-12-2021 09:52	4.8	16.9	62.4	29.78462	77.85137	9	T	S	V
6	29-12-2021 09:53	5.2	16.9	62.5	29.78471	77.85164	9	T	S	V
7	29-12-2021 09:57	23.6	17.4	63.3	29.78385	77.85052	10	T	S	V
8	29-12-2021 09:59	22.1	17.5	63.5	29.78345	77.84948	10	T	S	V
9	29-12-2021 10:02	23.8	17.7	63.9	29.78352	77.84738	12	T	S	V
10	29-12-2021 10:03	25.5	17.9	64.2	29.784	77.84737	14	T	S	V
11	29-12-2021 10:08	5.9	18	64.4	29.78216	77.84698	11	T	S	V
12	29-12-2021 10:08	15	18	64.4	29.78198	77.84683	12	T	S	V
13	29-12-2021 10:10	25.7	18	64.5	29.78153	77.84707	11	T	S	V
14	29-12-2021 10:11	21.7	17.9	64.3	29.78152	77.84668	11	T	S	V
15	29-12-2021 10:13	22.5	17.6	63.7	29.78114	77.84737	10	T	S	V
16	29-12-2021 10:15	24	17.6	63.7	29.78127	77.84842	13	T	S	V
17	29-12-2021 10:16	17.5	17.6	63.8	29.78121	77.84883	8	T	S	V
18	29-12-2021 10:18	24.1	17.9	64.2	29.78175	77.84884	10	T	S	V
19	29-12-2021 10:20	6	17.9	64.2	29.78185	77.84857	10	T	S	V
20	29-12-2021 10:28	14.9	18.1	64.7	29.78124	77.83866	11	T	S	V
21	29-12-2021 10:29	19.1	18	64.5	29.78136	77.83827	10	T	S	V
22	29-12-2021 10:30	18.3	17.8	64.1	29.78101	77.83846	11	T	S	V
23	29-12-2021 10:37	15.6	18.1	64.6	29.78026	77.83796	11	T	S	V
24	29-12-2021 10:38	6.6	18.4	65.1	29.77994	77.83797	12	T	S	V
25	29-12-2021 10:46	22.7	20.4	68.7	29.78281	77.83635	10	T	S	V
26	29-12-2021 10:49	23.6	20.4	68.8	29.78393	77.83457	10	T	S	V
27	29-12-2021 10:51	25.6	20.3	68.6	29.7842	77.83487	11	T	S	V
28	29-12-2021 10:54	20.8	20.4	68.8	29.78432	77.83326	9	T	S	V
29	29-12-2021 10:56	4.8	20.4	68.8	29.78462	77.83365	9	T	S	V
30	29-12-2021 10:57	5.5	20.4	68.8	29.78479	77.83354	10	T	S	V
31	29-12-2021 11:00	3.8	20.4	68.8	29.78397	77.8337	9	T	S	V
32	29-12-2021 11:00	22	20.5	68.9	29.78392	77.83383	12	T	S	V
33	29-12-2021 11:03	4.8	20.6	69	29.78487	77.83239	12	T	S	V

(8) Date: 10/02/2022_5cm depth

Sr. No.	Time	VWC_	Temp_Soil	Temp_Soil_	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC_Mode
1	10-02-2022	31.9	16.8	62.2	29.78433	77.85277	3	T	S	V
2	10-02-2022	24.1	17.3	63.1	29.78389	77.85327	8	T	S	V
3	10-02-2022	19.2	17.3	63.2	29.78404	77.85345	7	T	S	V
4	10-02-2022	33	17.9	64.2	29.78402	77.85136	8	T	S	V
5	10-02-2022	36	17.8	64.1	29.78387	77.85162	8	T	S	V
6	10-02-2022	33.8	17.7	63.9	29.78447	77.85097	9	T	S	V
7	10-02-2022	25.2	17.3	63.2	29.78461	77.85134	9	T	S	V
8	10-02-2022	32.9	17.6	63.7	29.78466	77.8508	10	T	S	V
9	10-02-2022	29.4	18.1	64.6	29.7835	77.84951	10	T	S	V
10	10-02-2022	20.5	18.3	65	29.78339	77.85006	10	T	S	V
11	10-02-2022	32.6	18.2	64.7	29.78353	77.85034	10	T	S	V
12	10-02-2022	31	17.9	64.3	29.78358	77.84738	11	T	S	V
13	10-02-2022	31	18	64.5	29.78395	77.84731	11	T	S	V
14	10-02-2022	29.3	17.8	64.1	29.78246	77.84635	11	T	S	V
15	10-02-2022	31	18.7	65.8	29.78131	77.83829	11	T	S	V
16	10-02-2022	33.6	19.1	66.4	29.78118	77.83847	13	T	S	V
17	10-02-2022	22.8	18.9	66	29.78101	77.83833	12	T	S	V
18	10-02-2022	20.9	19.3	66.7	29.78055	77.83821	11	T	S	V
19	10-02-2022	26.1	19.2	66.6	29.78036	77.83826	11	T	S	V
20	10-02-2022	33.5	22.7	72.8	29.78324	77.82785	13	T	S	V
21	10-02-2022	31	21.7	71.1	29.7836	77.82773	13	T	S	V
22	10-02-2022	35.4	20.4	68.8	29.78302	77.82897	13	T	S	V
23	10-02-2022	22.4	19.5	67.1	29.7823	77.8307	14	T	S	V
24	10-02-2022	31.2	19.5	67.1	29.78212	77.83092	14	T	S	V
25	10-02-2022	25.2	19.3	66.8	29.78131	77.83208	14	T	S	V
26	10-02-2022	29.7	19.8	67.7	29.78067	77.83353	14	T	S	V
27	10-02-2022	32.7	21	69.8	29.78246	77.83413	12	T	S	V
28	10-02-2022	22.7	20.4	68.8	29.7813	77.83609	14	T	S	V
29	10-02-2022	20.1	20.4	68.8	29.78191	77.83645	15	T	S	V
30	10-02-2022	23.7	21.1	70	29.78207	77.83641	14	T	S	V
31	10-02-2022	25.8	21.4	70.5	29.78228	77.83648	14	T	S	V
32	10-02-2022	31	21.5	70.7	29.7826	77.83625	16	T	S	V
33	10-02-2022	26	21.7	71	29.7817	77.83659	16	T	S	V

