



PRECISION AND ECO-EFFICIENT IRRIGATION MANAGEMENT FOR SUSTAINABLE AGRICULTURE



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INTRODUCTION

Water is the essence of life, and its scarcity can have far-reaching consequences for the environment, economy and human well-being. As a limited resource, it is imperative to harness water resources judiciously to meet the growing demands of our developing economy. Therefore, the conservation and management of water resources are crucial for sustainable development. Globally, irrigation accounts for the largest consumptive use of freshwater, with agriculture being the primary consumer. In a country like India, which shares 18% of the global population with only 2.4% of land and 4% of the freshwater resources, 80% is used in agriculture. The annual precipitation is nearly 4000 BCM, and the average flow of rivers is estimated to be 1869 BCM. The total annual replenishable groundwater potential in the country is estimated to be 433 BCM, of which rainfall contributes 74% to groundwater recharge, and the remainder is contributed by canals, ponds, and other water conservation practices. With an annual groundwater draft of 253 BCM, irrigation alone consumes nearly 91% of the total draft, irrigating 62% of the total irrigated area of the country. However, water scarcity is a growing problem worldwide, leading to stricter rules regarding water use in agriculture. In India, the average irrigation efficiency is only 38%, which is much lower than desired. This shows that we need better ways to use water in farming and reduce waste. To address this challenge, it is essential to adopt precision irrigation practices that optimize water use without compromising crop quality and yield. By leveraging cutting-edge technologies and innovative techniques, precision irrigation can help reduce water waste, promote sustainable agriculture, and ensure food security for future generations.

NEED FOR PRECISION IRRIGATION

Precipitation in India varies greatly in space and time, ranging from 11,000 mm to 90 mm yearly. The annual per capita water availability has decreased from 5000 cubic meters in 1950 to 1545 cubic meters in 2011, predicted to decline to 1341 and 1140 cubic meters in 2025 and 2050. Over 90% of groundwater is used for irrigation in agriculture, which employs 54.6% of the population. Groundwater has become the primary irrigation source due to its timely availability

and autonomous access. Between 2002 and 2016, the water table in 64% of the country depleted due to this reliance. This trend highlights the need to adopt precision irrigation techniques to optimize water usage. Using technologies like drip irrigation and sprinkler systems, farmers can reduce water waste and ensure crops receive required water. Currently, micro-irrigation covers only 19% of net irrigated areas and 13% of gross irrigated area; implementing precision irrigation is crucial for sustainable agriculture and food security. Precision irrigation is defined as applying precise water volumes to crops at specific times and places while maintaining field uniformity. This approach involves optimal management of temporal and spatial irrigation components. Given water scarcity, precision irrigation offers a targeted solution through precise water application ensuring field uniformity.

PRECISION IRRIGATION SYSTEM

Precision irrigation, as defined by the precision farming cycle, is a strategic approach involving four key

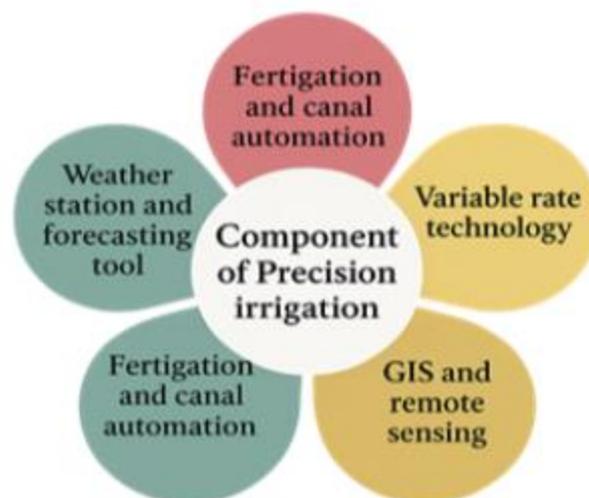


Figure 1: Components of Precision irrigation

steps: data collection, interpretation, control, and evaluation. It begins with gathering spatial and temporal data on soil and crop variability, followed by analysis to guide informed irrigation decisions. Advanced tools like sensors, machine learning, and automation enable precise water application, while regular evaluation ensures system efficiency and improved productivity.

Core components include sensors, fertigation, canal automation, GIS/GPS, drones, VRT, weather tools, and farm management software (Figure 1).

DIFFERENT METHODS AND TECHNOLOGIES OF PRECISION IRRIGATION

Precision irrigation encompasses technologies that maximize water efficiency, boost crop yields, and minimize ecological footprint, resulting in wholesome agronomic management. Precision irrigation water management uses micro-irrigation to optimize water and nutrient utilization. Recent technology breakthroughs have enabled automation in agriculture and water management, enhancing irrigation efficiency. This system includes furrow-based irrigation and micro-irrigation with high water and nutrient efficiency.

