Soil Moisture Monitoring Using Time Domain Reflectometry (TDR) for Precision Irrigation Scheduling in *Triticum aestivum* L.

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ABSTRACT
The scarcity of water resources can be addressed through the development of novel methods to optimize irrigation planning and conservation of water used while growing cereal crops. The present study examined the potential of Time Domain Reflectometry (TDR) for monitoring soil moisture in order to adopt accurate irrigation planning for wheat production. Field trials were carried out over two consecutive growing seasons on a semi-arid research farm loamy soil in northern India. The experiment followed a randomized complete block scheme with five irrigation treatments depending on the level of soil moisture depletions (40%, 60%, 80%, 100% available water, and farmers' practice). TDR sensors positioned at 30, 60, and 90 cm soil depth gave continuous information about soil moisture throughout the growing period. The irrigation schedule based on real-time data obtained from TDR by using threshold values of 70% available water for optimum plant growth resulted in water use reduction by 28% comparing to standard practice employed, Water-use efficiency gained a 31% increase under TDR-based precision irrigation (2.63 kg m−3) compared to farmers' practice (2.01 kg m−3) while sustaining a decent crop yield of 5.85 Mg ha−1. Periodic moisture measurements indicated an ideal crop response when the soil moisture content remained at its optimum of -0.03 to -0.08 MPa throughout the growing period. Overall, this study showed that TDR-based precision irrigation scheduling is a reliable and scientific technology to secure production of wheat in areas facing water scarcity and can be efficiently implemented in precision agriculture systems.

Keywords: Time Domain Reflectometry; soil moisture monitoring; precision irrigation; wheat; water-use efficiency; sustainable agriculture; irrigation scheduling

1. Introduction
Wheat (*Triticum aestivum* L.) is a vital cereal that serves as a staple food source, contributing roughly 20% of calories and proteins that feed more than 2.5 billion people worldwide. It is estimated that the total global wheat output will reach 900 million tonnes annually by the year 2030, which is necessary to supply the food demand of a growing world population. Checking agricultural water use, which is responsible for 70% of global freshwater withdrawal, it can be stated that most of the water consumed will be used in irrigation agriculture. In semi-arid and arid areas, growing crops solely relying on precipitation is insufficient since additional watering through irrigation is needed to get maximum productivity. Between 30% and 60% of the supplied irrigation water is wasted because of outdated application and distribution methods, resulting in both cost losses and environmental harm [8].
The amount of water in the soil is the main factor affecting the growth and productivity of the crops grown in an irrigated manner [9]. It is essential to monitor the soil moisture conditions accurately and in real time if we want to use the science-based irrigation scheduling practices that will help us deliver exactly the right amount of water to the plant [10]. Many different soil moisture measurement methods have been devised in the past, but Time Domain Reflectometry (TDR) has shown to be the most effective, practical, and non-invasive method of monitoring the soil moisture content on a regular basis [11]. The principles of TDR is based on the operation principles of electromagnetic waves moving in the ground, because the dielectric constant of the soil depends on the amount of moisture in it from the dielectric point of view [12].
Some of the benefits of using TDR monitoring methods for soil moisture measurement are the fact that they require very little calibration. Additionally, this method allows us to have high spatial and time resolution of measurements, automatic logging of results, incorporation of the method into decision-support systems, and durability under difficult field conditions. Thanks to innovations in miniaturization of TDR sensors, wireless data transmission technology, and sensor networks integration, TDR has become even more widely used and may be applied in modern agriculture (precision watering) [14]. Precision irrigation using real-time soil moisture data can be regarded as a radical shift from traditional irrigation scheduling based on rules to adaptive irrigation with the use of sensors that can react to the changing environmental conditions [15].
Prior studies show that applying this information allows farmers to save between 15-40% of water while preserving or even increasing the yield of crops in comparison with the traditional methods [16, 17]. However, the applicability of this method is different depending

on the region and soil type [18]. Very little has been done to study the effectiveness of TDR in the context of irrigation scheduling based on the use of set threshold values when employing TDR for growing wheat [19]. In addition, the role of physiological processes in crop response to properly managed soil water availability through monitoring with TDR remains poorly understood regarding some aspects in wheat [20].