(9) Date: 11/03/2022_5cm depth

Sr. No.	Time	VWC%	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	11-03-2022 09:57	21.7	24.5	76.1	29.78415	77.85303	0	T	S	V
2	11-03-2022 09:57	31.7	24.5	76.2	29.78407	77.85313	0	T	S	V
3	11-03-2022 09:58	19.5	24.5	76.1	29.78403	77.85331	5	T	S	V
4	11-03-2022 09:58	21.2	24.5	76.1	29.78397	77.85332	4	T	S	V
5	11-03-2022 10:04	16	26.9	80.4	29.7842	77.85098	6	T	S	V
6	11-03-2022 10:04	17	26.9	80.5	29.78415	77.85107	5	T	S	V
7	11-03-2022 10:06	12.5	27.2	80.9	29.78408	77.85129	6	T	S	V
8	11-03-2022 10:07	12.5	27.3	81.1	29.78396	77.85149	6	T	S	V
9	11-03-2022 10:08	15.2	27.2	81.1	29.78389	77.85162	8	T	S	V
10	11-03-2022 10:13	32.7	28.1	82.6	29.7846	77.85121	9	T	S	V
11	11-03-2022 10:15	33.6	27.3	81.1	29.78462	77.85082	9	T	S	V
12	11-03-2022 10:19	10.7	27.9	82.3	29.7835	77.85027	9	T	S	V
13	11-03-2022 10:24	32.2	29.4	85	29.78367	77.84737	10	T	S	V
14	11-03-2022 10:35	30.1	29.9	85.8	29.78125	77.83831	11	T	S	V
15	11-03-2022 10:36	35.1	29.6	85.3	29.78126	77.83847	10	T	S	V
16	11-03-2022 10:36	27.4	29.2	84.6	29.78115	77.83851	10	T	S	V
17	11-03-2022 10:37	34.3	29	84.3	29.78111	77.83857	11	T	S	V
18	11-03-2022 10:37	27.2	28.8	83.9	29.78107	77.83864	10	T	S	V
19	11-03-2022 10:38	31.1	28.7	83.7	29.78106	77.83872	11	T	S	V
20	11-03-2022 10:38	29.4	28.6	83.5	29.78103	77.83875	11	T	S	V
21	11-03-2022 10:40	31.1	28.4	83.2	29.78106	77.83831	11	T	S	V
22	11-03-2022 10:40	27.4	28.4	83.2	29.78095	77.8383	11	T	S	V
23	11-03-2022 10:43	30.2	28.5	83.3	29.78048	77.83808	10	T	S	V
24	11-03-2022 10:43	29	28.3	83	29.78044	77.83817	9	T	S	V
25	11-03-2022 10:44	30.5	28.2	82.8	29.78039	77.83827	10	T	S	V
26	11-03-2022 10:56	29.7	31.7	89.2	29.78295	77.82894	10	T	S	V
27	11-03-2022 10:59	27.5	31.2	88.2	29.78326	77.82795	9	T	S	V
28	11-03-2022 11:00	31.9	30.5	87	29.78339	77.82766	10	T	S	V
29	11-03-2022 11:16	16.1	31.4	88.6	29.7813	77.83606	9	T	S	V
30	11-03-2022 11:17	19.9	31.5	88.8	29.78131	77.83599	10	T	S	V
31	11-03-2022 11:18	15.1	31.7	89.2	29.78137	77.83585	11	T	S	V
32	11-03-2022 11:18	14.5	31.7	89	29.78129	77.83583	9	T	S	V
33	11-03-2022 11:21	16	31.5	88.8	29.78202	77.83637	12	T	S	V

