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Water Use Efficiency in Irrigation Systems

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Abstract

Water use efficiency (WUE) in irrigation systems has emerged as a central concern in global agricultural sustainability. With irrigation accounting for nearly 70% of freshwater withdrawals worldwide, inefficiencies resulting from evaporation, runoff, and deep percolation threaten food security and environmental balance. WUE, defined as the ratio of crop yield to water consumed through evapotranspiration, highlights the urgency of maximizing agricultural output with minimal water input. Different irrigation methods—surface, drip, sprinkler, and subsurface—offer varying levels of efficiency, with drip irrigation demonstrating the highest potential, often exceeding 90%. Measurement of WUE through both quantitative metrics, such as yield per unit of water applied, and qualitative assessments, such as soil texture and climatic conditions, provides a holistic understanding of irrigation performance. Technological advancements, including automated irrigation, soil moisture sensors, and weather-based controllers, further enable precise water management, while best practices such as crop selection, optimized scheduling, and system maintenance strengthen long-term sustainability. Case studies confirm that improved irrigation management not only conserves water but also enhances yields and resilience to climate variability. Despite economic, environmental, and policy barriers, integrating sustainable irrigation practices with innovative technologies remains essential for achieving global food security and preserving water resources for future generations.

Keywords: Water Use Efficiency, Irrigation Systems, Sustainable Agriculture, Drip Irrigation, Soil Moisture Sensors, Climate Resilience, Water Management

Introduction

Water's role as a fundamental driver in biological systems underscores its increasing value as a limited resource worldwide, intensifying demands on water supply and the imperative to optimize water use efficiency (H. Pair, 1963). Expanding arid zones make water scarcity and drought persistent challenges. Yet even in water-rich regions, irrigation-purpose water must be used efficiently to avoid economically damaging shortages. Ensuring water's multiple uses to society depends not only on sustainable supply but also on sustainable, efficient use. Efficiency involves achieving greater output with less input—a priority for all water users. Agricultural production, however, relies heavily on water, and in many regions, irrigation accounts for up to 90% of freshwater consumption. Worldwide agriculture uses about two-thirds of all fresh water, and about 50% is lost before reaching the field; preventing misuse is essential (E. Jensen et al., 1967). When applied water is insufficient for full evapotranspiration, growth and yields drop, but water losses through deep percolation or runoff reduce irrigation efficiency and waste a finite resource.

Through careful management and technological integration, irrigation can enhance productivity and resource conservation; a key factor in effective water use. New concepts and technologies support improved irrigation efficiency, resource management, and sustainable development.

Understanding Water Use Efficiency

Water use efficiency (WUE) — the ratio of crop yield to water depleted by evapotranspiration — is critical to sustainable agriculture (E. Jensen et al., 1967). As freshwater scarcity intensifies, increasing the efficiency of irrigation water use enhances food security while limiting environmental degradation. Efficient water use also bolsters economic resilience by reducing dependence on costly external water supplies and buffering against drought (H. Pair, 1963). Little rain falls during the growing season in many crop production regions, so irrigated agriculture applies about 70% of available freshwater globally. Total water use combines extraction and consumption, usually excluding run-off. Losses originate at every stage, with delivery infrastructure and in-field irrigation the largest contributors, reducing irrigation efficiency to typically 25–40% of the water supplied by reservoirs. Key factors influencing water use include irrigation system design and performance; agricultural water management and operation; the crop system and its environment; and the whole-farm system.

Water use efficiency (WUE) has recently received considerable attention because of the increasing demand for food production and limited available fresh water resources. Water use efficiency can be defined as the ratio of the amount of water applied to the crop to the amount of water effectively used by the crop. The biological use efficiency (BUE) of water is defined as the amount of fresh water used productively by the crop relative to the total water depletion for the crop (E. Jensen et al., 1967). Detailed information on water requirements of crops coupled with information on deterioration of water quality during its transport to the crop can lead to quantification of net benefits of various measures involving water use (Jensen, 1978). The availability of water and energy strongly influences the development of irrigated agriculture. Since irrigation has played a role as a principal driver of economic development, it is important to use water efficiently and to produce greater crop yield when water supplies become scarce or costly.

