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Precision Water Management for Resource Conservation in India's Dryland Agriculture: Strategies and Technologies

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Water is a critical input for agricultural production systems. Increasing water productivity in field crops through precision water management (PWM) is essential for optimizing resource use. PWM aims to achieve maximum crop yield with optimal water utilization, enhancing productivity and crop quality through judicious irrigation. Proper crop monitoring related to applied irrigation helps growers

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manage their fields efficiently, saving water, time, and costs while improving yields compared to conventional systems. Analysing crop-water requirements and applying irrigation based on these parameters is crucial. Geographic Information System (GIS) technology integrates spatial and temporal data, aiding practical managerial decisions for irrigation. Proper adoption of precision irrigation can save up to 25% more water than conventional practices. Agriculture, the largest water consumer, uses 70% of global water resources, with drylands producing over half of the world's food. In India, drylands encompass 68% of the net sown area, contributing significantly to crop production but facing freshwater scarcity, global warming, and erratic rainfall, impacting productivity. Despite efforts to improve irrigation efficiency in India, overall efficiency remains between 35% and 40%. Advances in irrigation systems and technologies now enable site-specific application of water within fields, enhancing water use efficiency and reducing overall water usage for sustainable crop production, particularly in arid and semi-arid regions. This paper explores recent developments in Variable-Rate Irrigation (VRI) technologies, including drip and central pivot irrigation systems. Effective precision water management can significantly boost crop yields, ensuring food security and contributing to sustainable development goals (SDG).

Keywords: Precision water management (PWM); Central pivot system; water footprint; Sustainable development goals (SDG); Low Energy Precision Application (LEPA); Variable rate technology (VRT).

1. INTRODUCTION

Agriculture is the largest consumer of water, utilizing 70% of the total consumption [1]. Over half of the world's food is produced on drylands, which represent 41.3% of global agricultural land [2]. In India, drylands encompass 177 districts and 68% of the net sown area (136.8 million hectares). These regions account for 68% of the area used for non-food crops and 48% for food crops. Nearly half of India's rural labour force and 60% of its livestock are concentrated in arid zones [3]. Sustainable rainfed agriculture in these drylands is essential for global food supply due to increasing freshwater scarcity. However, global warming and erratic rainfall patterns are depleting water resources and limiting agricultural productivity in these areas [1]. Agricultural cropping systems rely heavily on water resources for their survival, and the water requirements can vary across different areas within a field due to variations in soil characteristics like texture, topography, water-holding capacity, infiltration, and drainage rate. Consequently, the need for irrigation may differ from one zone to another within the same field. Conventional moving irrigation systems apply water at uniform rates, which can lead to some areas receiving too much water while others receive too little. Precision Water Management (PWM) aims to optimize water use for sustainable management by applying the right amount of quality water at the right time, place, and crop growth stage across the target area. Various strategies and technologies have been developed to support PWM, including computer-aided tools designed to enhance irrigation project management. Water is a critical input for crop growth and yield, influencing plant health and productivity. Both excess and deficit water conditions can cause significant stress to crops. Excess water can lead to root rot, which compromises root function and nutrient uptake. Conversely, water deficit conditions can cause wilting, reducing photosynthesis and potentially leading to plant death. Efficient water management is essential to maintain optimal soil moisture levels, ensuring crops receive adequate hydration without the risk of waterlogging or drought stress. Therefore, it is essential to provide crops with the optimal amount of water to maximize yield potential. Water quality, including factors such as salinity and pH, is vital for the effective growth of crops. This makes Precision Water Management (PWM) an essential practice, as it takes into account both the quality and quantity of water used [4].

1.1 Significance of Precision Water Management in Indian context

Recent news reports from sources like the ‘Times of India’ (2024), highlight the severe impact of drought in regions such as Maharashtra and Saurashtra (Gujarat), where crop failure and farmer suicides have become alarmingly common [5]. To address these issues, the government has promoted drip irrigation and other water-saving techniques, as evidenced by headlines like "Farmers take to drip irrigation to cut costs and save water" and

"Make every drop of water count for sustainable agriculture." Despite these efforts, there remains a significant gap between the created and utilized irrigation potential. By the end of the Eleventh Plan, only 87.86 million hectares of the total 113.53 million hectares of irrigation potential had been utilized, leaving a gap of 25.67 million hectares [6]. The gap between IPC and IPU is widening due to declining irrigation efficiency. Factors such as inadequate irrigation infrastructure and shifts in agricultural practices, like the intensive rice-wheat cropping system, also contribute to this growing disparity. According to a Central Water Commission report from 2015, the overall irrigation efficiency of major irrigation projects in India ranges between 35% and 40%, which is low compared to global standards. Improving irrigation efficiency is essential to meet the increasing water demands for food, the environment, urban areas, and industry [6].

The low productivity in rainfed agricultural regions is due to various constraints, including environmental factors (drought, flooding, soil compaction), socioeconomic conditions of farmers, and other agronomic management issues. Rockström *et al.* noted that India's actual crop yield is only 45% of its potential yield, suggesting that proper management in rainfed areas could significantly boost yields [7]. Recent research by Bal *et al*. indicated that the effect of dry spell (DSI) on crop yield decreases linearly, with regression coefficients of 0.63 for groundnut and 0.545 for maize [8]. To ensure food security and achieve potential yields, it is crucial to focus on efficient water management in agriculture.