(10) Date: 23/03/2022_5cm depth

Sr. No.	Time	VWC%	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	23-03-2022 09:37	24.4	28.1	82.6	29.78412	77.85317	5	T	S	V
2	23-03-2022 09:38	24.6	27.9	82.3	29.78402	77.85319	4	T	S	V
3	23-03-2022 09:38	27.6	27.8	82.1	29.78399	77.85334	5	T	S	V
4	23-03-2022 09:39	27.8	27.5	81.6	29.78391	77.85339	7	T	S	V
5	23-03-2022 09:48	10.6	29	84.2	29.78384	77.85168	7	T	S	V
6	23-03-2022 09:53	15.5	30.1	86.2	29.78459	77.85123	8	T	S	V
7	23-03-2022 09:54	19.4	30	86.1	29.7847	77.85133	8	T	S	V
8	23-03-2022 09:55	31.5	29.9	85.9	29.78478	77.85142	9	T	S	V
9	23-03-2022 10:00	22.4	30.7	87.2	29.78467	77.85097	8	T	S	V
10	23-03-2022 10:00	18.3	30.6	87.2	29.78467	77.85079	8	T	S	V
11	23-03-2022 10:01	24.6	30.6	87.2	29.78456	77.85079	9	T	S	V
12	23-03-2022 10:01	22.3	30.7	87.3	29.78459	77.8507	8	T	S	V
13	23-03-2022 10:03	19.7	30.7	87.3	29.78463	77.85056	9	T	S	V
14	23-03-2022 10:09	17.1	32.4	90.3	29.78361	77.84739	9	T	S	V
15	23-03-2022 10:19	14.3	32.4	90.4	29.78117	77.83843	10	T	S	V
16	23-03-2022 10:20	15.2	32.1	89.9	29.78103	77.83859	12	T	S	V
17	23-03-2022 10:20	24.2	32.2	89.9	29.7811	77.83868	12	T	S	V
18	23-03-2022 10:22	25.2	32.1	89.8	29.78103	77.83883	10	T	S	V
19	23-03-2022 10:23	25.8	31.9	89.4	29.78101	77.83895	11	T	S	V
20	23-03-2022 10:25	14.2	32.4	90.4	29.781	77.83835	11	T	S	V
21	23-03-2022 10:29	15	33.1	91.7	29.78049	77.83794	11	T	S	V
22	23-03-2022 10:29	17.4	33.1	91.6	29.78049	77.83807	12	T	S	V
23	23-03-2022 10:30	16.6	33	91.4	29.78043	77.8382	11	T	S	V
24	23-03-2022 10:40	25.9	34.4	93.9	29.78358	77.82774	12	T	S	V
25	23-03-2022 10:40	23.2	34.3	93.7	29.78367	77.8278	12	T	S	V
26	23-03-2022 10:41	24	34.1	93.5	29.78377	77.82788	12	T	S	V
27	23-03-2022 10:43	19.5	33.6	92.4	29.78361	77.8276	12	T	S	V
28	23-03-2022 10:44	21.6	33.5	92.4	29.7837	77.82765	13	T	S	V
29	23-03-2022 10:44	21	33.4	92.1	29.7838	77.82772	12	T	S	V
30	23-03-2022 10:44	22.8	33.3	92	29.78393	77.82779	12	T	S	V
31	23-03-2022 10:45	22.7	33.2	91.9	29.78399	77.82766	12	T	S	V
32	23-03-2022 10:46	23.4	33	91.4	29.78371	77.82747	12	T	S	V
33	23-03-2022 10:57	19.3	32.1	89.9	29.78037	77.828	11	T	S	V

(11) Date: 30/03/2022_5cm depth

Sr. No.	Time	VWC%	Temp_Soil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	30-03-2022 09:58	18.4	31.9	89.4	29.78026	77.8379	7	T	S	V
2	30-03-2022 10:05	9.6	32.6	90.7	29.78017	77.83818	11	T	S	V
3	30-03-2022 10:07	15.5	33	91.5	29.78	77.83874	9	T	S	V
4	30-03-2022 10:08	14.2	33.4	92.2	29.78037	77.83864	11	T	S	V
5	30-03-2022 10:14	20.7	34.3	93.7	29.78114	77.83866	10	T	S	V
6	30-03-2022 10:26	10.8	35.3	95.6	29.7829	77.83611	10	T	S	V
7	30-03-2022 10:29	16.7	35.6	96.2	29.78407	77.8344	10	T	S	V
8	30-03-2022 10:31	16.4	35.9	96.7	29.78467	77.83365	10	T	S	V
9	30-03-2022 10:34	13.4	35.7	96.3	29.78443	77.83316	9	T	S	V
10	30-03-2022 10:36	11.7	36.2	97.2	29.78483	77.83236	9	T	S	V
11	30-03-2022 10:43	12.9	37.2	98.9	29.78555	77.82708	12	T	S	V
12	30-03-2022 10:46	13.6	37.1	98.8	29.78427	77.8263	10	T	S	V
13	30-03-2022 10:55	18.7	36.5	97.7	29.78211	77.82532	7	T	S	V
14	30-03-2022 10:58	9.7	36.5	97.8	29.78115	77.82569	8	T	S	V
15	30-03-2022 10:59	11.9	36.6	98	29.78065	77.82563	9	T	S	V
16	30-03-2022 11:02	19.7	36.8	98.3	29.78057	77.8272	9	T	S	V
17	30-03-2022 11:07	14.9	36.9	98.4	29.77978	77.82787	8	T	S	V
18	30-03-2022 11:11	29.9	36.8	98.3	29.78	77.82848	8	T	S	V
19	30-03-2022 11:14	11.4	36.7	98.1	29.77902	77.82867	7	T	S	V
20	30-03-2022 11:17	12.5	37.1	98.8	29.77892	77.82982	7	T	S	V
21	30-03-2022 11:20	11.1	37	98.6	29.77856	77.83171	8	T	S	V
22	30-03-2022 11:29	15.6	38.6	101.5	29.7822	77.83095	8	T	S	V
23	30-03-2022 11:30	7.5	38.9	102	29.78238	77.83078	9	T	S	V
24	30-03-2022 11:31	13.6	39.3	102.8	29.78249	77.83033	10	T	S	V
25	30-03-2022 11:33	13.2	39.4	103	29.7829	77.82969	9	T	S	V
26	30-03-2022 11:41	11.3	38.6	101.5	29.78199	77.82736	8	T	S	V
27	30-03-2022 11:45	16.3	38.6	101.5	29.78376	77.82747	8	T	S	V
28	30-03-2022 11:54	14.6	38.2	100.9	29.78398	77.83003	8	T	S	V
29	30-03-2022 12:00	9.8	38.2	100.8	29.78307	77.83062	9	T	S	V
30	30-03-2022 12:03	25.4	38.4	101.2	29.78216	77.83376	10	T	S	V