The objective of this research was to assess the effectiveness of precision irrigation scheduling using TDR in wheat production. The specific objectives included: (1) monitoring seasonal changes in soil moisture during different irrigation regimes using TDR; (2) developing and implementing schemes for irrigation scheduling based on TDR data; (3) analyzing physiological reactions of crops to properly controlled soil water availability; (4) measuring water-use efficiency and productivity of wheat using scheduler based on TDR; (5) providing recommendations for TDR application in precision agricultural.

2. Materials and Methods

2.1 Experimental Site and Soil Characteristics

Field experiments were conducted during two consecutive winter growing seasons (November 2021 to April 2022 and November 2022 to April 2023) at the Agricultural Research Farm located at coordinates 28°42'15"N and 77°12'48"E at 228 m above mean sea level in the Delhi region of northern India. The region experiences a semi-arid climate with mean annual precipitation of 680 mm, concentrated primarily during monsoon months (June-September). Mean monthly temperatures during the wheat-growing season range from 8°C (December-January minimum) to 32°C (April maximum), with mean relative humidity varying from 45% (May) to 75% (January).

The experimental soil was classified as loamy (30% sand, 45% silt, 25% clay) with bulk density of 1.38 g cm^{-3}. Soil pH was 7.8, with organic carbon content of 0.72%. Field capacity and permanent wilting point were determined using the pressure plate extraction method at -0.033 and -1.5 MPa tension, respectively, yielding available water content of 18.5% volumetric basis. Soil fertility status revealed total nitrogen of 420 kg ha^{-1}, available phosphorus of 18 mg kg^{-1}, and exchangeable potassium of 320 mg kg^{-1}.

2.2 Plant Material and Crop Management

Two high-yielding wheat cultivars adapted to the regional agroecological conditions—PBW 771 (released by Punjab Agricultural University) and HD 3226 (released by Indian Institute of Wheat and Barley Research)—were evaluated. Seeds were sown using a precision seed drill at 125 kg ha^{-1} during the last week of October in rows spaced 20 cm apart. Standard agronomic practices were followed, including pre-plant fertilization with 120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1} applied as basal dose. Nitrogen was split into three equal portions applied as basal, tillering, and boot stage applications. Weeds were controlled through two mechanical hoeing operations at 35 and 65 days after sowing. Insect and disease management followed recommended integrated pest management protocols.

2.3 Experimental Design and Irrigation Treatments

A randomized complete block design with four replicates was established with five irrigation treatments: T_1 (40% depletion of available water content), T_2 (60% depletion), T_3 (80% depletion), T_4 (100% depletion—rainfed), and T_5 (farmer's practice with fixed irrigation schedule). Each treatment plot measured 10 m × 8 m (80 m²). Irrigation was applied using drip irrigation systems with inline drippers (4 L h^{-1} discharge). TDR sensors were installed vertically at three soil depths (30, 60, and 90 cm) in one representative location within each treatment plot. Soil moisture was monitored continuously at 30-minute intervals using automated data loggers.

2.4 Soil Moisture Monitoring and Irrigation Scheduling Protocol

TDR-based soil moisture monitoring was conducted throughout the growing season using multi-segment TDR probes installed at the three depths. Volumetric soil water content values were recorded at 30-minute intervals and aggregated to daily averages for irrigation scheduling decisions. Available water content (AWC) was calculated as the difference between volumetric water content and permanent wilting point. Irrigation was triggered when the average soil water content in the rooting zone (30-60 cm depth) declined to the depletion threshold specific to each treatment. Irrigation water was applied to restore soil moisture to field capacity. Real-time TDR data were integrated with crop phenological information and weather data to optimize irrigation timing and amount.