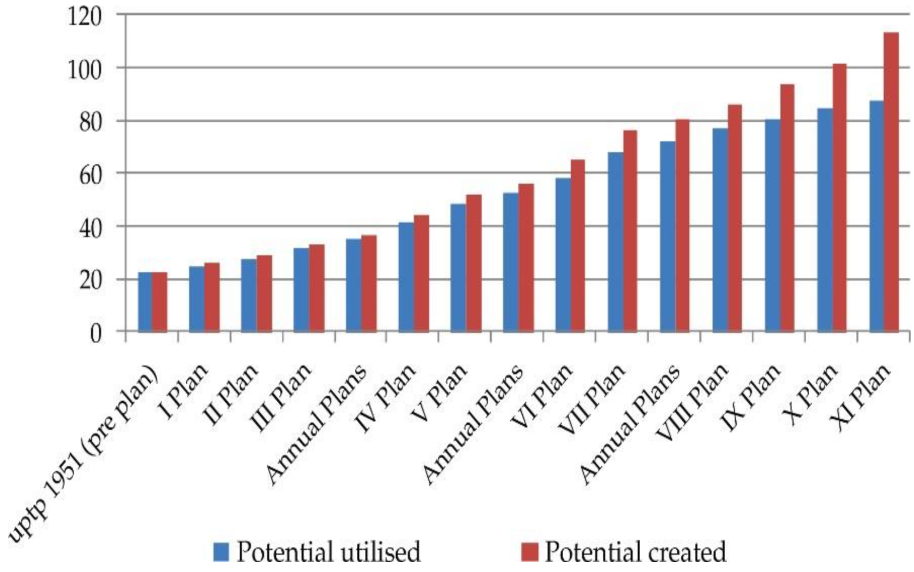


Fig. 1. Gap between irrigation potential created Vs irrigation potential utilized (Source: 6)

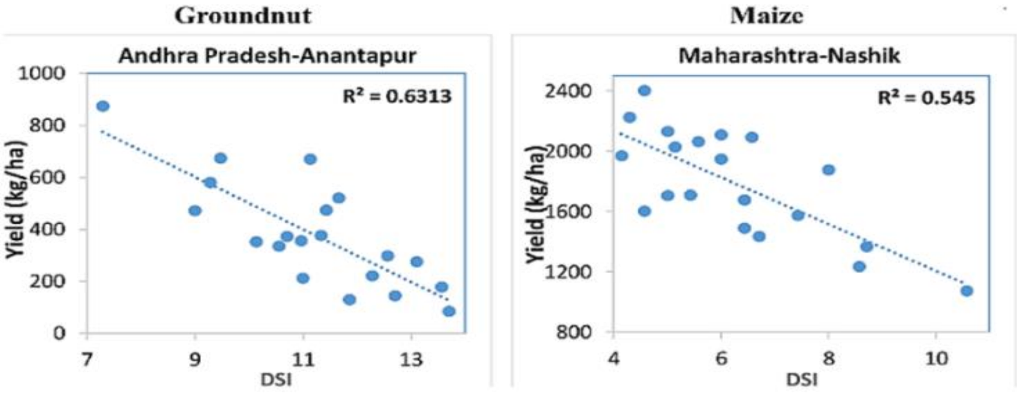


Fig. 2. Effect of dry spell on groundnut and maize yield (Source: 8)

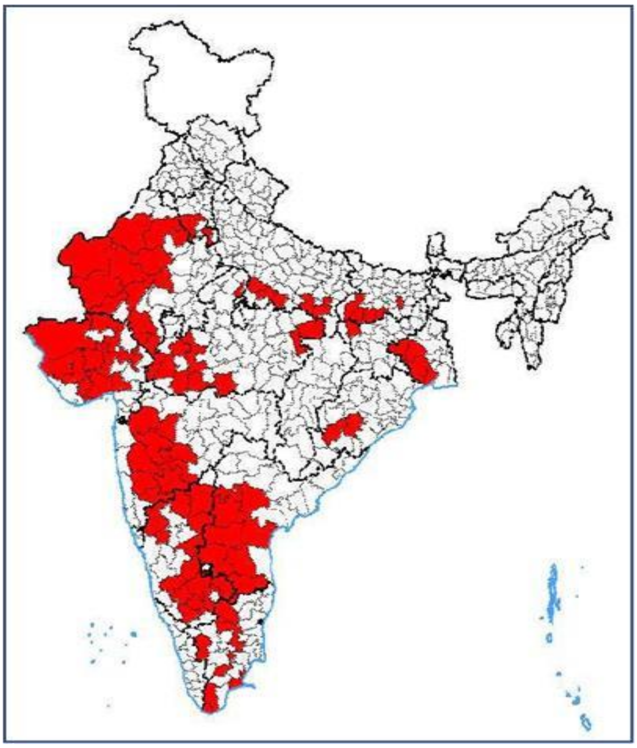


Fig. 3. Drought affected area of India

2. WATER AND DRYLAND SCENARIO OF INDIA AND ITS CONTRIBUTION TO INDIAN ECONOMY

India holds about 4% of the world's freshwater resources but must support around 17% of the global population. Despite this, it uses 2 to 4 times more water than countries like China and the USA to produce the same quantity of major agricultural products [9]. Annually, India receives approximately 4,000 billion cubic meters (BCM) of water, mainly from rainfall and some snowfall, but the distribution is highly variable across regions and seasons, impacting water availability. Of the 4,000 BCM of water received, around 1,869 BCM are accessible as water resources, with only 1,123 BCM (690 BCM from surface water and 433 BCM from groundwater) being usable. In 2000, water demand in India was 634 billion cubic meters (BCM). Projections indicate that total water demand will rise to 814 BCM by 2025 and reach 1,077 BCM by 2050. Per capita water availability in India has significantly declined, from 5,000 cubic meters annually in 1950 to an estimated 1,465 cubic meters by 2025, underscoring a sharp reduction in water resources for agriculture. In 2010, out of 781 BCM of total water withdrawals, around 91% (688 BCM) was utilized for agriculture, making it the largest consumer of freshwater in the country.

Globally, out of the 1.5 billion hectares (ha) of cropland, 1.223 billion ha (82%) is rainfed, contributing to 70% of the world's staple food [10]. In India, out of 143.8 million ha of arable land, 32% (43.8 million ha) is irrigated, and the remaining 68% (100 million ha) is used for dry farming. Within this 100 million ha, 65.5 million ha is rainfed, and 34.5 million ha is dry farming [11]. India's drought-prone areas, marked in red on the map, include almost all of Rajasthan (except Ganganagar district), the Kutch and Gujarat region, the rain shadow areas of the Western Ghats, parts of Tamil Nadu, Karnataka, and Andhra Pradesh, Bankura and Purulia districts of West Bengal, and the Bundelkhand region. The arid zone covers about 12% of India’s geographical area, with 32 million ha of hot arid land spread across Rajasthan (61%), Gujarat (20%), Andhra Pradesh and Karnataka (10%), and Punjab and Haryana (9%). Dryland agriculture accounts for approximately 91% of the area for coarse cereals (sorghum, pearl millet, maize, and finger millet), 91% of pulses (chickpea and pigeon pea), 80% of oilseeds (groundnut, rapeseed, mustard, and soybean), and 65% of cotton. Additionally, about 50% of the rice area and 19% of the wheat area are rainfed [12].

