Irrigation scheduling based on canopy temperature and soil moisture status

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Issues of water availability and quality are major concerns under the climatic change scenarios. For sustainable agriculture, improved irrigation techniques can play a crucial role in the conservation of water and increase crop production. This article delineates the necessity of irrigation scheduling based on sound scientific principles. To effectively manage irrigation and crop water requirements, all irrigation scheduling methods should focus on a soil-plant-atmosphere approach.

Keywords: Canopy temperature, irrigation scheduling, remote sensing, soil moisture, water stress.

WATER is an important input in agriculture. Globally, 20% of the total cultivated area is represented by irrigated agriculture, which contributes 40% of the total food produced[1]. In traditional practices of irrigation like flood irrigation, a massive amount of water is used, which leads to over-irrigation in certain parts of the field, whereas the other parts are devoid of it. So, when water is applied in excess, it may often lead to ponding, waterlogging, run-off and seepage, thereby causing leaching of the applied nutrients and contaminating water bodies. Water scarcity across the world has forced scientists to analyse various methods for its management. In India, water consumption per capita has declined from 5000 m^3 annually in 1950 to 1545 m^3 in 2011. This is expected to decrease even further to 1341 and 1140 m^3 in 2025 and 2050 respectively[2] (Figure 1). The rapid decline in groundwater levels has led to the non-availability of irrigation water during the crop-growing season, especially in Punjab, India. An International Water Management Institute (IWMI) study found that an increase in irrigation effectiveness by the year 2025 can meet about 50% of the rise in water demand[3]. Thus, for judicious and efficient utilization of water, it is important to schedule irrigation.

The concept of irrigation scheduling is based on the measure of profitability per input when labour and cultural practices restrict irrigation water supply. Farmers generally schedule irrigation according to the plant's water needs or according to calendar dates regardless of weather conditions or cropping patterns. The effective application of irrigation water depends on the insights and the scheduling principles to establish a management plan and the efficacious application of the plan[4]. Several methods of irrigation scheduling are available, varying their intricacies and functionality[4]. Scheduling of irrigation is achieved using different approaches such as (a) water balance of evapotranspiration-based approach, (b) soil moisture status and (c) plant indices approach. Appraisal of crop evapotranspiration from climatic parameters provides an equitable criterion for scheduling irrigation. During evapotranspiration, water lost from the root zone is replenished to meet the water requirements of plants. In the soil moisture approach, available soil moisture in the root zone of plants is estimated to determine the demand for irrigation. The plant indicator approach takes into account the water status of plants for irrigation scheduling. Plant canopy temperature has been a useful measure of plant water status[5,6]. Irrigation scheduling helps maximize the efficiency and enables the sustainability of irrigated agriculture.

Canopy temperature as the basis of irrigation scheduling

Canopy temperature has been used as a key factor for scheduling irrigation. It can be used as an indicator of plant water status because when a non-stressed plant transpires, it leads to the cooling of its environment. Whereas in water-stressed plants, the closing of stomata will reduce transpiration, thereby increasing the temperature[6]. Measurement of canopy temperature with an infrared thermometer has been an effective tool for scheduling irrigation. To schedule irrigation based on canopy temperature, different indices have been used, viz. crop water stress index (CWSI), temperature–time threshold (TTT) and temperature stress days (TSD)[7].

Crop water stress index method

Plants suffer from stress when there is insufficient soil moisture, which results in the closure of stomata and an increase in leaf temperature. The difference in canopy temperature is the basis of CWSI. Two approaches are used to determine CWSI: the empirical crop water stress index proposed by Idso *et al.*[6] and a theoretical approach developed by Jackson *et al.*[8].

The empirical method CSWI schedules irrigation based on the difference between canopy temperature and air