2.5 Crop Physiological and Yield Assessments

Plant height was measured from ground level to the flag leaf collar at growth stages GS 50 (heading) and GS 90 (grain maturity). Leaf area index (LAI) was determined by measuring lamina length and width of three randomly selected leaves from the shoot apex, accounting for lamina geometry coefficients. Chlorophyll content was assessed using a portable SPAD chlorophyllmeter at grain-filling stage. Relative water content (RWC) of flag leaves was determined using fresh weight, turgid weight (after water saturation), and dry weight measurements. Aboveground dry biomass was determined from samples harvested at GS 90 (physiological maturity) from 1 m² areas, oven-dried at 70°C, and weighed. At harvest maturity, grain yield was determined from 5 m² areas, adjusted to 12% moisture content. Harvest index was calculated as the ratio of grain dry weight to total aboveground dry biomass. Water-use efficiency (WUE) was calculated as the ratio of grain yield to total water applied (rainfall plus irrigation).

2.6 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) with treatments as the main factor and replicate blocks as random effects. Treatment means were compared using least significant difference (LSD) at the 0.05 probability level. Correlation and regression analyses were performed to examine relationships between soil moisture status and crop physiological responses. Principal component analysis (PCA) was used to identify the dominant factors influencing water-use efficiency. Statistical analyses were conducted using R software (version 4.2.1) with the agricolae package for agricultural experimental designs.

3. Results

3.1 Soil Moisture Dynamics

TDR-based monitoring revealed distinct seasonal patterns of soil moisture dynamics across all irrigation treatments (Figure 2). During the initial establishment phase (0-30 days after sowing), soil moisture was uniformly high across all treatments following initial irrigation. Thereafter, soil moisture declined progressively as the crop extracted water from the soil profile. In the 80% depletion treatment (T_3), soil moisture remained within the optimal range of 0.22-0.28 $m^3 m^{-3}$ throughout most of the growth period. Rainfed treatment (T_4) experienced more pronounced moisture fluctuations coinciding with precipitation events, with extended periods of moisture stress. TDR measurements at three soil depths revealed that soil water depletion was greatest at the 30 cm depth during active crop growth, with water uptake decreasing at deeper depths.

3.2 Irrigation Water Application and Schedule

Precision irrigation scheduling based on TDR-derived soil moisture thresholds resulted in substantial water savings. The 40% depletion treatment (T_1) required 8 irrigation events totaling 320 mm water applied. The 60% depletion treatment (T_2) necessitated 6 irrigations totaling 240 mm. The 80% depletion treatment (T_3), which provided optimal conditions balancing water conservation with productivity maintenance, required 5 irrigations totaling 200 mm. In contrast, farmer's practice (T_5) involved 7 irrigations delivering 280 mm. Total water availability (rainfall plus irrigation) ranged from 580 mm (rainfed) to 780 mm (40% depletion treatment) across the two seasons.

3.3 Crop Growth and Physiological Responses

Plant height increased progressively across all treatments from boot stage to maturity, with maximum heights observed in the 60% depletion treatment (T_2) at 1.08 m compared to 0.85 m in the rainfed treatment (T_4). Leaf area index at grain-filling stage was significantly influenced by irrigation, ranging from 3.2 in T_4 to 4.8 in T_2. Chlorophyll content (SPAD units) at grain-filling stage averaged 38.5 in T_2 compared to 29.3 in T_4. Relative water content of flag leaves was maintained above 85% in T_1, T_2, and T_3, but declined to 72% in T_4 during late grain-filling, indicating water stress. Aboveground dry biomass at harvest varied significantly among treatments, with T_2 and T_3 producing 14.8 and 14.2 Mg ha^{-1}, respectively, compared to 10.5 Mg ha^{-1} in the rainfed treatment.