Over the past 25 years, significant changes have occurred in the area and yield of key crops in rainfed regions. The area for coarse cereals decreased by approximately 10.7 million hectares, mainly affecting sorghum. Conversely, the area for oilseeds increased by 9.2 million hectares, largely due to irrigated rapeseed, mustard, and soybean. The total area for pulses and cotton remained stable, although more cotton became irrigated, and there were regional shifts in crop areas. The area for chickpea decreased in the northern belt but increased in the central belt. This shift was driven by the expansion of the rice-wheat cropping system, which displaced chickpea, as well as pearl millet to a large extent and maize to a lesser extent [11].

2.1 Water Footprints and Water Management of Field Crops

The concept of the water footprint was introduced by Hoekstra in 2003 [13]. It represents the total volume of water used to produce a product, typically measured in cubic meters per tonne (m^3/tonne). This includes the water used in all process steps involved in manufacturing the product. The water footprint for a specific geographic area, such as a province, state, basin, or river basin, is the cumulative water footprint of all processes occurring within that area.

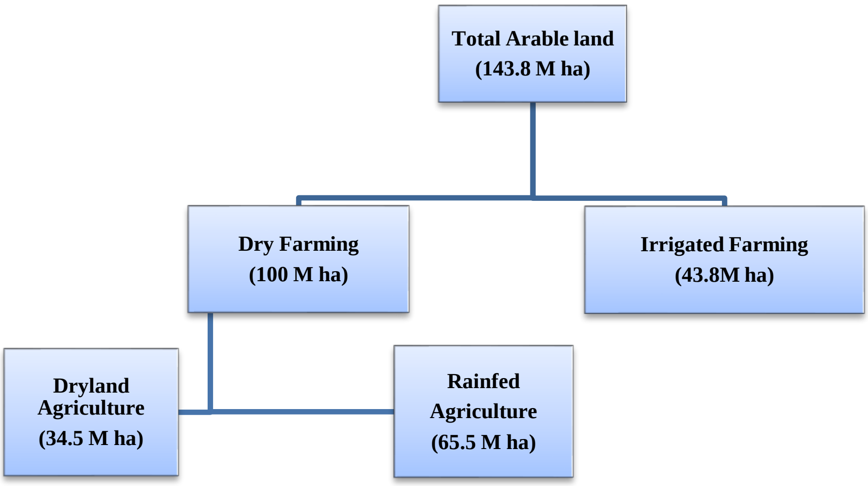


Fig. 4. Distribution of Dryland area in India (Source: 12)

Table 1. Types of water footprint [14]

Types of water footprint	Characteristics
Blue Water Footprint	This represents the volume of surface and groundwater consumed (evaporated) during the production of goods.
Green Water Footprint	This denotes the volume of rainwater used for the crop production and another use
Gray Water Footprint	This indicates the volume of freshwater required to dilute pollutants to meet existing water quality standards.

Table 2. Average Water Footprint (m^3/tonne) of different crops [15]

Crop Type	Average Water Footprint (m^3/tonne)
Sugar crops	~200
Vegetables	300
Roots and tubers	400
Fruits	1,000
Cereals	1,600

Fig. 5. 17 Sustainable development goals of UN (Source: 44)

Agricultural activities consume more than 70% of freshwater resources, amounting to 1,500 billion m³ out of the total 2,500 billion m³ used annually for crop production and related enterprises [16]. However, about 40% of this water is lost in developing countries through evaporation or percolation beyond the root zone of plants [17]. In these regions, nearly half (48.8%) of the cultivated area benefits from assured irrigation, while the remainder relies on rainfed conditions, out of a total cultivated area of 140 million hectares. As water availability per capita declines to around 1,000-1,100 m³, countries risk falling into the water-stressed category, making efficient water management crucial to enhance water use efficiency and reduce production costs [18]. To address this, efforts over the past four decades have focused on micro-irrigation methods like drip and sprinkler irrigation across various parts of the world. Despite these advancements, a universally perfect irrigation method suitable for all weather conditions, soil structures, and crop varieties remains elusive. In developing countries, many small and marginal farmers depend on rainfall for their crops due to the high costs of powered irrigation. Therefore, preventing water loss and misuse through the development of efficient irrigation scheduling systems is essential. These systems must deliver the right amount of water at the right time and place, optimizing irrigation efficiency.

Agricultural production is intricately linked to water sources, quality, and quantity, with variations due to soil characteristics (topography, texture, water-holding capacity, and drainage), crop type (short or long duration, water requirements), and regional climate. Consequently, water needs differ across agro-climatic zones, and irrigation frequency varies between fields and crops. Inefficient water distribution can harm crops, increase cultivation costs, and deplete water resources. Given the insufficient natural precipitation in different zones, irrigation from canals, rivers, bore-wells, and storage tanks become essential. Precision irrigation, therefore, emerges as the best option to enhance water productivity and efficiency. The concept of precision water management (PWM) is critical for the judicious use of water, ensuring it is applied in the right quantity, at the right time, place, and crop growth stage. This approach supports the achievement of FAO's sustainable development goals (SDG6) by optimizing water productivity and use efficiency across various agricultural settings [19].

3. PRECISION WATER MANAGEMENT AND TECHNOLOGICAL INNOVATIONS

Precision water management traditionally involves applying precise amounts of water to crops at specific locations and times, uniformly across the field. However, it is best viewed as a management approach where crops grow and yields are maximized only if soil moisture remains high and water is readily available throughout the growing season. Precision water management evaluates crop water requirements and applies the optimal quantity of water at the right time, place, and manner to enhance water use efficiency and crop productivity.

Defined generally, precision water management means applying the precise quantity of water to crops at precise locations and times [20]. Other definitions include "applying water in the right place with the right amount" [21], and "the application of water to a given site in a volume and at a time needed for optimum crop production and profitability" [22]. It also involves irrigation management based on crop needs, defining sub-areas of a field as management zones [23], and accurately applying water to meet specific plant requirements while minimizing environmental impact [4].