Water use efficiency was defined as the ratio of water beneficially used in crop production to the amount of water applied (H. Pair, 1963). Quantitative water-use efficiency (WUE) consists of the amount of irrigated water used by the crops and the crop yield obtained. For example, in-field water-use efficiency was defined as the amount of water stored in the root zone for use by plants. Water-use efficiency decreases with the evaporation rate, and WUE increases with a rise in water application (E. Jensen et al., 1967). The amount of water evaporated, transpired and infiltrated varies in time depending on the EVTD; therefore, the total water lost and the WUE depends on the EVTD. WUE is controlled by several important factors such as crop characteristics, climate, soil type, water quality, and irrigation management.

Crop characteristics govern water-use efficiency, such as crop water requirements, timing of water requirements in the growing season, average depth of the root zone, and rate of root development. Semi-permanent crops such as fruit trees have deeper root systems and thus a higher water-holding capacity, which increases water-use efficiency. Climate also affects water-use efficiency: increased temperature and wind speed lowers water-use efficiency, whereas an increase in relative humidity improves water-use efficiency. Evaporation losses from small water surfaces can be significantly increased by wind because the local atmosphere becomes unsaturated. Soil type is an important factor affecting WUE. Soil with poor infiltration, i.e. clayey, will require higher irrigation intensities to obtain the same efficiency as sandy or silty soils that have much higher infiltration rates, due to runoff potential. Water quality data should be collected regularly to monitor any changes in water-use efficiency. Management factors and practices that influence WUE can be subdivided into management of water, crops or soil; irrigation system design and system operation. These factors are outside the scope of this research, but they are discussed briefly in later sections.

Types of Irrigation Systems

The use of large quantities of irrigation water places an increasingly greater importance on achieving high efficiency in utilization. Efficiency refers to the conservation of some limited resource, such as time, fuel, water, or labor, in an economical manner. The efficiency of water use in agricultural irrigation may be considered as the ratio of that quantity of water beneficially used to the quantity applied. Four general classes of irrigation-water application methods have developed in establishing an irrigated agriculture in the western United States and other similar areas. These include surface or flood, sprinkle, subsurface, and localized or drip application. One or more of these methods has generally been adapted to local conditions in an area of irrigated farming. Many studies of the efficiencies of various irrigation systems have been conducted in different countries and in various regions of the United States. Practical methods of measuring water-use efficiency have been investigated and several are undergoing field-testing (H. Pair, 1963).

(i) Surface Irrigation: Surface irrigation entails the application of irrigation water to the soil surface, followed by infiltration and lateral movement within the soil. The supplied water advances over the field, contacts the crop, and either infiltrates the root zone or drains from the area. Three basic forms of surface irrigation exist: flood, furrow, and border. Flood irrigation involves directing water along the entire field length, allowing it to stand and penetrate the soil. Furrow irrigation consists of channeling water both along and between crop rows via furrows. Border irrigation resembles flooding but uses strips divided by low berms instead of inundating the total field area.

(ii) Drip Irrigation: In percolation terms, surface irrigation can cause soil water levels to rise above the water table, while in drip-irrigation scenarios, the root zone extends deeper than the supplying emitters, preventing a direct connection between soil water and the deep water table. (H. Pair, 1963) reports that surface irrigation, practiced on 29% of USA irrigated land, is popular due to its low capital cost; however, the central difficulty of surface irrigation is the dependency on water conveyance and distribution systems with limited pressure control facilities. High peak water delivery rates are required to achieve reasonable application times, and the head required for even water application in furrow- or basin-irrigated fields approaches several meters or more of water. At rising head, evaporation losses can be expected to increase, but the major losses occur through infiltration, and more so in heavy, expansive soils, which have lower infiltration rates and smaller intake windows. Uneven infiltrations and runoff are also significant for surface irrigation. Generally, 33–66% of the water diverted for surface irrigation actually reaches the plant, whereas 90% is usual for a pipe-delivered system.