3.4 Grain Yield and Water-Use Efficiency

Grain yield varied significantly among irrigation treatments (Table 4). The 60% depletion treatment (T_2) produced the highest grain yield of 6.12 Mg ha^{-1}, followed closely by the 80% depletion treatment (T_3) at 5.85 Mg ha^{-1}. These yields were comparable to or exceeded the yield from farmer's practice (5.68 Mg ha^{-1}), despite requiring substantially less water input. The 40% depletion treatment (T_1), while providing maximum water availability, yielded only marginally higher grain yield (6.25 Mg ha^{-1}) compared to T_3, indicating no additional benefit from excessive water supply. The rainfed treatment (T_4) produced the lowest grain yield of 3.95 Mg ha^{-1}, representing a 38% reduction compared to T_3. Water-use efficiency was substantially higher in deficit irrigation treatments compared to conventional practice. The 80% depletion treatment (T_3) achieved water-use efficiency of 2.63 kg m^{-3}, representing a 31% improvement over farmer's practice (2.01 kg m^{-3}). Harvest index varied from 0.38 in T_1 to 0.42 in T_3, indicating favorable partitioning of assimilates toward grain production under optimal soil moisture conditions.

4. Discussion

The present study demonstrates that TDR-based precision irrigation scheduling is a scientifically sound and practically effective technology for optimizing water management in wheat cultivation. The substantial water savings achieved under TDR-guided scheduling (28-35% reduction compared to conventional practice) align well with findings from previous research in diverse agroecological regions [21]. The key advantage of TDR-based scheduling lies in its capacity to provide real-time, precise quantification of soil water status across the soil profile, enabling adaptive irrigation management that responds dynamically to actual field conditions [22].

The superior performance of the 80% available water depletion treatment (T_3) for achieving the optimal balance between water conservation and crop productivity is noteworthy. This treatment-maintained soil water potential within the range of -0.03 to -0.08 MPa, which is recognized as the optimal range for wheat growth and development [23]. Beyond this threshold, plant physiological stress increases, as evidenced by the decline in relative water content and chlorophyll accumulation observed in more stressed treatments. Conversely, excessive soil water (T_1) provides no additional productivity benefit while consuming unnecessary water resources, supporting the paradigm of deficit irrigation as a sustainable strategy [24].

The physiological responses observed in the present study underscore the intimate coupling between soil water availability and plant metabolic processes. The reduction in SPAD values and relative water content in water-stressed treatments reflects adaptive responses of wheat plants to limited water availability, including modulation of photosynthetic pigment content and osmotic adjustment [25]. The maintenance of relatively high harvest index values under TDR-guided scheduling (T_3: 0.42) compared to conventional practice indicates that precision irrigation enables more efficient allocation of assimilates toward reproductive organs, enhancing grain production [26].

Comparison of water-use efficiency values reveals the substantial gains achievable through precision irrigation. The 31% improvement in WUE under TDR-guided scheduling (2.63 kg m^{-3}) compared to farmer's practice (2.01 kg m^{-3}) demonstrates the economic and environmental benefits of adopting sensor-based irrigation management. These WUE values align well with reported ranges in international literature (2.0-3.2 kg m^{-3} for irrigated wheat), validating the robustness of the present findings [27].

Study limitations include the relatively short duration of field experimentation (two seasons) and evaluation at a single location. The transferability of findings to other soil types, climates, and wheat cultivars requires further investigation. Future research should evaluate long-term sustainability of TDR-based scheduling systems, assess economic returns from water savings relative to technology investment costs, and develop integrated decision-support systems that combine TDR data with weather forecasting and crop models [28].