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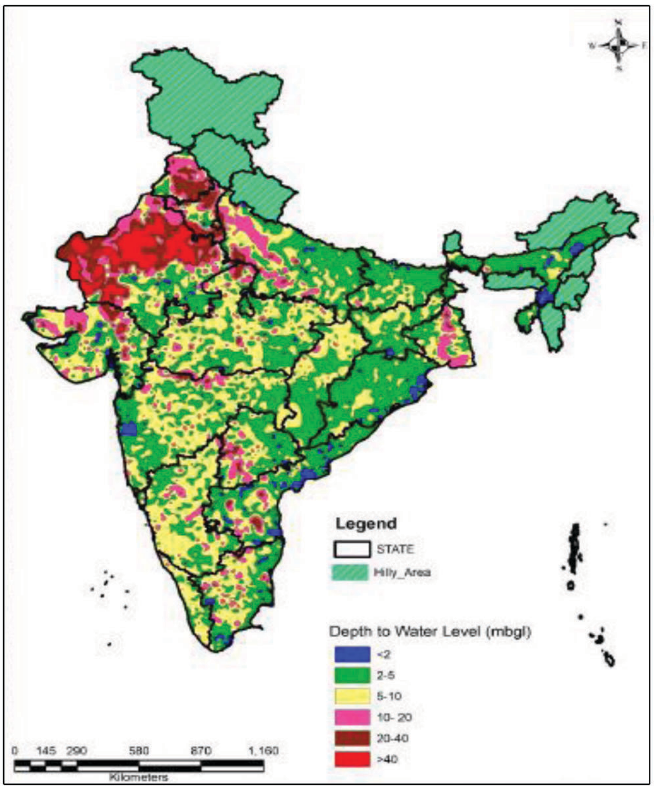

Figure 1. Map showing the depth to water level in India during January 2020. (Source: Ground Water Year Book, India, 2019–20, Central Ground Water Board.)

temperature, which is calculated at different stages of vapour pressure deficit (VPD). In this method, the non-water-stressed baselines are established through experiments with fully stressed and non-stressed treatments[9]. A linear relationship between canopy air temperature difference and VPD was observed[6]. Changes in the architecture of the canopy, stomatal opening and plant height, along with weather parameters can alter the baselines. This method is often used to determine the timing of irrigation by evaluating CWSI under various irrigation treatments. The theoretical approach developed by Jackson *et al.*[8] relies on the energy available and aerodynamic properties of the crops, whereas the performance of the lower baselines is dependent on the net radiation, canopy resistance and aerodynamics resistance and VPD. Based on upper and lower baselines, CWSI indicates crop water stress at any time. The CWSI range lies between 0 and 1. CWSI can be expressed as

$$\text{CWSI} = \left(\frac{(T_c - T_a) - (T_c - T_a)_{\min}}{(T_c - T_a)_{\max} - (T_c - T_a)_{\min}} \right),$$

where $(T_c - T_a)_{\max}$ is the maximum canopy and air temperature difference for the stressed crop (maximum stressed baseline); $(T_c - T_a)_{\min}$ the lower limit of the canopy and air temperature difference for the well-watered crop (the non-stressed baseline), T_c the measured canopy surface temperature and T_a is the ambient air temperature. Measuring the canopy temperature during the early stages of crop growth is often considered a shortcoming of this method[8]. Canopy temperature can be evaluated using the infrared thermometer. This is a non-destructive and relatively inexpensive method compared to other methods for measuring plant water status. With the advancement in digital thermal imaging technology, it can also be used for measuring canopy temperature for its application in scheduling irrigation[10,11].

In the TTT method, the application of irrigation is done only when the canopy temperature exceeds a crop-specific threshold for more than a specific time within a day[12]. The amount of water to be applied depends upon the daily evapotranspiration. The drawback of this method is that canopy temperature can be affected by the surrounding temperature, i.e. it can be high on a hot day even if the crop is well watered. This approach only considers the canopy temperature threshold and the period when there will be an escalation in the threshold temperature. No consideration is given to the extent to which it can be increased. Further, the quantity of water to be applied depends upon the evapotranspiration, which can be unreliable and may lead to deep seepage. The temperature stress days method is based on the difference between the stressed and non-stressed canopy temperature of the crop[13].

Soil moisture status as the basis of irrigation scheduling

Soil moisture-based irrigation scheduling mainly emphasizes establishing when irrigation should be applied to the root zone to maintain soil moisture within a pertinent range[14]. In this method, the available soil water is held between field capacity (FC) and the permanent wilting point (PWP) in the effective root zone depth is taken as a guide to determine irrigation schedules. Soil moisture tension can also be used as a guide for irrigation schedules. Soil moisture-based irrigation scheduling system allows variable rate of irrigation scheduling due to their capacity to measure spatial and temporal variability in moisture in the field. Time-domain transmission sensors or reflectometry probes, neutron probes, capacitance sensors, granular matrix sensors, etc. are used to measure the soil moisture status[15,16]. To quantify the soil water available for plant use, soil moisture, soil moisture tension or soil matric potential is measured using tensiometers. This soil moisture-based approach compares the actual available soil water content (AWC%) with a soil moisture threshold (AWC_{th})

$$\mathrm{AWC} = 100 \times \left(\frac{\theta_{\mathrm{a}} - \theta_{\mathrm{pwp}}}{\theta_{\mathrm{fc}} - \theta_{\mathrm{pwp}}} \right),$$

where θ_a is the actual volumetric soil water content, θ_{fc} and θ_{pwp} corresponds to the field capacity and permanent wilting point.