Irrigation water is critical in agriculture as crop yields often maximize when soil moisture remains high throughout the growth period, and yields generally increase linearly with water transpired by the crop. Water quality is also crucial under precision water management. The main challenge is to improve water use efficiency and sustainability, achievable by increasing crop water productivity, reducing water losses through soil evaporation, and increasing soil water storage within the plant rooting zone through better soil and water management practices at both farm and area-wide scales. Environmental inputs such as climate, water quality, and soil properties, along with management practices and crop requirements, are key in designing precision irrigation. The optimized outcomes of precision irrigation include improved soil and water availability, optimal salt distribution and storage, reduced deep drainage and runoff, and ultimately, optimized crop production and sustainable water and salt load to the catchment.

3.1 Tools and Technologies used in Precision Water Management

To effectively gather and utilize information, those interested in precision farming should become acquainted with the available technological tools. These include hardware, software, and best practices.

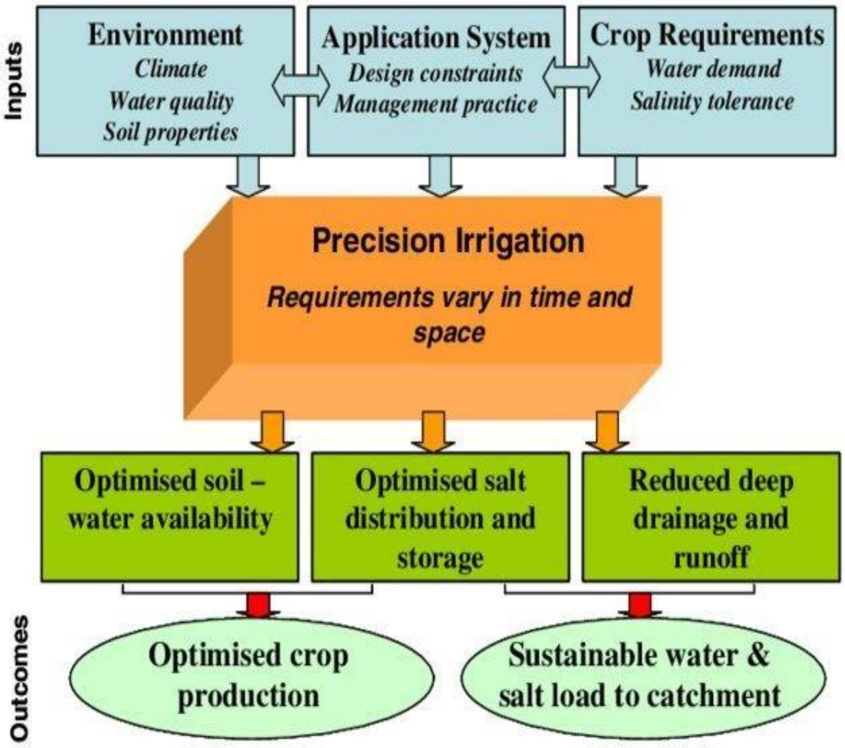


Fig. 6. Input and output of precision irrigation system (Source: 45)

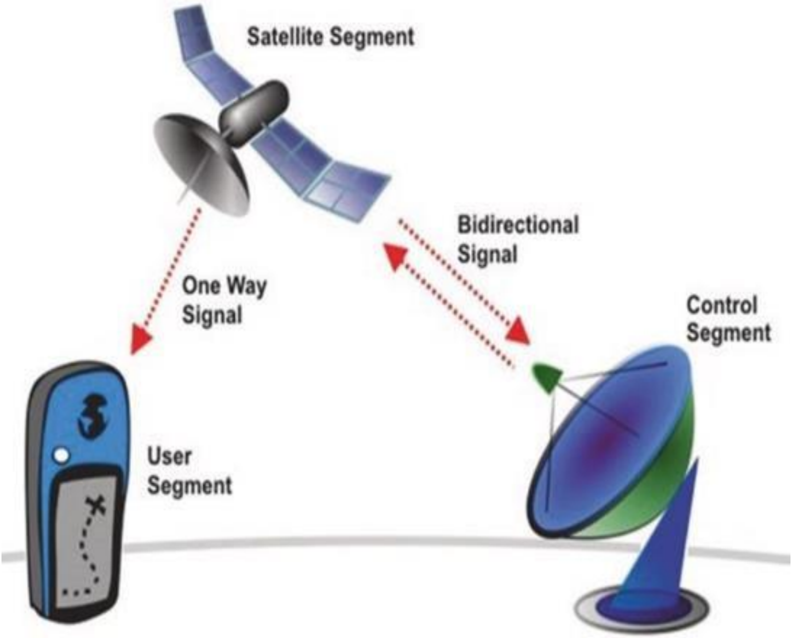


Fig. 7. Working of GPS System (Source:19)

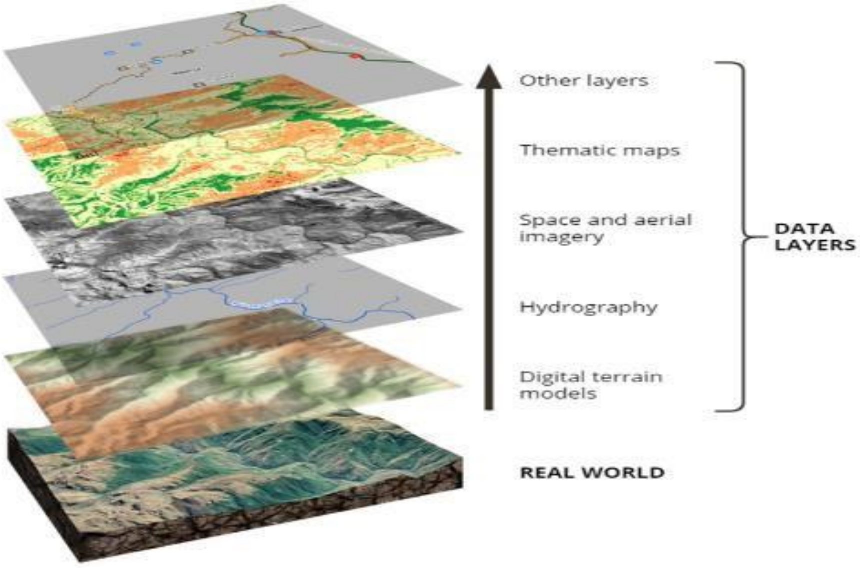


Fig. 8. GIS produced thematic layers (Source: 46)

Global Positioning System (GPS): Satellite-based navigation, known as GPS, was developed by the US Department of Defense in the 1970s for military use in positioning and timing. Today, GPS has wide-ranging applications, including commercial use, agriculture, robotics, and clock synchronization. GPS, using a satellite network records positional information (latitude, longitude, elevation) with an accuracy of 100 to 0.01 meters [24]. In agriculture, GPS helps farmers identify precise field locations (soil type, pests, weeds, water holes, boundaries, obstructions) using an automated system with a DGPS, antenna, and receiver. GPS signals allow receivers to calculate positions, enabling targeted application of seeds, fertilizers, pesticides, herbicides, and irrigation based on field performance and past inputs [25].