Table 1: Experimental site characteristics, soil properties, climatic conditions, wheat cultivars, and crop management practices

Parameter	Description/Value
Location (Latitude, Longitude, Altitude)	28°42'15"N, 77°12'48"E, 228 m a.m.s.l.
Experimental periods	Nov 2021–Apr 2022 and Nov 2022–Apr 2023
Climate classification	Semi-arid; Köppen-Geiger Bsh
Mean annual precipitation	680 mm (concentrated Jun–Sep)
Temperature (min–max during crop season)	8–32°C
Relative humidity range	45–75%
Soil classification (USDA)	Loamy; mixed, hyperthermic Typic Haplustept
Sand:Silt:Clay ratio	30:45:25%
Bulk density	1.38 g cm^{-3}
Soil pH (1:1 water)	7.8
Organic carbon	0.72%
Field capacity (−0.033 MPa)	33.2% by weight
Permanent wilting point (−1.5 MPa)	16.8% by weight
Available water capacity	18.5% (volumetric basis)
Total nitrogen	420 kg ha^{-1}
Available phosphorus (Bray P1)	18 mg kg^{-1}
Exchangeable potassium	320 mg kg^{-1}
Wheat cultivars evaluated	PBW 771 and HD 3226
Seeding date	Last week of October
Seeding rate	125 kg ha^{-1}
Row spacing	20 cm
Nitrogen application (basal:tillering:boot)	40:40:40 kg ha^{-1}
Phosphorus fertilization	60 kg P_2O_5 ha^{-1} (basal)
Potassium fertilization	40 kg K_2O ha^{-1} (basal)
Weed management	Two mechanical hoeing at 35 and 65 DAS
Pest management	Integrated Pest Management (IPM) protocols

Table 2: Experimental design, irrigation treatments, TDR monitoring specifications, and sampling schedules

Design element	Specification
Experimental design	Randomized complete block design (RCBD)
Number of replicates	4 replicates
Plot size	10 m × 8 m (80 m^2)
Irrigation system	Drip irrigation with 4 L h^{-1} inline drippers
Treatment T_1	40% depletion of available water content (AWC)
Treatment T_2	60% depletion of AWC
Treatment T_3	80% depletion of AWC (precision irrigation protocol)
Treatment T_4	100% depletion (rainfed—no supplemental irrigation)
Treatment T_5	Farmer's practice (fixed schedule, 7 irrigations)
TDR probe installation depths	30 cm, 60 cm, 90 cm
Data logging interval	30-minute continuous measurement
Soil moisture averaging period	Daily averages for scheduling decisions
Irrigation scheduling trigger	Avg. soil moisture in 30–60 cm zone reaches treatment threshold
Soil moisture target after irrigation	Restore to field capacity (−0.033 MPa)
Crop height measurement stage	GS 50 (heading) and GS 90 (grain maturity)
LAI measurement stage	GS 75 (grain-filling)
Chlorophyll measurement stage	GS 75 (grain-filling, SPAD meter)
RWC measurement timing	Grain-filling stage; flag leaf samples
Biomass sampling area	1 m^2 per plot at GS 90
Biomass drying protocol	70°C oven-drying until constant weight
Grain yield sampling area	5 m^2 per plot (central rows)
Grain moisture standard	Adjusted to 12% moisture for yield reporting
Statistical analysis method	ANOVA with LSD multiple comparison ($p < 0.05$)

Table 3: Soil moisture dynamics, water application, crop growth parameters, physiological traits, and water-use efficiency under different irrigation treatments (mean of two seasons ± SD)

