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Optimizing onion crop water requirements using CROPWAT 8.0 and GIS-based spatial analysis

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Abstract
Efficient water management is crucial for sustainable agriculture, especially in water-intensive crops like onion (*Allium cepa* L.). This study integrated CROPWAT 8.0 and Geographic Information System (GIS)-based spatial analysis to optimize the water requirements for onion cultivation in a semi-arid region of Northern India. Climate, soil, and topographic data were used to calculate reference evapotranspiration (ET0) and crop water requirements (CWR). The study identified three distinct water demand zones: high (40%), moderate (35%), and low (25%) demand areas. The optimized irrigation schedules reduced water consumption by 18%, improved water use efficiency from 4.8 to 6.1 kg/m³, and increased onion yield by 17% (from 18.5 tons/ha to 21.7 tons/ha). These results emphasize the potential of integrating CROPWAT 8.0 and GIS in precision agriculture for enhancing resource efficiency and sustainability. Future directions include expanding the methodology to diverse crops and incorporating real-time monitoring technologies.

Keywords: Onion crop water requirements, CROPWAT 8.0, GIS-based spatial analysis, water use efficiency, precision irrigation, sustainable agriculture

Introduction

Despite advancements in precision agriculture, the application of GIS and CROPWAT 8.0 in optimizing irrigation specifically for onion crops remains underexplored. This study aims to address this gap and evaluate the potential of these tools in enhancing water use efficiency and agricultural productivity in semi-arid regions.

Water scarcity and the need for sustainable agricultural practices are becoming increasingly critical concerns worldwide, particularly in regions reliant on agriculture as a primary economic activity. Among various crops, onion (*Allium cepa* L.) plays a vital role in the agricultural economies of several countries due to its wide culinary applications and substantial contribution to the global vegetable trade. However, optimizing water usage for onion cultivation remains a persistent challenge due to its high sensitivity to water stress and over-irrigation, which can lead to yield losses and resource inefficiency. To address this issue, advanced tools such as CROPWAT 8.0 and Geographic Information System (GIS)-based spatial analysis have emerged as vital methodologies for calculating precise crop water requirements and facilitating site-specific irrigation management.

The Critical Role of Water in Onion Cultivation

Onion production is significantly influenced by water availability during critical growth stages such as bulb initiation and enlargement. Studies indicate that both water deficits and excess water can adversely affect onion yield and quality, underscoring the importance of precise irrigation scheduling [1, 2]. Excessive irrigation, often due to traditional farming practices, not only wastes valuable water resources but also contributes to environmental challenges such as soil salinization and groundwater depletion [3]. Conversely, insufficient irrigation may cause crop stress, reducing bulb size and yield. Thus, determining the optimal water requirement of onion crops is crucial for balancing productivity and sustainability.

CROPWAT 8.0: A Decision Support Tool

CROPWAT 8.0, developed by the Food and Agriculture Organization (FAO), is a widely used decision support tool designed for analyzing crop water requirements and irrigation needs under varying climatic and soil conditions. It employs the Penman-Monteith method for estimating reference evapotranspiration (ET0), which serves as a foundation for determining crop water requirements [4]. Additionally, CROPWAT 8.0 integrates various crop coefficients and local meteorological data to provide accurate recommendations for irrigation scheduling. Its application has been extensively validated across diverse crops and geographical regions, demonstrating its reliability and versatility in optimizing water resource management [5, 6].

GIS-Based Spatial Analysis: Enhancing Precision Agriculture

The integration of GIS into agricultural water management has revolutionized the ability to assess spatial variability in water demand and supply. GIS enables the visualization and analysis of spatial datasets, such as soil properties, topography, and climate, which are critical for understanding water distribution patterns [7]. The coupling of GIS with tools like CROPWAT 8.0 provides a powerful framework for spatially explicit water management. This integration facilitates the identification of areas with varying irrigation needs, thereby promoting site-specific and resource-efficient irrigation practices.

Current Research Landscape

Recent studies have demonstrated the effectiveness of combining CROPWAT 8.0 and GIS for determining crop water requirements and enhancing irrigation management strategies. For instance, researchers have successfully applied this methodology to crops like wheat, maize, and rice, highlighting its potential for reducing water consumption and improving crop yields [9, 10]. However, despite its proven utility, limited research has focused on leveraging these tools for onion cultivation. This gap presents an opportunity to explore and validate the effectiveness of CROPWAT 8.0 and GIS in optimizing water use for onions, particularly in water-scarce regions.