(12) Date: 30/11/2021_20cm depth

Sr. No.	Time	VWC %	Temp_S oil	Temp_Soil (F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	30-11-2021 10:22	30.5	21.7	71.1	29.78127	77.83536	10	L	S	V
2	30-11-2021 10:31	16.5	22.8	73	29.7808	77.83848	9	L	S	V
3	30-11-2021 10:32	17.5	23	73.4	29.78071	77.83877	7	L	S	V
4	30-11-2021 10:36	14.4	23.8	74.8	29.7828	77.83609	10	L	S	V
5	30-11-2021 10:38	22.3	24.5	76.2	29.78388	77.83465	9	L	S	V
6	30-11-2021 10:46	11.7	24.2	75.6	29.78434	77.83314	10	L	S	V
7	30-11-2021 10:47	16.4	24.4	75.9	29.78393	77.83286	8	L	S	V
8	30-11-2021 10:51	14.7	24.2	75.6	29.78479	77.83139	9	L	S	V
9	30-11-2021 10:53	20	24.6	76.2	29.78474	77.83091	10	L	S	V
10	30-11-2021 10:53	21.8	24.7	76.4	29.7849	77.83104	9	L	S	V
11	30-11-2021 11:00	16.3	25.8	78.4	29.78522	77.82744	10	L	S	V
12	30-11-2021 11:08	20	25.9	78.6	29.7831	77.82818	10	L	S	V
13	30-11-2021 11:12	16.1	25.7	78.3	29.78269	77.82568	8	L	S	V
14	30-11-2021 11:14	19.3	26	78.7	29.78237	77.82642	8	L	S	V
15	30-11-2021 11:18	19	26	78.9	29.78234	77.82495	9	L	S	V
16	30-11-2021 11:20	23.3	26.2	79.2	29.78211	77.82476	7	L	S	V
17	30-11-2021 11:23	23.1	26.3	79.3	29.78114	77.82562	9	L	S	V
18	30-11-2021 11:26	22	26.1	78.9	29.7807	77.82772	8	L	S	V
19	30-11-2021 11:27	20.6	26.4	79.5	29.78029	77.82779	9	L	S	V
20	30-11-2021 11:29	18.4	26.3	79.4	29.78005	77.82813	9	L	S	V
21	30-11-2021 11:30	18.5	26.4	79.5	29.78003	77.82842	8	L	S	V
22	30-11-2021 11:43	20.5	26.9	80.4	29.7755	77.83837	10	L	S	V
23	30-11-2021 11:44	20.9	27.1	80.8	29.77567	77.83913	8	L	S	V
24	30-11-2021 11:48	16.5	28.3	82.9	29.77664	77.83988	10	L	S	V
25	30-11-2021 11:56	13.9	28.7	83.7	29.77426	77.84306	8	L	S	V
26	30-11-2021 12:00	16.8	28.4	83.1	29.77366	77.84288	8	L	S	V
27	30-11-2021 12:06	34.3	28.4	83.2	29.7804	77.83622	9	L	S	V
28	30-11-2021 12:07	33.2	27	80.5	29.7803	77.83647	10	L	S	V
29	30-11-2021 12:08	33	27	80.7	29.78051	77.83666	9	L	S	V
30	30-11-2021 12:09	34.4	26	78.9	29.78064	77.83634	10	L	S	V