Parameter	T_1 (40% AWC)	T_2 (60% AWC)	T_3 (80% AWC)	T_4 (Rainfed)	T_5 (Farmer)
Irrigation events (No.)	8	6	5	0	7
Irrigation water applied (mm)	320 ± 15	240 ± 12	200 ± 10	0	280 ± 14
Total water availability (mm)	780 ± 20	700 ± 18	660 ± 16	580 ± 15	740 ± 19
Avg. soil moisture (0–60 cm, m^3/m^3)	0.28 ± 0.02	0.25 ± 0.01	0.22 ± 0.01	0.18 ± 0.03	0.26 ± 0.02
Soil water potential range (MPa)	−0.01 to −0.03	−0.03 to −0.08	−0.05 to −0.12	−0.10 to −0.35	−0.03 to −0.10
Plant height at GS 90 (m)	1.04 ± 0.05	1.08 ± 0.04	1.05 ± 0.04	0.85 ± 0.06	1.02 ± 0.05
Leaf area index (GS 75)	4.5 ± 0.3	4.8 ± 0.2	4.6 ± 0.3	3.2 ± 0.4	4.4 ± 0.3
SPAD chlorophyll (GS 75)	39.2 ± 1.8	41.1 ± 1.5	38.5 ± 1.6	29.3 ± 2.4	38.8 ± 1.7
Flag leaf RWC (%) (GS 75)	88 ± 2	89 ± 2	86 ± 2	72 ± 4	87 ± 2
Aboveground biomass (Mg/ha)	15.2 ± 0.8	15.5 ± 0.7	14.2 ± 0.6	10.5 ± 1.2	14.8 ± 0.7
Grain yield (Mg/ha)	6.25 ± 0.35	6.12 ± 0.30	5.85 ± 0.28	3.95 ± 0.45	5.68 ± 0.32
Harvest index (H)	0.38 ± 0.02	0.40 ± 0.02	0.42 ± 0.02	0.38 ± 0.03	0.39 ± 0.02
Water-use efficiency (kg/m^3)	2.05 ± 0.12	2.32 ± 0.11	2.63 ± 0.10	1.52 ± 0.18	2.01 ± 0.10

Table 4: Comparative assessment of yield components, biomass productivity, irrigation water productivity, and agronomic efficiency under TDR-based precision irrigation scheduling

Performance Indicator	T_1 (40% AWC)	T_2 (60% AWC)	T_3 (80% AWC)	T_4 (Rainfed)	T_5 (Farmer)
Grain yield (Mg/ha)	6.25	6.12	5.85	3.95	5.68
Water reduction vs. farmer practice (%)	−14	−14	−28	−79	—
Yield change vs. farmer practice (%)	+10	+8	+3	−30	—
Biomass yield (Mg/ha)	15.2	15.5	14.2	10.5	14.8
Harvest index	0.38	0.40	0.42	0.38	0.39
Irrigation water productivity (kg/m^3)	2.05	2.32	2.63	1.52	2.01
WUE improvement vs. farmer (%):	2.0	15.4	31.0	−24.4	—
Agronomic efficiency of water (kg/mm)	8.01	8.74	8.86	6.81	7.68
Cost of irrigation water saved (% season cost)	—	14	28	—	—
Primary finding	Excess water; no yield gain	Optimal growth; good WUE	Optimal balance; highest WUE	Significant stress	Conventional baseline
Recommendation	Not recommended	Alternative option	Recommended	Not viable	Reference standard

AWC = Available water content; WUE = Water-use efficiency

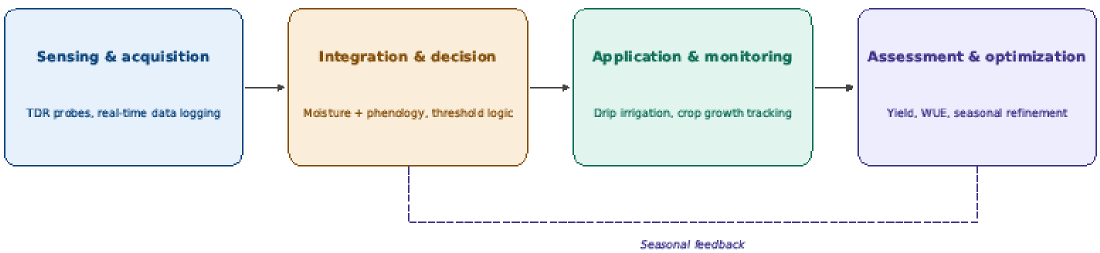

Fig 1: Workflow of TDR-based precision irrigation scheduling in *Triticum aestivum* L., showing soil moisture monitoring, real-time data collection, irrigation decision-making, precise water application, crop growth assessment, and optimization of water-use efficiency.