With advancements in technology, the use of electromagnetic mapping techniques has the potential to attain a high spatial resolution in both soil moisture and soil properties. Thus, soil moisture should be mapped at a higher resolution, allowing for the scheduling of irrigation is at more precise rate[15]. The inaccuracy of soil moisture measurement using sensors can be considered one of the shortcomings of the soil moisture-based irrigation method[17].

Remote sensing-based irrigation scheduling

Measurement of canopy temperature with the help of an infrared thermometer has been used in various studies. However, alternative methods, such as remote sensing, should also be used to detect water stress in plants. Narrowband indices, which are based on the visible and red-edge spectral region, can be used to detect crop water stress[18–20]. In some plants, the relationship between canopy temperature and stress levels is not explicit due to diurnal variations in stomatal conductance. Due to high VPD, an escalation in evaporative demand was observed. This leads to a reduction in leaf conductance, even when the crops are well watered[21]. To monitor the large cropped area, appropriate imagery at high spatial and spectral resolution is required, which is possible with the remote sensing technique[18]. With advancements in technology, there is widespread adoption of remote sensing techniques[22,23]. The potential applications of remote sensing include crop scouting, mapping canopy coverage, determining plant water stress, measurement of soil moisture, managing the variable rate of irrigation and crop yield estimation. The total water available in the soil was estimated by integrating evapotranspiration data with multispectral imagery[24]. Remotely sensed image has been used to map soil moisture for efficient water management and agriculture practices in the Mediterranean region[25]. Real-time mapping and image analysis are utilized for early detection of plant water stress and to promptly schedule irrigation, which is likely to acquire information from the leaf to canopy/fields levels[26]. Several recent studies have analysed alternative narrow-band hyperspectral indices for detecting crop water stress[19,27]. Spectral vegetation indices such as normalized difference vegetation index (NDVI) (Figure 2), renormalized difference vegetation index (RDVI), optimized soil adjusted vegetation index (OSAVI), photochemical reflectance index (PRI_{570}), normalized PRI (PRI_{norm}), water index (WI) are now used to measure water stress in crops[28]. NDWI can also be used to measure soil moisture content (Figure 3).

Canopy air temperature difference and crop water stress index for scheduling irrigation in different crops

Plant water stress measurement combined with a more coherent irrigation system enables farmers to maximize crop yield through better management of irrigation. Irrigation scheduling can result in economic and often higher yields, with less water application along with traditional irrigation practices. A new canopy temperature-based index, also known as plant water stress index (PSI), has been used to schedule irrigation[29]. A relationship between soil moisture depletion and PSI was developed in wheat crops. It was reported that to obtain an optimum yield of wheat, a PSI value of 0.5 should be maintained[29]. Quantification of CWSI was to schedule irrigation in wheat by developing a relationship between canopy air temperature and VPD for no-stress conditions. A linear relationship was observed between them. An average upper limit of 0.3 was observed for CWSI. If this limit is exceeded, irrigation should be applied to the wheat crop[9]. In maize, phenological-based irrigation scheduling was done by estimating CWSI[30]. The baseline equations were developed, and CWSI was obtained from canopy air temperature. The study reported the range of CWSI as 0.42–0.48 at the silking stage; it was lower than the recommended value (0.60)[30]. Similarly, baseline equations were developed to determine the CWSI in wheat. It was observed that using a non-water-stress baseline along with the data collected, CWSI can monitor water status and irrigation scheduling[31]. In sunflowers, CWSI values were evaluated to schedule irrigation[32]. It was found