Geographic Information System (GIS): This system integrates hardware, software, and procedures to support compiling, storing, retrieving, and analysing feature attributes and location data for map production. GIS consolidates diverse information for easy retrieval. Unlike traditional maps, computerized GIS maps contain multiple layers of data such as yield, soil surveys, rainfall, crops, soil nutrients, and pests. GIS uses statistical and spatial methods to analyse geographic features and data. A agricultural GIS database can detail field topography, soil types, surface and subsurface drainage, soil tests, irrigation, chemical usage, and crop yields. Analysing this data helps understand the interrelationships affecting crops at specific locations [26].

Sensor Technologies: Various technologies like electromagnetism, conductivity, photoelectricity, and ultrasound measure humidity, vegetation, temperature, texture, structure, physical characteristics, nutrient levels, and vapor. Remote sensing data differentiates crop species, locates stress conditions, identifies pests and weeds, and monitors drought, soil, and plant conditions. Sensors collect extensive data without lab analysis. Wireless sensor networks (WSNs) use distributed sensors for automatic, wireless monitoring of weather, water status, and soil conditions. They are cost-effective and efficient compared to ground-based sensors, providing continuous, real-time measurements. WSNs employ sensor nodes across an area, each with wireless communication [27], integrated with cellular and internet technologies for remote measurement, data transmission, and access. This approach ensures long-term soil parameter monitoring without disturbing sensors during field operations like ploughing.

Fig. 9. Soil moisture sensor (Original Picture)

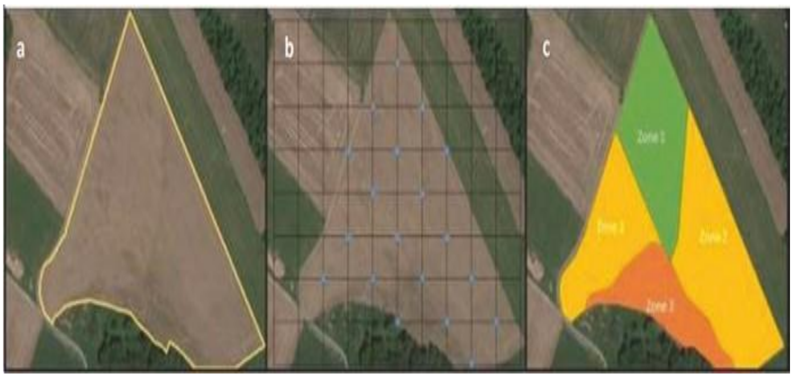


Fig. 10. A digital soil map of crop field (Source: 27)

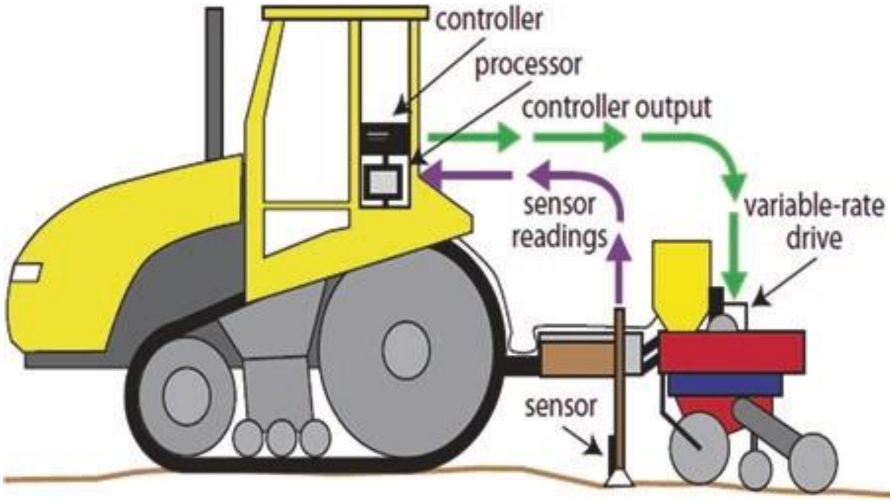


Fig. 11. VRT hardware in tractor (Source: 19)

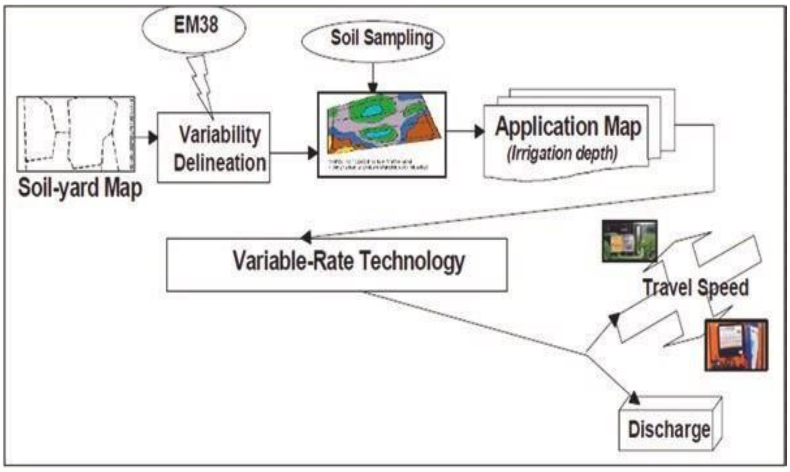


Fig. 12. Steps involved in Precision irrigation application (Source:19)