(13) Date: 13/12/2021_20cm depth

Sr. No.	Time	VWC %	Temp_S oil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	13-12-2021 10:20	24.8	18.3	64.9	29.78343	77.85027	7	L	S	V
2	13-12-2021 10:23	13.9	17.6	63.8	29.78343	77.84939	6	L	S	V
3	13-12-2021 10:25	19.1	17.6	63.7	29.78354	77.84738	6	L	S	V
4	13-12-2021 10:26	15.5	17.7	63.9	29.78398	77.84733	8	L	S	V
5	13-12-2021 10:29	13.7	18.1	64.5	29.78246	77.84659	9	L	S	V
6	13-12-2021 10:30	28.3	17.9	64.2	29.7823	77.84648	9	L	S	V
7	13-12-2021 10:36	32.8	18.3	64.9	29.78132	77.83859	10	L	S	V
8	13-12-2021 10:36	28.7	18.3	65	29.78135	77.83832	10	L	S	V
9	13-12-2021 10:37	32.4	18.2	64.7	29.78099	77.83846	9	L	S	V
10	13-12-2021 10:39	14.7	18.3	64.9	29.7804	77.83784	8	L	S	V
11	13-12-2021 10:40	31.7	18.3	65	29.78023	77.83789	10	L	S	V
12	13-12-2021 10:41	30.2	18.4	65.1	29.78021	77.83814	8	L	S	V
13	13-12-2021 10:42	14.9	18.5	65.3	29.77993	77.83796	9	L	S	V
14	13-12-2021 10:51	34.4	19.6	67.2	29.78428	77.83322	9	L	S	V
15	13-12-2021 10:52	16.5	19.7	67.4	29.78468	77.83366	9	L	S	V
16	13-12-2021 11:01	15.3	22	71.7	29.78484	77.83242	6	L	S	V
17	13-12-2021 11:03	16.4	22.6	72.6	29.78512	77.83165	7	L	S	V
18	13-12-2021 11:04	12.7	22.7	72.8	29.78478	77.83142	9	L	S	V
19	13-12-2021 11:05	20.3	22.9	73.2	29.78482	77.83117	8	L	S	V
20	13-12-2021 11:06	31.1	22.6	72.6	29.78445	77.83157	10	L	S	V
21	13-12-2021 11:13	21	20.9	69.5	29.78832	77.83074	8	L	S	V
22	13-12-2021 11:16	19.5	20.3	68.5	29.78858	77.83009	9	L	S	V
23	13-12-2021 11:18	19.1	20.4	68.8	29.7879	77.83088	5	L	S	V
24	13-12-2021 11:20	18.9	20.5	68.9	29.78769	77.83146	8	L	S	V
25	13-12-2021 11:24	16.6	20.7	69.2	29.78598	77.83014	9	L	S	V
26	13-12-2021 11:26	26.7	21	69.8	29.78656	77.82986	6	L	S	V
27	13-12-2021 11:28	24.4	21.2	70.2	29.78666	77.82896	10	L	S	V
28	13-12-2021 11:31	23	21.2	70.2	29.78549	77.82711	9	L	S	V
29	13-12-2021 11:32	17.7	21.2	70.2	29.78478	77.82712	7	L	S	V
30	13-12-2021 11:38	18.2	21.4	70.5	29.78472	77.82627	6	L	S	V
31	13-12-2021 11:40	22.9	21.4	70.5	29.78322	77.82585	10	L	S	V
32	13-12-2021 11:45	23.5	21.7	71	29.78115	77.82567	9	L	S	V
33	13-12-2021 11:47	14.9	21.9	71.4	29.78057	77.82589	10	L	S	V

(14) Date: 17/12/2021_20cm depth

Sr. No.	Time	VWC %	Temp_S oil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	17-12-2021 10:05	35.7	15.5	59.9	29.7838	77.85148	8	L	S	V
2	17-12-2021 10:06	36.9	15.8	60.5	29.78395	77.85126	8	L	S	V
3	17-12-2021 10:11	34	15.5	59.9	29.78376	77.85203	7	L	S	V
4	17-12-2021 10:14	21.2	16.4	61.5	29.78457	77.85065	7	L	S	V
5	17-12-2021 10:15	32.7	16.2	61.2	29.78455	77.85088	7	L	S	V
6	17-12-2021 10:18	18.9	16.5	61.6	29.78478	77.85154	9	L	S	V
7	17-12-2021 10:19	22.5	16.5	61.7	29.78454	77.85204	9	L	S	V
8	17-12-2021 10:29	16.1	17.5	63.5	29.78243	77.84661	10	L	S	V
9	17-12-2021 10:33	30.9	16.9	62.5	29.78149	77.84668	8	L	S	V
10	17-12-2021 10:41	28.7	16.4	61.6	29.78143	77.83832	8	L	S	V
11	17-12-2021 10:41	29.6	16.4	61.5	29.78128	77.83866	9	L	S	V
12	17-12-2021 10:45	27.6	16.8	62.2	29.78022	77.83791	10	L	S	V
13	17-12-2021 10:46	21.3	16.6	61.9	29.77991	77.83796	9	L	S	V
14	17-12-2021 10:47	20.1	16.5	61.6	29.77978	77.83784	9	L	S	V
15	17-12-2021 10:48	23.5	16.3	61.4	29.77964	77.83823	8	L	S	V
16	17-12-2021 10:48	21.6	16.4	61.6	29.77976	77.83835	9	L	S	V
17	17-12-2021 10:52	26.9	17.1	62.8	29.78028	77.83831	9	L	S	V
18	17-12-2021 11:00	33.4	18.9	66	29.7829	77.83619	10	L	S	V
19	17-12-2021 11:03	36	18.1	64.6	29.78397	77.83447	10	L	S	V
20	17-12-2021 11:04	38.5	17.4	63.3	29.78412	77.83478	10	L	S	V
21	17-12-2021 11:07	21.3	18.2	64.7	29.78403	77.83369	7	L	S	V
22	17-12-2021 11:07	39.1	18.1	64.6	29.78394	77.83374	8	L	S	V
23	17-12-2021 11:09	32.5	17.7	63.9	29.78432	77.8332	10	L	S	V
24	17-12-2021 11:10	19.3	17.6	63.8	29.7847	77.83356	9	L	S	V
25	17-12-2021 11:10	16.8	17.9	64.2	29.78474	77.83341	7	L	S	V
26	17-12-2021 11:11	21.6	18.1	64.5	29.78486	77.83347	7	L	S	V
27	17-12-2021 11:12	18.5	18.5	65.2	29.78514	77.83366	9	L	S	V
28	17-12-2021 11:13	22.7	18.6	65.4	29.78535	77.83381	9	L	S	V
29	17-12-2021 11:15	19.8	19.3	66.7	29.78493	77.83237	10	L	S	V
30	17-12-2021 11:21	18.5	20.9	69.6	29.78525	77.83161	8	L	S	V
31	17-12-2021 11:22	21.1	20.5	69	29.78492	77.83115	6	L	S	V
32	17-12-2021 11:23	29.5	20.4	68.8	29.78438	77.8315	8	L	S	V
33	17-12-2021 11:29	25	21	69.8	29.7867	77.82985	7	L	S	V