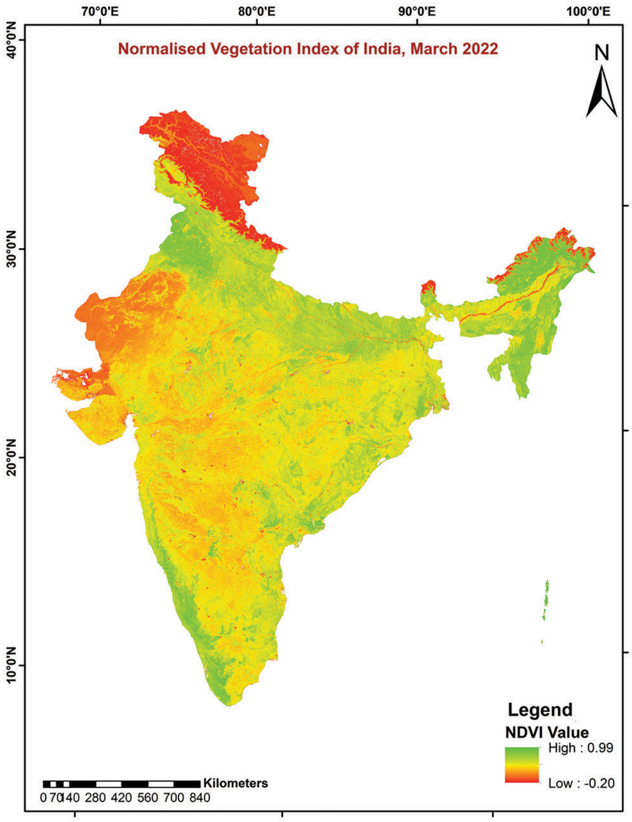

Figure 2. Map showing the classification of NDVI of India. (Data source: Google Earth Engine.)

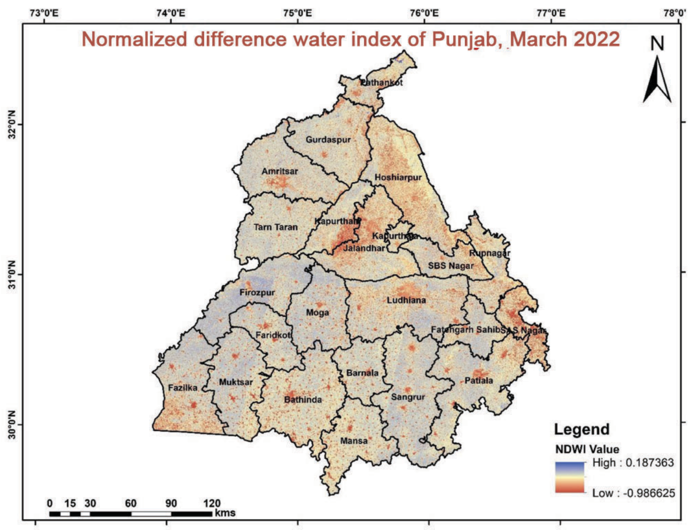

Figure 3. Map showing the classification of NDWI of Punjab. (Data source: USGS Earth Explorer.)

that when CWSI reached a value of 0.6, irrigation should be applied[32]. Also, in grain sorghum, it was observed that CWSI and time threshold index had the potential to be utilized as tools for deficit irrigation scheduling[33]. The effectiveness of this approach was compared to well-watered, moderately stressed and dryland treatments of maize, soybean and cotton. This method significantly improved irrigation water use efficiency in cotton and corn[34]. Similarly, it was suggested that irrigation should be done in cotton crops when CWSI approaches 0.36. Thus, it can be a useful tool for irrigation scheduling[35]. A polynomial relationship between CWSI and water use efficiency (WUE) was developed in soybean crops. The highest WUE was observed when the CWSI value was 0.6. Thus, a study conducted in