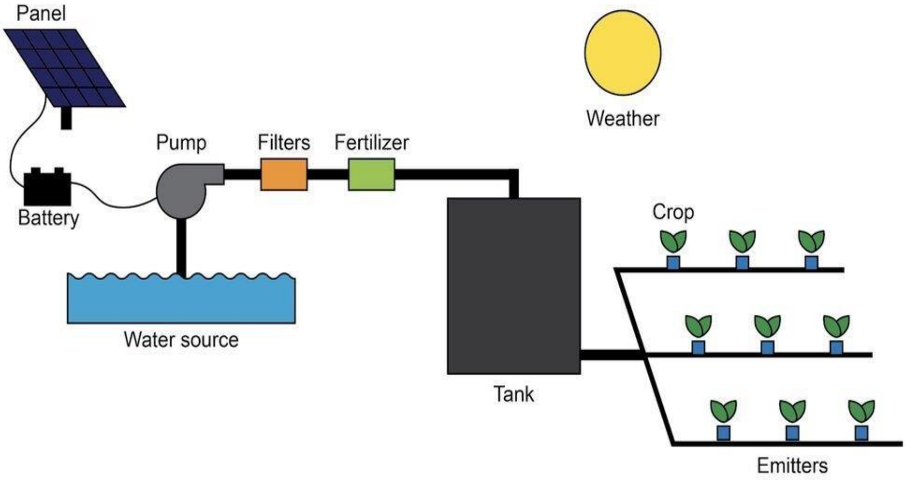


Fig. 13. A systematic diagram of precision drip irrigation system (Source: 47)

Digital Soil mapping: Digital soil mapping involves creating and populating a soil database with geographic references. This is done at a specific resolution using field and lab observations, coupled with environmental data, to establish quantitative relationships. Efforts have been made to create digital soil maps (DSMs) that integrate soil type, weather patterns, and chemical composition in a GIS. These maps aim to illustrate the fertility of agricultural regions or predict their productivity. Notably, the Natural Resources Conservation Service (NRCS) has developed a prominent regional soil map [28].

Software: Precision agriculture often relies on specialized software for tasks like interfacing display controllers, mapping information layers, and analyzing farm data. Key functions include generating yield and soil maps, filtering data, and creating variable rate application maps for inputs like irrigation, fertilizer and chemicals. These software solutions are crucial for efficient farm management in today's data-driven agricultural systems. They vary in complexity and cost, with some offering comprehensive mapping, statistical analysis, and record-keeping features. Challenges remain in data transfer between farmers, cooperatives, and consultants, and in effectively overlaying maps such as soil and yield data [29].

Variable rate technologies: Variable rate technologies (VRT) automate various farming tasks by adjusting input delivery rates based on soil type from soil maps. GIS-derived data directs processes like seeding, irrigation, fertilizer and pesticide application, and herbicide use, ensuring optimal variable-rate applications. VRT is widely adopted in the US, with grid soil sampling enhancing traditional soil sampling by intensifying sampling frequency and enabling precise mapping using location-tagged data [30].

3.2 Steps in Variable Rate Irrigation/ Precision water management

Hillel (1990) defines a well-managed irrigation system as one that efficiently distributes water spatially and temporally to maximize crop growth, yield, and economic returns [31]. Given the site-specific and seasonal nature of irrigation conditions, there is no universal solution for optimal development and management. Figure depicts the framework for precision irrigation strategy. Initial spatial variability data is derived from soil maps available at agricultural planning offices, but these maps alone are insufficient for precision irrigation due to their broad-scale coverage. Next, in-field data is gathered using fast, non-destructive real-time sensors and surrogate properties like electrical conductivity (EC). This data informs soil sampling and correlation with specific properties (e.g., EC vs. available water capacity, AWC). Management zone maps (application maps) are then created to guide field activities, such as irrigation, specifying depths and locations [32]. Integration of variable rate technologies into existing machinery or new introductions is decided, involving evaluations of parameters like travel speed and discharge rate.

4. PRECISION IRRIGATION METHODS FOR DRYLAND AGRICULTURE

Precision irrigation management, aided by data analytics, significantly enhances crop monitoring and water use efficiency. Advanced tools now support growers in optimizing irrigation practices, thereby conserving water, saving time, reducing costs, and improving crop yields compared to traditional methods. Effective irrigation management relies on accurate data, such as weather forecasts, evaporation rates, soil moisture levels, and crop types. This information helps determine additional soil moisture needs, ensuring irrigation is precisely tailored to crop requirements.

Geographic Information Systems (GIS) integrate hardware and software for managing spatially referenced data, linking spatial information with descriptive details. GIS technology supports effective decision-making by synchronizing spatial and temporal data. It is particularly useful in rice farming for managing water resources through both simple and complex operations. GIS provides necessary numerical and graphical data for timely irrigation, enhancing water management efficiency. This approach minimizes costs and avoids over-irrigation, which can damage crops and increase cultivation expenses.

4.1 Precision Drip Irrigation system

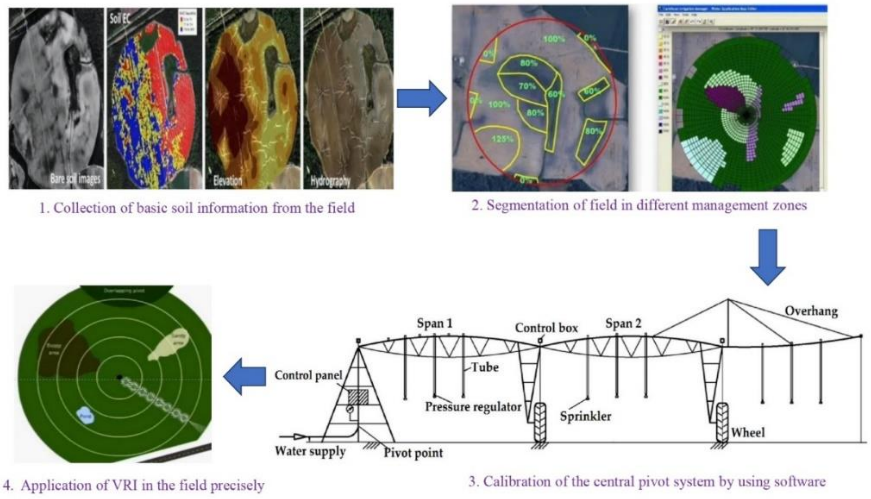
Drip irrigation is a highly efficient precision irrigation method widely used in agriculture. It significantly reduces water losses compared to conventional irrigation methods. Water is delivered through a filter into drip pipes, also known as drip-tape or drip-line, which have tiny emitters that release water directly into the root zone at low pressure maintained by software.