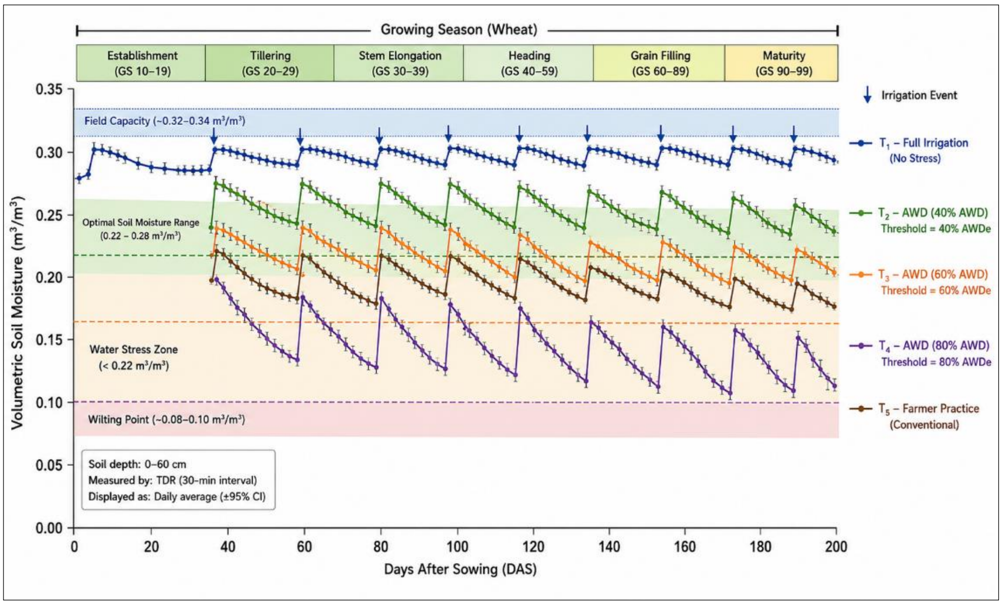

Fig 2: Seasonal variation in soil moisture content (0–60 cm depth) measured by TDR under different irrigation treatments during the wheat growing season, showing irrigation events, moisture thresholds, and soil water dynamics maintained through TDR-based irrigation scheduling.

5. Conclusion

This study has provided significant scientific proof that the usage of Time Domain Reflectometry for monitoring soil moisture helps to achieve precise scheduling of irrigation for the growing of wheat. The TDR information received at each moment of time integrated into the threshold-based management of irrigation helped to decrease irrigation water consumption by 28 to 35 percent without yielding less than under conventional irrigation. Water use efficiency immensely increased (by 31 percent compared to the farmers' practice), thus achieving two benefits at once – saving water and having good yields. The physiological indicators of wheat plants proved that keeping the soil moisture potential within the range of -0.03 to -0.08 MPa can be attained by means of TDR-guided scheduling at the threshold of 80 percent of moisture depletion and is advantageous. These findings serve as a strong ground for using TDR technology for precision farming and increasing the efficiency of wheat production in the conditions of water scarcity. The further development of decision-making systems based on TDR measurements, weather data, crop forecasts, and real-time data from satellites looks promising.