Table 1. Techniques for irrigation scheduling in different crops

Crop	Study	Location	Results and reference
Wheat	PSI and CWSI	Roorke, India	PSI at 0.5 was recorded as the best[29].
Maize	CWSI	Odisha, India	The range 0.42–0.48 of CWSI was observed at silking stage[30].
Sunflower	CWSI	Tekirdag, Turkey	Seed yield was affected significantly by the level of irrigation. The highest seed yield (4.38 tonne/ha) was obtained when the CWSI value was 0.2, and was similar at 0.4 and 0.6 (ref. 32).
Grain sorghum	CWSI	Phoenix, USA	A significant difference was observed in WUE (between irrigation control methods)[33].
Cotton	Vapour pressure deficit	Missouri, USA	Irrigation use efficiency of cotton was improved when irrigation was applied with the help of CWSI[34].
Corn	Vapour pressure deficit	Missouri, USA	This method resulted in 85% of maximum yield while using less than 50% of irrigation water[34].
Cotton	CWSI	Turkey	Irrigation should be applied when the CWSI value reaches 0.36 (ref. 35).
Soybean	CWSI	Turkey	The polynomial relationship between WUE and CWSI depicts that the highest WUE can be obtained at CWSI value close to 0.6 (ref. 36).
Black gram	CWSI	Urmia, Iran	This method can be used to determine the irrigation time along with growth stages of the crop. Also, irrigation should be applied when CWSI is 0.15 (ref. 38).
Potato	Pan evaporimeter method	Yucheng Comprehensive Experimental Station, China	Under controlled irrigation conditions, potatoes should be irrigated using a pan evaporation factor of more than 0.75 (ref. 42).
Potato	Soil matric potential threshold	LAES, Hebei Province, China	An increase in yield and WUE was observed when irrigation was applied at a soil matric potential of –25 kPa (ref. 43).
Cotton and wheat	MAD (management allowed depletion)	Landhi, Karachi, Pakistan	Cotton and wheat had the highest WUE when MAD was 65% and 55% respectively[45].
Cotton	Pan evaporimeter and gravimetric approach	Aydin, Turkey	Pan evaporation method resulted in higher yields than gravimetric applications[49].
Iranian wheat varieties	CWSI	Shiraz, Iran	CWSI, water supply volume, and flag leaf net photosynthetic rate were all found to be negatively correlated. The CWSI values for varieties Shiraz and Yavroz were 0.73 and 0.71 respectively, while for Bahar, Pishtaz and Sistan it ranged from 0.61 to 0.64 under severe drought conditions[50].
Potato	MAD	India	As MAD is increased from 45% to 75%, the fresh tuber yield is reduced due to depletion in water availability[51].

Turkey concluded that CWSI could be used to evaluate crop water stress and improve irrigation scheduling under sub-humid climatic conditions[36]. CWSI values of 0.42, 0.37 and 0.29 were also observed to result in maximum water productivity for growth, and development in the middle and final stages of plant growth of soybean[37]. Furthermore, black-gram irrigation was scheduled using CWSI. A CWSI value of 0.15 can be used to schedule irrigation. It could also be used to determine the irrigation time along with different growth stages[38]. A decrease in corn yield was observed when the average mean value of CWSI increased by 0.22. So, it was deduced that CWSI can be useful for monitoring and quantifying water stress in corn[39]. In crops like watermelon, different threshold values of CWSI were evaluated to schedule drip irrigation. It was detected that fruit yield was significantly affected by irrigation levels. Maximum WUE and irrigation WUE were obtained with a CWSI value of 0.6. Thus, CWSI can be used to schedule irrigation in watermelon[40]. The feasibility of canopy temperature-based CWSI was evaluated in Indian mustard (*Brassica juncea*). It was established that a CWSI value of 0.4 can be used to detect stress and schedule irrigation for the crop[41].

Soil moisture status-based irrigation scheduling in different crops

To improve irrigation, scheduling with the help of soil moisture status can also be considered an effective method. The soil's moisture content status can be used to identify water scarcity. Also, application of excess irrigation water

Table 2. Techniques for irrigation scheduling in different crops using remote sensing

Crop	Imagery used	Location	Results and reference
Wheat	Canopy hyperspectral reflectance	Northwest China	Water stress was determined using indices like semi-arid water index-1, semi-arid water index-2, and red edge normalized difference vegetation index (NDVI)[19].
Wheat	Multispectral indices derived from Landsat-Tm	India	Crop water stress was determined using vegetation indices like vegetation water stress index (VWSI) and land surface wetness index water stress factor (Ws_LSWI). It was observed that Ws_LSWI was preferred to detect water stress[28].
Potato	Hyperspectral imagery	USA	The soil moisture content was found to be strongly correlated with spectral indices including Red Edge NDVI, Modified NDVI, Modified Red Edge SRI, Vogelmann Red Edge Index (VOG REI) 1, 2 and 3. Thus, there is potential for the development of spectral sensors for non-contact soil-moisture content monitoring systems, which could lead to automatic irrigation systems for preserving the ideal amount of soil moisture content during the potato growing season[52].
Maize	Airborne hyperspectral imagery	Northern Italy	Mapping hyper stress classes utilizing hyperspectral indices is effective and establishes the applicability of remote sensing data for optimizing irrigation management[53].
Bell pepper	Spectral data obtained from reflectance	Canada	Among the spectral indices PRI_{553}, water index (WI), renormalized difference vegetation index (RDVI), PRInorm (normalized photochemical reflectance index), normalized difference vegetation index (NDVI) were successfully used to detect water stress in plants[54].