This system can be fully automated, minimizing human effort. Advanced moisture-sensitive sensors enable automation, providing real-time data on temperature, evaporation, humidity, and soil moisture to regulate water supply. The system's automation helps monitor and control the water flow accurately, ensuring the right amount is delivered to the crops. Water flow meters connected to sensors adjust the water quantity based on crop requirements. Additionally, analyzing the capacity of water discharge by the motor or irrigation pump ensures precise water application, enhancing water use efficiency and crop yield.

The ICAR-Indian Institute of Water Management in Bhubaneswar developed a sensor-based automated drip irrigation system for bananas, saving 25% water and increasing yield by 13% compared to manual drip irrigation. The All India Coordinated Research Programme on Irrigation Water Management (AICRP-IWM) in Bhubaneswar introduced precision irrigation techniques like drip fertigation, mini portable sprinkler systems, and alternate furrow irrigation. Studies showed drip irrigation significantly improves water use efficiency (WUE), with increases ranging from 14.3% in Chiplima, Odisha to 270.4% in Sri Ganganagar, Rajasthan. At Rahuri, Maharashtra, drip fertigation enhanced tomato WUE by 77% and nitrogen uptake by 811% [33]. Drip fertigation increased productivity of bitter gourd, ladies' finger, and cowpea by 59.1%, 66.6%, and 141.6%, respectively, in a 2018 ICAR-IIWM study.

4.2 Centre Pivot (sprinkler) and Lateral Move Machines

The central pivot system is a type of sprinkler irrigation method that distributes water through a rotating mechanism, where water is sprayed into the air and falls onto the crop effectively simulating natural rainfall. This process is accomplished by forcing water through small nozzles or orifices under pressure. The central pivot irrigation system, enhanced by GIS, GPS, and NDVI (Normalized Difference Vegetation Index) technology, offers a sophisticated approach to water management. GIS and GPS technologies optimize the system by mapping field layouts, tracking the movement of pivot units, and ensuring precise water application. NDVI, a remote sensing technique, monitors crop health and water stress levels by analysing vegetation indices from satellite or drone imagery. This data helps in adjusting irrigation schedules and quantities based on real-time crop needs, reducing water waste and improving efficiency. By integrating these technologies, the central pivot system achieves uniform water distribution across large areas and diverse crops. It minimizes issues such as water stagnation and soil compaction while maintaining adequate air circulation for rapid seed germination. This approach not only enhances water use efficiency (WUE) but also adapts to varying field conditions and crop requirements. The use of GIS and NDVI further helps in addressing water scarcity challenges and supports sustainable agriculture by optimizing irrigation practices and reducing labour costs [34].



1. Collection of basic soil information from the field

2. Segmentation of field in different management zones

3. Calibration of the central pivot system by using software

4. Application of VRI in the field precisely

Fig. 14. Diagram of field level implementation of central pivot irrigation system controlled by software (Modified form of [20]

The field application of variable rate irrigation (VRI) through a central pivot system involves several key steps to optimize water use and enhance crop yield. Initially, the field's location is determined using GPS technology, followed by remote sensing to capture detailed imagery. This data is processed with Geographic Information System (GIS) software to create thematic maps, highlighting soil conditions, electrical conductivity, elevation, and hydrogeographic features. The field is then segmented into management zones based on soil and crop characteristics, which can also be refined through grid soil sampling. Calibration of the VRI system's hardware follows, utilizing algorithms or programming software to ensure precise water delivery tailored to the varying needs of crops and soil conditions. The calibrated central pivot system then delivers water variably, aligning irrigation with crop requirements and soil conditions to optimize water usage and field management [20].

A two-year field study evaluated the potential of Site-Specific Irrigation Management (SSIM) to enhance potato yield, quality, and economic return compared to Conventional Uniform Irrigation Management (CUIM). Both irrigation methods used near real-time soil water content for scheduling, with similar water application rates. Although tuber yield under SSIM was 4% higher, the difference was not statistically significant. However, SSIM resulted in a 4-6% increase in yield per unit of water applied and an average gross income increase of $159/ha. Despite this, the income gain likely covers only half the cost of commercial SSIM technology. This improvement is attributed to an increase in the average water-holding capacity and enhanced water use efficiency [35].

5. IMPACT OF PRECISION WATER MANAGEMENT ON CROP YIELD AND SUSTAINABILITY

In Tamil Nadu, a state-sponsored NADP project successfully implemented precision irrigation in the semi-arid regions of Dharmapuri and Krishnagiri districts. Over three years, 750 acres were equipped with drip irrigation and fertigation, delivering nutrients precisely at critical crop stages. This resulted in a 60-80% increase in crop yields, with sugarcane yields especially improving by 90%, due to the precise application of water-soluble fertilisers to the root zone and maintenance of of ideal soil moisture regime of 60% and aeration of 40 %. The project also achieved a 30-40% reduction in water and pesticide use, along with higher quality produce. To address small farm sizes and lack of farmer compatibility, a cluster approach was adopted, grouping 20 farmers in 20-hectare clusters for better logistics. Training and monitoring, guided by the Tamil Nadu Agricultural University (TNAU), ensured technology transfer and success, making the project a model for other farms in the state [36].

In Gujarat's Chandrala village, precision irrigation through micro-irrigation significantly boosted vegetable yields by 20-30% and increased mechanization, despite reduced groundwater levels. The village's consolidated land holdings facilitated the adoption of drip irrigation, leading to a shift towards labor-intensive crops like vegetables and cotton. Surprisingly, laborers supported mechanization as it improved working conditions and maintained employment through increased irrigated areas. However, farmers noted that there were no savings on fertilizer costs due to the lack of subsidies on water-soluble fertilizers used in drip irrigation [37]. Similarly, in Chanvelly village, Andhra Pradesh, 70% of farmers adopted micro-irrigation after visits to government model farms, despite sufficient groundwater. Benefits included labor cost savings, expanded irrigated areas, reduced weed growth, and improved yields. The remaining farmers faced challenges due to a lack of awareness about subsidies and high initial costs [37].