(iii) Sprinkler Irrigation: Sprinkler irrigation applies water to the soil surface by means of high pressure, centrifugally driven nozzles, so that a wetting pattern is established on the soil surface. It is most suitable for irrigating a wide range of crops and soil types, is used primarily on medium- and light-textured soils, and occupies approximately 56 million ha globally. Application efficiencies range from 68 to 90 %, largely as a function of the wetted area. Losses under sprinkler irrigation are caused by interception of the spray by targets, evaporation from the air stream during delivery, intercepted precipitation by wind, and deep percolation (E. Jensen et al., 1967).

(iv) Subsurface Irrigation: Subsurface irrigation involves the application of water below the soil surface, directly targeting the root zone (H. Pair, 1963). The water supply for such systems is provided solely to the surface of the porous pipe. Water reaches the plants through lateral movement; therefore, the wetted area depends on soil type. Intense and more frequent irrigations are required to maintain high soil moisture throughout the root zone, often resulting in a small wetted soil volume and limited effective root zone. However, subsurface irrigation offers several advantages, including absence of soil erosion, reduced soil surface evaporation, elimination of surface runoff, and less obstruction to field operations. Consequently, this method offers considerable potential to enhance water use efficiency.

Technologies Enhancing Water Use Efficiency

Technology in agricultural water management development follows no particular blueprint and draws from related fields such as industrial engineering, environmental instrumentation and microelectronics. Examples includes automated irrigation, electronic remote sensing, soil–water–plant sensing, flow measurement, weather monitoring and datalogging. Much contemporary research addresses the integration of a range of technologies into a comprehensive irrigation management system. Precision irrigation targets water to optimize growth and minimize supply. Technologies applied to irrigation control include hydraulic, pneumatic, electrical and mechanical devices. Microprocessors provide a flexible technology dovetailing with microsensors, enabling scheduling decisions to take account of many parameters simultaneously (J. Greenwood et al., 1970).

(iii) Automated Irrigation Systems

Irrigation can be automated using computer-controlled systems that activate irrigation pumps according to schedules programmed by the user. Micro-irrigation—such as micro-sprinkle, drip, and trickle irrigation—provides targeted watering that supports higher water use efficiency (WUE) relative to other irrigation methods (Pardossi et al., 2009). Water use represents a critical resource for agricultural production. Nearly 40% of the world's food is produced by irrigated agriculture, which accounts for approximately 70% of global freshwater withdrawals. In Italy, irrigation accounts for about 50% of total water use and covers 27% of farmland. Consequently, improving irrigation efficiency is a key strategy for increasing crop yield and conserving water. Efficiency depends largely on the type of irrigation, but also on the scheduling of water application, which influences overall consumption and crop yield. Both excessive and insufficient irrigation can reduce crop quality, increase the need for fertigation and other inputs, and cause environmental problems. Appropriate water management thus helps minimize waste, increases pollutant containment, and improves crop performance. Although plant-based methods for irrigation scheduling are still being researched, root-zone sensors offer promising capabilities to maintain soil water content within narrow limits.

Water application efficiency quantifies the percentage of water delivered to a field that is effectively stored in the soil within the crop root zone (H. Pair, 1963). Water is typically applied by flooding, furrows, sprinkler systems, or subirrigation methods. Surveys of irrigation districts, government projects, and farm fields in the United States reveal considerable variation in water application efficiency. For example, project-level efficiencies from state engineer records generally exceed those reported for individual farm fields. Proper utilization of irrigation water maximizes returns from fertilizer and other inputs, reduces labor and water pumping costs, and minimizes problems associated with waterlogging, surface crusting, and drainage.