can lead to waterlogging and leaching below the root zone. In potatoes, an experiment was performed in which different irrigation regimes were evaluated. It was observed that potatoes should be irrigated using a pan evaporation factor of more than 0.75 ($K > 0.75$), which is a guideline. A significant reduction in the yield of potato tuber was observed when the pan evaporation factor was lower than 0.75 ($K < 0.75$)[42]. Similarly, the yield of the potato crop was evaluated with different soil matric potential. It was deduced from the results that the evapotranspiration, yield and WUE were influenced by both soil matric potential and drip irrigation frequency. Maximum yield and WUE were obtained when the soil matric potential threshold was –25 kPa with an irrigation frequency of once a day[43].

Reduction in dry matter and grain yield along with evapotranspiration and deep percolation was observed when deficit irrigation was applied at different growth stages in maize. When deficit irrigation was applied to any of the growth stages of maize, no significant reduction in biomass was observed, whereas grain yield was reduced. Maximum WUE was obtained when deficit irrigation was applied at the vegetative stage. Thus, it was concluded that irrigation WUE can be improved when deficit irrigation is applied at the vegetative stage in maize crops[44]. Optimum WUE for various management allowed depletion (MAD) levels was evaluated for both cotton and wheat crops. The highest WUE was observed when MAD was 65% for cotton and 55% for wheat[45]. Further, analysis of root development and uptake of water in winter wheat under different irrigation methods and scheduling in North China revealed that these approaches influenced root development, the profile root distribution pattern and profile root water uptake. Thus, water uptake and water productivity were the highest in surface drip irrigation at 60% of FC, and a maximum grain yield of 9.53 tonne/ha was obtained[46]. Cutbacks in grain yield and crop WUE were observed when soil moisture depletion levels were below the recommended values in hybrid maize. Also, appropriate irrigation intervals at each crop growth stage soil were identified[47]. In wheat crops, irrigation scheduling using a soil moisture approach and climate-based approach was adopted and compared. A significant increase in grain yield was observed in soil moisture-based treatments compared to climate-based treatments[48]. A pan evaporation approach with irrigation level-100% was suggested to produce cotton. Also, regarding seed cotton yield for deficit irrigation strategy, irrigation treatments with a gravimetric approach should be employed[49]. Table 1 provides details of various techniques for scheduling irrigation for different crops.

Remote sensing-based irrigation scheduling in different crops

Remotely sensed data are highly amenable to the immediate changes in plant physiology and thus provide real-time information regarding crop response to abiotic conditions. Several studies have used remote sensing techniques to determine crop water stress in various crops. Hyperspectral imaging can be used to determine the changes in spectral reflectance of plants considering various soil moisture levels. Also, for mapping water stress, airborne hyperspectral imagery was used in maize crops. PRI_{570} was used to map stress in the field, as it showed prominent results when matched against classes of water stress, consistent with the amount of irrigation used in the field. Similarly, canopy hyperspectral reflectance data were used to determine the canopy water stress in wheat. At a different level of water stress, the relationship between canopy reflectance and canopy water content was analysed. It was concluded that canopy reflectance can be used to identify crop water stress[19]. In greenhouse conditions, spectral indices such as the NDVI, RDVI, OSAVI, PRI_{570}, photochemical reflectance index at 553 nm (PRI_{553}), PRInorm and WI were used to detect plant water stress in horticultural crops like bell peppers. Thus, it can be concluded that this method can be used to assess water stress and improve irrigation management[28]. Table 2 provides details of techniques for scheduling irrigation based on remote sensing.

Conclusion

Climate change will impact agriculture by increasing the demand for water, reducing agricultural output and decreasing water supply in regions where irrigation is most necessary or advantageous. Thus, irrigation scheduling is a crucial approach for maximizing the water-holding capacity of agricultural systems and making the most of the limited water supply. In many aspects, irrigation scheduling has changed from being a scientific endeavour to a useful application, or at the very least a more sophisticated version of one that already exists. However, several novel approaches to irrigation scheduling have been developed recently that have not yet gained widespread acceptance. Many of these methods have been used primarily for experimental or research purposes. Different irrigation scheduling methods based on canopy temperature evaluation and soil moisture status have demonstrated the potential to optimize water use, albeit with some limitations. A real impetus for developing new precision irrigation scheduling systems, which take into account the irrigation requirements, will likely come from the need for improved water use efficiency and better precision in irrigation systems.

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