Precision irrigation significantly enhances crop yields by tailoring water delivery to each crop's unique requirements [38]. In summer crops such as Maize, Moong (Green Gram), Urad (Black Gram), Sesame (Til), Groundnut, Sorghum (Jowar), Pearl Millet (Bajra) Tomato, Cucumber, Bitter Gourd, Pumpkin, Watermelon, Muskmelon etc, where irrigation supplements up to 75% of the maximum water requirement, LEPA (Low Energy Precision Application) proves more advantageous than sprinkler systems. Subsurface drip irrigation (SDI) is a method of irrigation where water is delivered directly to the root zone of plants through a network of polyethylene tubing and emitters buried beneath the soil surface. This technique allows for precise water application, reducing evaporation and runoff, and improving water use efficiency. Under irrigation treatments in semi-arid regions providing less than 50% of the total water needed, SDI (Subsurface Drip Irrigation) achieves significantly higher yield of 14% than LEPA, while LEPA outperforms sprinklers by 16%. LEPA continues to be an important water conservation tool in semi-arid regions facing declining irrigation availability. At irrigation levels above 50%, sprinkler systems yield slightly more than LEPA, with SDI yields being 7% higher than LEPA. The LEPA irrigation method is the catalyst for innovations in chemigation, no-till planting, and site-specific irrigation. [39]. Sprinkler irrigation, applied at 80% of crop evapotranspiration (ETC) alongside precise fertilizer management, results in significantly higher grain (2.63t/ha) and biological yields (8.37t/ha). This suggests that combining System of Crop Intensification (SCI) protocols with sensor-based precision fertilizer and irrigation control can enhance soybean yields and resource-use efficiency [40]. The System of Crop Intensification (SCI) is an agricultural methodology aimed at enhancing crop productivity, resource conservation, and sustainability across various crops by improving root growth and soil fertility while reducing inputs like water, fertilizers, and agrochemicals. It integrates precision irrigation, which uses technologies like soil moisture sensors and automated systems to optimize water use, and precision fertilizer management, employing sensor-based tools and variable rate technology to ensure efficient nutrient application. This holistic approach results in improved crop yields, water and nutrient use efficiency, and reduced environmental impact, addressing modern agricultural challenges such as climate change and resource constraints. In addition to improving crop yields, precision irrigation revolutionizes soil health management. By applying the optimal amount of water, it prevents soil from becoming too wet, reduces waste, maintains a loose and crumbly soil structure, and inhibits erosion and salt buildup. This approach enhances water absorption and prevents soil compaction, which can suffocate roots and essential bacteria. Loose soil allows for better movement of water, nutrients, and roots, promoting root growth. Early, frequent light watering can keep soil at field capacity for optimal root development, especially in loose areas [41].

5.1 Barriers to Adoption of Precision Water Management

The adoption of precision water management (PWM) technologies, such as drip and sprinkler irrigation systems, faces significant socio-economic challenges in India.

1. **Small Land Holdings:** Precision irrigation systems are more viable for large farms, typical in the USA and Europe. However, in India, 82% of farmers have less than 2 ha of land, making it challenging to adopt such systems. Drip and sprinkler systems require significant investment, unsuitable for small land sizes [42].
2. **Lack of Investment Capacity**: Small and marginal farmers in India invest only 9% of their total assets in agriculture. The high initial cost of precision water management (PWM) systems is unaffordable for most, limiting adoption [43].
3. **Insufficient Infrastructure:** The rural areas lack the necessary infrastructure, such as computers and controllers, required for PWM. This infrastructure gap hinders the implementation of these advanced systems [44].

The adoption of Precision Water Management (PWM) systems faces several challenges. There is a shortage of technically qualified personnel to operate and maintain these complex systems, particularly in rural areas where farmers often lack the necessary skills. Additionally, the limited field demonstrations reduce farmers' awareness and understanding of PWM benefits. Furthermore, the development of micro-irrigation is uneven across Indian states, with Andhra Pradesh and Maharashtra leading in adoption, while many other states fall behind, hindering widespread implementation and effectiveness [44].

Addressing these barriers through targeted policies, infrastructure development, training programs, and extensive field demonstrations is essential to enhance the adoption of precision water management in India.

5.2 Policy Recommendations and Research Needs

To address these challenges, government policies should incentivize the formation of farmers' cooperatives, increase comprehension, application, and adoption of precision water management techniques and technologies, and support deeper research and development. Research and development should focus on developing cost-effective PWM technologies suitable for small and marginal farmers, creating robust and scalable supporting infrastructure in rural areas, and implementing training programs to develop local technical expertise [45]. Additionally, research on adaptive cropping systems that align with the precision irrigation framework is essential [46]. Extensive field demonstrations and pilot projects are needed to showcase the benefits and practical applications of PWM technologies, promoting their widespread adoption [47]. By addressing these areas, PWM can become a viable option for small and marginal farmers, enhancing agricultural sustainability and water use efficiency in India [48,49,50].

6. CONCLUSION

In the context of climate change, utilizing water resources judiciously is crucial to address scarcity and quality issues. Precision water management (PWM) enhances water and nutrient use efficiency, ensuring food security. In India, 68% of the total net sown area (136.8 mha) is dry land, spread over 177 districts, with dry land crops accounting for 48% of food crop area and 68% of non-food crop area. Despite advances in some nations, precision irrigation is still primitive in India, facing challenges such as small landholding sizes, high investment needs, and field heterogeneity. Adoption can increase through cooperative farming models, national research projects, public-private partnerships, and mobile app-based digital solutions. This transition requires significant human and capital infrastructure, supported by government policies. To meet global food demands and achieve sustainable development goals (SDG 6), enhancing water use efficiency is vital. Precision water use in agriculture boosts production, water productivity, and crop quality. PWM aims to maximize yield with optimal water use, economizing water, saving time, reducing costs, and improving yields compared to conventional systems. Reliable information on weather, evaporation, soil moisture, and crop types is essential for determining soil moisture needs. GIS technology integrates spatial and temporal data for informed irrigation decisions. Accurate irrigation, applied only when necessary, can save up to 25% of water compared to conventional practices, highlighting the importance of adopting precision irrigation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

As the author of this manuscript, I confirm that no AI or large language models were utilized in its creation.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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