(ii) Soil Moisture Sensors: Soil moisture sensors have long been used for irrigation management in intensive agriculture. They combine the advantages of automated and demand irrigation, avoiding supply of extra water to a drying crop and maintaining root zone water content within a favourable range of values to optimize crop quality and yield. The sensors do not provide a direct measurement of the substrate water content but a signal related to an accurate calibration curve; the latter, quite elaborated for open-field soils, is often unavailable or inadequate. Such calibration constitutes a permanent weakness in the reliability and practical use of the sensors. Horticultural plants grown in containers under high and variable evaporative conditions often need precise watering. A system based on dielectric substrate moisture sensors, interfaced with a datalogger and solenoid valves, has been tested to maintain the soil water content at a constant level. Measurements in the upper 5 cm of the substrate were taken every 20 min and the water content was held within 2–3% of the selected reference value. Different irrigation intervals (2–6 h) were used and the results compared with scheduled irrigations of 2 and 4 h duration applied daily and every 4 days. To keep the number of wet/dry cycles within adequate limits, pressure-compensating nozzles with uniform discharge at low rate (60 L h"1) should be installed on the emitter lines. Uniform and low discharge rate, in turn, ensure synchronization of both substrate moistening and RZS response. Too fast irrigation may lead to over-watering before RZS senses "stop" conditions. Finally, irrigation effectiveness can be improved by recovering the drainage water in a closed system, whereas in open systems leaching should be maintained well below 10–15%. Scheduled irrigation based on soil moisture sensors may result in significant water saving. Embedded sensors that detect the presence of free water cut off irrigation if puddling occurs, thus preventing excessive drainage losses in lawns and urban landscapes. Availability of soil sensors capable of monitoring salinity has also enabled automatic control of fertigation and the option of dual-water irrigation. Laboratory tests with a prototype fertigation device, which adjusts nutrient content and source water according to EC measurements of the growing medium, show that during the growing season, use of saline water, fresh water or both in variable ratios coupled with WET-based scheduling can reduce overall seasonal water use by 35% compared with timer-based irrigation, mainly because of the application of saline water. Finally, reliable irrigation management calls for the integration of ET information and soil moisture monitoring to improve overall system performance and to ensure continuity of irrigation in case of sensor failure (J. Greenwood et al., 1970) (Pardossi et al., 2009).

(iii) Weather-Based Irrigation Controllers: A weather-based irrigation controller (or "smart controller") is an automated irrigation system that adjusts the amount of irrigation water it applies based on an estimate of crop water need. The controller is connected to a source of weather information and uses weather data in an algorithm to estimate crop water need or reference ET, then determines the appropriate irrigation schedule. The original idea for an automated system that schedules irrigation based on weather in real time came from (E. Jensen et al., 1970). The initial methods relied on daily input of maximum and minimum daily temperature, as well as other crop-specific data, and used these inputs in a modified Penman method to calculate potential evapotranspiration (ETp). This method demonstrated that irrigation scheduling techniques for crops could be developed that were dependent on weather and the stage of crop development. Building upon these principles, smart controllers began entering the landscape market in 2002 and have since continued to rapidly increase the variety of available models and functions (Fipps & Swanson, 2012).

A single-group, battery-powered controller with 28 storage stations was studied from August 2010 to November 2011. Persistence of the product was an issue throughout the period as the integrated capacitor on the controller board leaked, preventing the valves from turning on at all. The controller's manufacturer was contacted after the third data collection event and advised of the problem.

Best Practices for Improving Water Use Efficiency

Best management practices (BMPs) strengthen water-use-efficiency (WUE) potential. Crop selection, cropping schedules, and irrigation frequency and amount directly affect consumptive use. When water is a limiting factor, planting low crop-water-demand varieties that tolerate heat and salt reduce irrigation demand. Planting early in the growing season further optimizes evapotranspiration. Spray schedules should coincide with crop needs and weather patterns (H. Pair, 1963). Excessive irrigation leads to lower WUE from increased evaporation, runoff, and deep-percolation losses; insufficient irrigation reduces crop-availability. Effective irrigation scheduling integrates soil-water measurements, meteorological, agronomic, and physiographic information, and water balances to apply precise delivery. Soil moisture sensors, in particular, provide accurate data to optimize water application (J. Greenwood et al., 1970). Incorporating BMPs within an integrated management system can substantially increase effective water use and offset rising energy, labor, and capital costs of irrigation.