(15) Date: 24/12/2021_20cm depth

Sr. No.	Time	VWC %	Temp_S oil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	24-12-2021 10:32	34.2	18.7	65.7	29.79154	77.85402	4	L	S	V
2	24-12-2021 10:36	37.5	19.8	67.6	29.7918	77.85059	7	L	S	V
3	24-12-2021 10:38	37.5	19	66.3	29.79147	77.8503	7	L	S	V
4	24-12-2021 10:40	39.7	18.6	65.5	29.79178	77.84979	7	L	S	V
5	24-12-2021 10:44	21.5	18.9	66	29.79269	77.8511	6	L	S	V
6	24-12-2021 10:49	35.6	20.4	68.7	29.79478	77.84773	8	L	S	V
7	24-12-2021 10:51	17.5	19.6	67.3	29.79579	77.84797	7	L	S	V
8	24-12-2021 11:00	33.4	21.4	70.6	29.79436	77.84479	6	L	S	V
9	24-12-2021 11:04	38.9	20.9	69.5	29.79472	77.84248	6	L	S	V
10	24-12-2021 11:13	19.5	21.4	70.6	29.78899	77.83878	8	L	S	V
11	24-12-2021 11:16	10.9	21.9	71.4	29.7881	77.83981	6	L	S	V
12	24-12-2021 11:24	11.8	23.8	74.9	29.7876	77.8378	8	L	S	V
13	24-12-2021 11:25	13.7	24.2	75.5	29.78773	77.83754	8	L	S	V
14	24-12-2021 11:26	23.5	24.2	75.5	29.7874	77.83714	7	L	S	V
15	24-12-2021 11:28	33.8	24.6	76.4	29.78792	77.83767	8	L	S	V
16	24-12-2021 11:32	7	23.6	74.6	29.78627	77.83824	8	L	S	V
17	24-12-2021 11:34	26.6	23.5	74.2	29.7864	77.83851	6	L	S	V
18	24-12-2021 11:35	26.4	23.3	74	29.78642	77.839	8	L	S	V
19	24-12-2021 11:37	29.8	23.5	74.3	29.78609	77.83949	5	L	S	V
20	24-12-2021 11:44	31.6	24.3	75.8	29.78288	77.8363	8	L	S	V
21	24-12-2021 11:49	38.2	23.1	73.6	29.78421	77.83474	8	L	S	V
22	24-12-2021 11:54	14.6	24.6	76.4	29.78394	77.83367	6	L	S	V
23	24-12-2021 11:54	35.8	24.4	76	29.78392	77.83373	7	L	S	V
24	24-12-2021 11:56	30.8	24.5	76.1	29.78428	77.83327	7	L	S	V
25	24-12-2021 11:56	16.1	24.7	76.5	29.78464	77.83355	7	L	S	V
26	24-12-2021 11:58	13.5	25.1	77.2	29.78482	77.83242	8	L	S	V
27	24-12-2021 12:00	17.6	25.5	77.9	29.7852	77.83165	7	L	S	V
28	24-12-2021 12:01	25.9	25.2	77.4	29.78458	77.83151	8	L	S	V
29	24-12-2021 12:12	36	25.1	77.2	29.78199	77.83479	6	L	S	V
30	24-12-2021 12:20	13.2	25.4	77.8	29.78246	77.83615	7	L	S	V
31	24-12-2021 12:21	21.9	24.9	76.8	29.78193	77.83625	7	L	S	V