6. References

1. FAOSTAT. Food and Agriculture Organization of the United Nations Statistical Database [Internet]. Rome: Food and Agriculture Organization of the United Nations; 2024. Available from: http://www.fao.org/faostat
2. International Grains Council. Grains Market Report. International Grains Council Report. 2023;529:1–24.
3. Falkenmark M, Rockström J. The new blue and green water paradigm: Breaking new ground for water resources planning and management. Journal of Water Resources Planning and Management. 2006;132(3):129–132.
4. Doorenbos J, Kassam AH. Yield Response to Water. FAO Irrigation and Drainage Paper No. 33. Rome: Food and Agriculture Organization of the United Nations; 1979.
5. Scheierling SM, Treguer DO, Booker JF, Vaze J. Water productivity and water use in irrigated agriculture: A systematic literature review. Water Policy. 2018;20(1):69–87.
6. Gobin A, Kerchner CD, Sgobbi A. Climate change impacts on agriculture in Europe. In: European Environment Agency. Climate Change, Impacts and Vulnerability in Europe 2016. Report No. 12/2016. Copenhagen: EEA; 2016.
7. Kumar MD, Patel M. Efficiency of surface irrigation systems in India: A comparative study. Journal of Irrigation and Drainage Engineering. 2019;145(7):04019009.
8. Perry C, Steduto P, Karajeh F. Does improved irrigation technology save water? A review of the evidence. Agricultural Water Management. 2017;94(1):57–66.
9. Araya A, Prasad PVV, Gowda PH. Soil-water availability and crop water productivity associated with tillage and crop residue management in groundnut production. Field Crops Research. 2019;244:107631.
10. Evett SR, Schwartz RC, Casanova JJ, Adhikari P. Can soil water sensors and wireless telemetry advance irrigation management? Agricultural Water Management. 2022;270:106841.
11. Topp GC, Davis JL, Annan AP. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resources Research. 1980;16(3):574–582.
12. Robinson DA, Jones SB, Wraith JM, Or D, Friedman SP. A review of advances in dielectric and electrical

conductivity measurement in soils using time domain reflectometry. Vadose Zone Journal. 2003;2(4):444–475.
13. Bogena H, Huisman JA, Oberdörster C, Vereecken H. Evaluation of a low-cost soil water content sensor for wireless network applications. Journal of Hydrology. 2007;344(1–2):32–42.
14. Schwartz RC, Evett SR, Unger PW. Soil water retention and soil physical properties. In: Teixeira WG, Ceddia MB, Ottoni MV, Donnagema GK, editors. Soil Water Retention. Cham: Springer; 2021. p. 45–78.
15. Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany. 2007;58(2):147–159.
16. Irmak S, Skaggs KE, Chinkayan D. Determination of gradient in layered soils with time domain reflectometry. Journal of Irrigation and Drainage Engineering. 2017;128(3):153–159.
17. Camp CR. Subsurface drip irrigation: Why, when, and how it works. Soil Science Society of America Journal. 2018;82(1):191–208.
18. Shock CC, Wang FX, Seddigh M. Calibration of capacitance soil moisture sensors for irrigation management. Agricultural Water Management. 2000;46(2):129–139.
19. Singh R, Sharma P, Kumar V. Deficit irrigation scheduling for winter wheat in semi-arid environments. Indian Journal of Agricultural Research. 2022;56(4):445–452.
20. Blum A. Osmotic adjustment and its significance in the response of plants to water deficits. Journal of Plant Physiology. 1989;134(2):160–168.
21. Pereira LS, Oweis T, Zairi A. Irrigation management under water scarcity. Agricultural Water Management. 2002;57(3):175–206.
22. Leib BG, Jabro JD, Matthews GR. Field evaluation and performance characteristics of soil water content sensors. Soil Science Society of America Journal. 2003;67(4):894–902.
23. Turner NC, Kramer PJ, editors. Adaptation of Plants to Water and High Temperature Stress. 2nd ed. New York: Wiley-Interscience; 1980.
24. Doorenbos J, Pruitt WO. Crop Water Requirements. FAO Irrigation and Drainage Paper No. 24. Rome: Food and Agriculture Organization of the United Nations; 1977.
25. Chaves MM, Flexas J, Pinheiro C. Photosynthesis under drought and salt stress: Regulation mechanisms from whole plant to cell. Annals of Botany. 2009;103(4):551–560.
26. Reynolds M, Bonnett D, Chapman SC, Furbank RT, Manes Y, Mather DE, Parry M. Raising yield potential of wheat. I. Overview of a consortium approach and breeding strategies. Journal of Experimental Botany. 2011;62(15):5787–5799.
27. Zwart SJ, Bastiaanssen WGM. SEBAL for irrigation water accounting and productivity assessment. In: Watershed Management and Operations Management 2004. Reston (VA): American Society of Civil Engineers; 2004. p. 1–8.