Crop selection is a primary factor influencing water use efficiency in irrigated agriculture. Irrigation efficiency is the ratio of total water lost by evapotranspiration to the total water diverted for irrigation, and it is controlled by several factors. Selecting the appropriate crop is essential to enhance this efficiency and optimize water use. Drip irrigation systems have proven advantageous in promoting the growth of crops that require careful watering and little moisture at their roots. Compared with sprinkler and surface irrigation methods, drip irrigation enables higher water application efficiencies and allows for the development of crops that might otherwise be difficult to cultivate under conditions of insufficient rainfall (H. Pair, 1963). Since approximately 40% of the world's food is produced by irrigated agriculture, the ratio between applied water and crop yield is critical for meeting the increasing global demand for food. Cultivating more water-efficient crops in combination with the implementation of efficient irrigation technology is a key strategy for improving this ratio.

Irrigation scheduling is the most important factor affecting irrigation efficiencies and crop yields. Proper scheduling in time and amount prevents overirrigation, which can cause waterlogged soils and reduce yields, leading to higher costs for water, fertilizer, and drainage. Water use is minimized when applied water matches crop consumptive use and leaching requirements. Improving current irrigation scheduling practices is essential for higher efficiency. Using climate-crop-soil data, computers for complex calculations, and field observations by experienced personnel provides management skills and net returns at a reasonable cost (E. Jensen et al., 1970).

Future Directions in Irrigation Research

Current irrigation practices use about 70% of worldwide water withdrawal, with crop water storage typically under 40%. Inefficient use leads to excess surface runoff, deep drainage, leaching, and pollution. Developing advanced irrigation technologies and cultural practices to improve the water-use efficiency (WUE) of irrigated crops is a priority. Subsurface irrigation offers long-term potential. Advances in simulation models, sensor techniques, and wireless telemetry now permit detailed quantitative analysis of the soil-water-plant system, identifying opportunities for practical application. Where water is abundant, cost and availability still govern irrigation practice; excessive water is commonly used to ensure yield. Farmers often rely on experience rather than measurements. Scientific methods, such as the Penman formula for evapotranspiration, continue to inform practice.

Many materials are available for irrigation water conveyance, but water loss between source and application point reduces the volume delivered to the crop. Efficient conveyance is a prerequisite for improving farm-level water application. Water application efficiency measures the fraction of water delivered to a field that is stored within the crop root zone. Flooding, furrow, sprinkler, and subirrigation are widely used methods in the United States; reported efficiencies vary widely. Efficient water use induces maximum crop yield, reduced labor and water costs, and minimizes waterlogging and drainage problems. Conveyance, farm application, and field application efficiencies all require attention to optimize water use. Other practices that preserve water quality and promote sustainability are at least as important as efficiency, and can actually increase overall use if more irrigation is necessary to maintain peak yields (J. Greenwood et al., 1970).

Irrigation accounts for almost 50% of total water use in Italy and a similar figure throughout the Mediterranean; increasing the storage capacity of soil for rain and irrigation water is therefore a major priority for agricultural and natural ecosystems (Pardossi et al., 2009). Efficient irrigation supplies the correct amount of water to the crop at the right time when plant-available soil water is below a specified threshold. Gaining crop water in the root zone relies heavily on the soil type, cultivation practices, and irrigation method. Irrigation efficiency is closely related to irrigation method and scheduling, impacting overall water use, crop yield, and environmental effects. Under-irrigation leads to yield reductions, while over-irrigation wastes water and increases nutrient leaching. Determining when to irrigate and assessing the volume applied are critical issues in irrigation management. Various monitoring techniques developed in the last two decades, including plant-based measurements, are the subject of ongoing research but are yet to find widespread commercial application.