Table 1: Water use efficiency of different irrigation methods

Irrigation method	Water use efficiency
Surface irrigation	50%
Sprinkler method	60-85%
Surface drip irrigation	80-90%
Subsurface drip irrigation	95%

Micro Irrigation

Micro-irrigation (MI) involves slow water release through drips, streams, or sprays above or below soil surface. This method conserves water efficiently, outperforming traditional surface irrigation methods that achieve 35-40% efficiency. Computerized GPS systems with wireless sensors enable precise water application based on soil and plant needs, achieving 50-90% water-use efficiency. Sprinkler and drip irrigation systems promote sustainable irrigation management. Sprinkler systems distribute water like rainfall, reducing evaporation and soil erosion. Drip irrigation delivers water directly to plant roots through tubes and emitters, ensuring precise delivery and minimizing waste. Both systems offer benefits in water conservation, energy efficiency, and improved crop yields. Sprinkler irrigation increases irrigable area 1.5-2 times compared to surface irrigation, saving 25-40% water. Drip irrigation achieves 90-95% water-use efficiency, saving 40-70% water compared to conventional methods. These systems help farmers optimize water use and promote sustainable practices.

Advanced technologies

Technological advancements have led to automated sensor-based irrigation systems, a breakthrough in precision irrigation water management. This system integrates components like

soil, crop, and weather data, crop models, and controllers to enable a robust decision support system for water application to crops. AI optimizes water use by considering factors such as crop type, climate, and area. Different crops have varying water needs; for example, rice and sugarcane need more water, while oilseeds and pulses need less. Precision irrigation systems use advanced algorithms and automation to achieve precise control over water flow and distribution for each crop, especially in the rhizosphere zone. Major technologies in precision irrigation include –

- **Canal automation** - Canal automation uses controllers like Arduino, PLCs, and Raspberry Pi, with sensors for soil moisture, ultrasonic, and rain detection to enable automatic irrigation through canal outlets. Traditional upstream canal management with fixed schedules is inefficient, but automation optimizes water usage. Arduino-based canal automation uses sensors to collect environmental data, which the controller processes to command actuators controlling canal gates or pumps, creating an efficient feedback loop for water flow management. Automation can improve WUE from 50% to over 65%, while automated groundwater irrigation can increase WUE from 70% to 85%. However, implementing automation in canal systems remains prohibitively expensive.
- **GIS and RS-based precision irrigation** - Precision farming using remote sensing and GIS provides tools for analyzing data for better agricultural methods and crop yields. Remote sensors on satellites, aircraft, UAVs, or ground devices collect data, and plant images are used to calculate water needs and timing. GIS and RS enable effective management of water and land resources for irrigation. GIS evaluates land suitability for irrigated agriculture by analyzing data on soils, land use, climate, water resources, slopes, and crops, mapping irrigated areas precisely. Data from satellites like MODIS, LandSat, and AVHRR detect irrigated areas, and spectral patterns classify irrigated versus non-irrigated areas and assess spatiotemporal variations.
- **Artificial intelligence and machine learning models** - AI has emerged as a groundbreaking technology in irrigation management, optimizing water usage and enhancing crop productivity. AI encompasses machine learning, deep learning, fuzzy logic, and expert systems in irrigation. Machine learning models, including decision trees, random forests, and support vector machines, predict soil moisture levels and determine irrigation schedules by analyzing weather conditions, soil types, and crop characteristics. ML algorithms analyze evaporation data to predict irrigation needs and detect soil moisture changes,

enabling informed decisions. Popular ML algorithms include Linear Regression, Random Forest, Boosting Classifiers, Support Vector Machines, and LSTM.

- **Mobile app-based operations:** Digital farming solutions are accelerating precision irrigation adoption in India. Mobile-based automation and sensor-based precision irrigation are gaining traction as Indian farmers use Android phones. Key applications include BLULEAF, a Decision Support System providing weather data, irrigation management tools, and plant disease alerts; Water Bee, which measures soil water content and environmental parameters; and EVAPO, which estimates potential evapotranspiration using NASA POWER data. In India, Nano Ganesh, developed by Ossian Agro Automation in Pune, enables farmers to remotely control irrigation pumps.

CHALLENGES

Precision irrigation systems demand significant investment. Technologies such as drip and sprinkler systems, along with automation and sensor-based irrigation, involve substantial costs for infrastructure, computing equipment, and control systems. These expenses often make such systems unviable for small-scale farmers with limited holdings. According to the National Statistical Office's (NSO) 77th round survey, small and marginal farmers who constitute over 86% of all farmers face significant challenges in agricultural investment. Despite operating approximately 68% of the country's agricultural land, these farmers allocate a low share of capital toward agricultural activities. The drip irrigation systems layout vary between rabi and kharif crops, posing a challenge for consistent use across diverse cropping systems. Several obstacles hinder its adoption in India, including cultivable land conditions, agro-ecological limitations, high expense of site-specific data, limited access to technology, institutional credit gaps, and lack of awareness and technical expertise among farmers.

CONCLUSION

Precision irrigation management is crucial for sustainable agriculture, utilizing technologies to optimize water usage in crop production. With global water scarcity, precision irrigation offers a targeted approach to conserve water, minimize over-irrigation risks, and promote environmentally friendly practices. In India, where agriculture consumes 80% of freshwater resources, irrigation efficiency is only 38%, highlighting the need for better management. Precision irrigation involves data collection, interpretation, control, and evaluation to deliver water where and when crops need it. Various technologies, including furrow irrigation, micro-irrigation (sprinkler and drip systems), automated sensor-based systems, canal automation, GIS and remote sensing, artificial intelligence and machine learning models, and mobile app-based operations, achieve precision in irrigation. By adopting these solutions, farmers can optimize water use, reduce costs, increase crop yields and contribute to a food-secure future.

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