(16) Date: 29/12/2021_20cm depth

Sr. No.	Time	VWC %	Temp_S oil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	29-12-2021 10:06	32.1	16.6	61.9	29.78414	77.85097	6	L	S	V
2	29-12-2021 10:08	33.5	16.6	61.9	29.78402	77.85128	8	L	S	V
3	29-12-2021 10:09	28.9	16.6	61.8	29.78381	77.85158	8	L	S	V
4	29-12-2021 10:10	37.7	16.3	61.4	29.78389	77.85199	7	L	S	V
5	29-12-2021 10:13	30.2	16.6	61.8	29.78452	77.85105	6	L	S	V
6	29-12-2021 10:14	18.2	16.4	61.6	29.78462	77.85134	6	L	S	V
7	29-12-2021 10:15	19.6	16.6	61.8	29.78477	77.85163	6	L	S	V
8	29-12-2021 10:19	30.5	17.1	62.8	29.78385	77.85054	8	L	S	V
9	29-12-2021 10:21	30.1	16.9	62.4	29.78341	77.84944	7	L	S	V
10	29-12-2021 10:23	33.4	17	62.6	29.78356	77.84738	8	L	S	V
11	29-12-2021 10:25	33.9	16.8	62.3	29.78401	77.84736	9	L	S	V
12	29-12-2021 10:29	7.9	16.6	61.9	29.78217	77.847	9	L	S	V
13	29-12-2021 10:30	21.4	16.6	61.8	29.78203	77.84683	10	L	S	V
14	29-12-2021 10:32	32.1	16.5	61.7	29.78153	77.84712	9	L	S	V
15	29-12-2021 10:35	29.8	16.8	62.2	29.78113	77.84741	10	L	S	V
16	29-12-2021 10:37	29.9	17	62.5	29.78133	77.84845	9	L	S	V
17	29-12-2021 10:38	23.8	16.9	62.5	29.78122	77.84882	9	L	S	V
18	29-12-2021 10:40	30.4	17.3	63.2	29.78184	77.84886	10	L	S	V
19	29-12-2021 10:41	12.5	17.5	63.5	29.78193	77.8486	7	L	S	V
20	29-12-2021 10:49	25	18.3	65	29.78131	77.83863	9	L	S	V
21	29-12-2021 10:58	21.1	19.6	67.2	29.78034	77.83792	8	L	S	V
22	29-12-2021 11:08	28.2	20.3	68.6	29.78284	77.83631	9	L	S	V
23	29-12-2021 11:11	34.8	20.5	68.9	29.78397	77.83458	9	L	S	V
24	29-12-2021 11:12	35.1	20.1	68.2	29.78423	77.83486	10	L	S	V
25	29-12-2021 11:16	28.7	20.6	69	29.78438	77.8332	10	L	S	V
26	29-12-2021 11:18	11.5	20.6	69.1	29.7847	77.83367	10	L	S	V
27	29-12-2021 11:18	16.3	20.6	69.1	29.78484	77.83351	7	L	S	V
28	29-12-2021 11:22	34.7	20.9	69.6	29.78395	77.8338	9	L	S	V
29	29-12-2021 11:26	19	21.5	70.7	29.78452	77.83215	8	L	S	V
30	29-12-2021 11:29	12.6	22.4	72.3	29.78522	77.83169	9	L	S	V
31	29-12-2021 11:36	32.4	21.6	70.9	29.78489	77.83141	8	L	S	V
32	29-12-2021 11:37	34.2	20.9	69.5	29.78493	77.83118	10	L	S	V
33	29-12-2021 11:40	21.4	20.3	68.6	29.7844	77.8315	8	L	S	V

(17) Date: 11/03/2022_20cm depth

Sr. No.	Time	VWC %	Temp_S oil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	11-03-2022 09:56	23.6	24.7	76.4	29.7842	77.85293	8	L	S	V
2	11-03-2022 09:57	25.7	24.8	76.6	29.78415	77.85303	8	L	S	V
3	11-03-2022 09:57	27.7	24.6	76.3	29.78407	77.85313	7	L	S	V
4	11-03-2022 09:58	28.5	23.8	74.9	29.78404	77.85328	8	L	S	V
5	11-03-2022 09:58	28	23.8	74.9	29.78399	77.85336	8	L	S	V
6	11-03-2022 10:04	23.4	25.2	77.3	29.78417	77.85107	5	L	S	V
7	11-03-2022 10:06	13.9	25.6	78.1	29.78419	77.85137	4	L	S	V
8	11-03-2022 10:13	37.4	26	78.7	29.7846	77.85117	7	L	S	V
9	11-03-2022 10:15	32.5	25.7	78.3	29.78466	77.8508	9	L	S	V
10	11-03-2022 10:24	33	28.1	82.6	29.78367	77.84729	9	L	S	V
11	11-03-2022 10:35	27.2	29.6	85.3	29.78125	77.83827	7	L	S	V
12	11-03-2022 10:36	35	28.9	84.1	29.78124	77.83841	8	L	S	V
13	11-03-2022 10:36	26.5	27.3	81.1	29.78112	77.83842	8	L	S	V
14	11-03-2022 10:37	34.8	27	80.6	29.78112	77.8385	8	L	S	V
15	11-03-2022 10:37	30.4	27	80.6	29.78105	77.83858	8	L	S	V
16	11-03-2022 10:38	32.3	26.8	80.3	29.78107	77.83864	8	L	S	V
17	11-03-2022 10:40	33.9	26.8	80.2	29.78102	77.83832	7	L	S	V
18	11-03-2022 10:43	32.2	26.7	80.1	29.78047	77.838	8	L	S	V
19	11-03-2022 10:44	30.7	26.1	79.1	29.78045	77.83823	7	L	S	V
20	11-03-2022 10:52	29.4	30.4	86.7	29.78183	77.83107	8	L	S	V
21	11-03-2022 10:58	25.3	29.9	85.8	29.78316	77.82819	7	L	S	V
22	11-03-2022 11:00	34.2	29	84.2	29.7834	77.82767	7	L	S	V
23	11-03-2022 11:09	31.4	29.5	85.1	29.78242	77.83409	10	L	S	V
24	11-03-2022 11:16	16.8	30.1	86.2	29.78129	77.83612	5	L	S	V
25	11-03-2022 11:18	16.8	30.3	86.6	29.78137	77.83588	9	L	S	V
26	11-03-2022 11:21	20.6	30.4	86.7	29.78198	77.83636	9	L	S	V
27	11-03-2022 11:22	27.4	29.8	85.6	29.78204	77.83628	10	L	S	V
28	11-03-2022 11:22	25.8	29.3	84.7	29.78202	77.83618	7	L	S	V
29	11-03-2022 11:23	26.7	28.4	83.1	29.78208	77.83623	10	L	S	V
30	11-03-2022 11:23	25.2	28	82.4	29.78209	77.83605	9	L	S	V
31	11-03-2022 11:24	24.1	27.9	82.1	29.78216	77.83593	9	L	S	V
32	11-03-2022 11:27	28	27.9	82.1	29.78269	77.836	8	L	S	V
33	11-03-2022 11:29	20.8	27.8	82	29.78249	77.83625	9	L	S	V
34	11-03-2022 11:30	21	27.8	82	29.78239	77.83645	10	L	S	V