(i) Innovative Irrigation Technologies: Modern irrigation systems are designed to maximize crop water-use efficiency by enabling more precise timing and placement of water. Liquid pipelines typically distribute water from a pumped source without appreciable storage. Pipelines branch into field laterals that support one of two primary delivery methods. The first method involves subsurface or surface micro-irrigation, which uses regularly spaced emitters along a lateral—either underground or at the surface each delivering low flow rates of water far below the soil-saturation rate. The second method employs multiple sprinklers or spray nozzles at the surface, spraying water over larger areas in an overlapping pattern. Microirrigation is appropriate for permanent crops, orchards, and vineyards, while sprinkler irrigation serves low- or medium-height vegetable crops, grain crops, trees, lawns, and golf courses (H. Pair, 1963).

(ii) Sustainable Practices: Sustainable resource management requires attention in how water is used in agriculture. Sustainable irrigation practices incorporate specific techniques and tools that enable the user to improve water use efficiency in ways that still allow for high-quality production. Water application equipment plays a fundamental role in using irrigation water efficiently. The choice of equipment depends on site and crop characteristics, production goals, investment, and operational costs (H. Pair, 1963). Water use efficiency (WUE) varies considerably among irrigation methods. The four main types of irrigation—surface, drip, sprinkler, and subsurface—can be distributed to the crop to different WUE levels depending on the system and the management approach. Among surface irrigation methods, the best water distribution uniformity and application efficiency is achievable with gated pipes. Drip irrigation is without a doubt the most water-conserving method and at the same time offers the highest yield and WUE (Pardossi et al., 2009). Proper management of drip irrigation involves the redesign or calibration of existing systems to reach the expected high water-saving potential. Experience shows that distributing the water near the plant, employing tools to reduce soil evaporation losses, and adopting devices that allow precise application leads to remarkable irrigation efficiency improvements. Moving towards sustainable irrigation calls for the introduction of efficient water- and energy-saving equipment, selection of optimal cultivars, and adoption of watering strategies to counteract climatic fluctuations in irrigation demands. Under climate change scenarios, irrigation will become essential in high-quality crop production and, at the same time, surface water will, in many areas, be insufficient to meet crop needs.

Root zone monitoring allows for control of water and fertilizer dynamics to improve sustainability in intensive agriculture. In the Mediterranean region, irrigation accounts for about half of total water use and farming operations are influenced by irrigation needs, pumping, and load scheduling. The ratio between applied water and crop yield is considered a key factor in agricultural water-use efficiency. Water scarcity, environmental protection regulations, pumping costs, and irrigation scheduling determination encourage the adoption of more efficient irrigation techniques and water-saving technologies. For precise regulation of water supply through automated irrigation, a means to continuously monitor water at the crop root system is mandatory. Many agrometeorological methods have been developed to evaluate crop water requirements and regulate irrigation on a larger scale; however, in intensive horticulture, it is preferable to monitor the soil portion directly surrounding the roots, which varies depending on the root system arrangement. Throughout the crop growth cycle irrigation optimization efforts have been proposed in terms of water volume and fertilization strategy.

Conclusion

The evaluation of water use efficiency (WUE) within irrigation systems underscores the importance of optimizing water resource management to achieve sustainable agriculture. The relative merits of various systems—namely surface, drip, sprinkler, and subsurface irrigation—are contextualized by an understanding of the factors influencing WUE, establishing a foundation for measurement methodologies applicable to each system. Both quantitative metrics and qualitative criteria furnish comprehensive tools for WUE assessment. Advances in irrigation technologies, including automated controls and sensor networks, facilitate precision water delivery, thereby enhancing WUE. Agronomic strategies—optimal crop selection, rotation, and sophisticated scheduling—further maximize efficiency, and illustrative case studies demonstrate the tangible benefits attainable through their implementation. Economic constraints, environmental considerations, and policy factors present persistent challenges; nevertheless, emerging technologies and sustainable practices offer promising avenues for future improvement. The integrative analysis elucidates the multifaceted nature of WUE in irrigation and informs targeted policy and operational decisions designed to promote water conservation and agricultural productivity.

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