(18) Date: 23/03/2022_20cm depth

Sr. No.	Time	VWC %	Temp_S oil	Temp_Soil(F)	Latitude	Longitude	Satellites	Rod Length	Soil Type	VWC Mode
1	23-03-2022 09:35	28.5	28	82.5	29.78435	77.85283	10	L	S	V
2	23-03-2022 09:36	29.8	27.8	82	29.78427	77.85285	9	L	S	V
3	23-03-2022 09:37	32.2	27.7	81.9	29.78423	77.85297	10	L	S	V
4	23-03-2022 09:37	32	27.9	82.1	29.78413	77.85306	10	L	S	V
5	23-03-2022 09:39	26.9	27.2	80.9	29.78396	77.85345	9	L	S	V
6	23-03-2022 09:40	32.5	26.8	80.3	29.78383	77.85349	10	L	S	V
7	23-03-2022 09:47	11.1	29	84.3	29.78394	77.85152	8	L	S	V
8	23-03-2022 09:52	29.1	29	84.2	29.78448	77.85104	8	L	S	V
9	23-03-2022 09:52	24	28.9	84	29.78458	77.85115	9	L	S	V
10	23-03-2022 09:53	19.5	28.9	84.1	29.78457	77.85125	9	L	S	V
11	23-03-2022 09:54	28.6	29.4	84.9	29.78471	77.85137	10	L	S	V
12	23-03-2022 09:59	26.9	30.4	86.7	29.78475	77.85108	7	L	S	V
13	23-03-2022 10:00	28.9	30.7	87.2	29.78468	77.85101	9	L	S	V
14	23-03-2022 10:00	20.7	30.7	87.3	29.78465	77.85079	6	L	S	V
15	23-03-2022 10:01	20.8	30.7	87.2	29.78456	77.85085	9	L	S	V
16	23-03-2022 10:01	26.7	30.6	87.1	29.78457	77.85073	9	L	S	V
17	23-03-2022 10:03	26	30.5	86.9	29.7846	77.85061	9	L	S	V
18	23-03-2022 10:17	31.9	32.6	90.7	29.78137	77.83857	9	L	S	V
19	23-03-2022 10:19	24.3	32.2	89.9	29.78112	77.83844	7	L	S	V
20	23-03-2022 10:22	29.6	31.4	88.5	29.78096	77.83872	8	L	S	V
21	23-03-2022 10:22	19.7	31.5	88.7	29.78094	77.83888	8	L	S	V
22	23-03-2022 10:25	19.7	31.8	89.2	29.78099	77.83839	10	L	S	V
23	23-03-2022 10:30	19.8	32.6	90.6	29.78039	77.8382	8	L	S	V
24	23-03-2022 10:39	17.6	34.5	94.2	29.78332	77.82784	6	L	S	V
25	23-03-2022 10:40	24.5	34.1	93.3	29.78365	77.82782	9	L	S	V
26	23-03-2022 10:41	24.2	33.8	92.8	29.78375	77.82791	7	L	S	V
27	23-03-2022 10:44	25.9	32.9	91.3	29.78389	77.82781	8	L	S	V
28	23-03-2022 10:45	24.8	32.8	91	29.78398	77.82769	10	L	S	V
29	23-03-2022 10:46	27.6	32.9	91.3	29.78388	77.8276	9	L	S	V
30	23-03-2022 10:46	25.9	32.8	91	29.78377	77.82756	8	L	S	V
31	23-03-2022 10:46	25.3	32.7	90.9	29.78364	77.82752	9	L	S	V
32	23-03-2022 10:48	32.4	32.8	91	29.78373	77.82722	9	L	S	V
33	23-03-2022 10:55	23.7	32.1	89.8	29.7805	77.82829	9	L	S	V
34	23-03-2022 10:57	23.5	32.2	90	29.78033	77.82802	8	L	S	V



Fig. 1: Cleaning of the watercourse



Fig. 2: Measurement of seepage in the minor



Fig. 3: Sample collection and multi-parameter device calibration and measurement