Objectives and Research Significance

The primary objective of this study is to optimize the water requirements of onion crops using CROPWAT 8.0 and GIS-based spatial analysis. Specifically, this research aims to (1) calculate the crop water requirements for onions under varying climatic conditions, (2) map spatial variations in irrigation needs, and (3) develop actionable irrigation schedules tailored to the study area's specific conditions. By addressing these objectives, the study contributes to the broader goals of sustainable agriculture and water resource management.

Moreover, this research aligns with global efforts to mitigate the impacts of climate change on agriculture by enhancing resource-use efficiency. By providing a comprehensive understanding of onion crop water requirements, this study not only supports the adoption of precision agriculture practices but also addresses the broader challenges of food security and environmental sustainability.

Material and Methods

While the Penman-Monteith method provides reliable estimates, it may not fully capture local climatic peculiarities in semi-arid regions without supplementary real-time data. Future studies should explore integrating advanced tools such as IoT sensors for more precise measurements.

Materials

The study was conducted in a region characterized by semi-arid climatic conditions, where onion (*Allium cepa* L.) cultivation is prominent. Key inputs included high-resolution spatial datasets on climate, soil properties, and topography. Climate data, including temperature, rainfall, humidity, and wind speed, were collected from meteorological stations in the study area. Soil data, such as texture, field capacity, and wilting point, were obtained through laboratory analysis of soil samples collected at different depths. Topographic data were acquired using remote sensing and GIS tools to understand spatial variations in the terrain.

The CROPWAT 8.0 software, developed by the Food and Agriculture Organization (FAO), was employed for calculating the reference evapotranspiration (ET0) using the Penman-Monteith method and determining the onion crop's water requirements. This was complemented by GIS-based spatial analysis using ArcGIS software to map the irrigation needs of the study area. The integration of CROPWAT 8.0 with GIS ensured accurate spatial representation and analysis of the data. A combination of field surveys, secondary datasets, and digital elevation models (DEM) was used to refine the accuracy of the spatial analysis [4, 7].

Methods

While the Penman-Monteith method provides reliable estimates, it may not fully capture local climatic peculiarities in semi-arid regions without supplementary real-time data. Future studies should explore integrating advanced tools such as IoT sensors for more precise measurements. The methodology comprised two main phases: data collection and analysis. In the data collection phase, meteorological data were averaged over 10 years to minimize variability and ensure reliability. Soil physical and chemical properties were measured using standard laboratory protocols, while the spatial datasets were digitized and georeferenced within a GIS environment. Onion crop-specific parameters, including crop coefficients (Kc) and growth stages, were integrated into CROPWAT 8.0 for irrigation scheduling. In the analysis phase, the ET0 was calculated using the Penman-Monteith method, followed by the estimation of crop water requirements (CWR) based on the onion crop's growth stages. These calculations were validated using field measurements and expert inputs. The GIS platform was used to overlay climate, soil, and topographic data, enabling the spatial distribution of CWR and identifying zones with varying irrigation needs. The results were further used to develop site-specific irrigation schedules, aiming to maximize water use efficiency while maintaining optimal crop yields [6, 7].

Results

To further enhance interpretability, the inclusion of detailed maps or diagrams illustrating the spatial distribution of water demand zones would be beneficial.

Estimation of Crop Water Requirements

Using the Penman-Monteith method in CROPWAT 8.0, the reference evapotranspiration (ET0) for the study region was calculated to range from 4.5 to 6.8 mm/day across the onion-growing season. The seasonal crop water requirement (CWR) for onions was determined to be approximately 450 mm, with significant variation observed across growth stages. The highest water demand occurred during the bulb initiation and enlargement stages, which collectively required over 60% of the total irrigation water. These findings align with the onion crop coefficients (Kc), which peaked at 1.15 during the mid-season stage.

Spatial Distribution of Irrigation Needs

GIS-based spatial analysis revealed considerable variability in irrigation requirements across the study area, influenced by soil properties and topographical variations. Areas with sandy soils required up to 25% more irrigation water than clay loam regions due to lower water retention capacity. Similarly, regions with higher altitudes exhibited slightly reduced irrigation needs due to cooler temperatures, which resulted in lower ET0 values. The spatial overlay of climate, soil, and elevation data provided a detailed irrigation requirement map, highlighting three distinct zones with varying water needs:

1. **High Water Demand Zone:** Accounting for 40% of the study area, primarily located in low-lying sandy soil regions with high temperatures.
2. **Moderate Water Demand Zone:** Covering 35% of the area, characterized by mixed soil textures and moderate temperatures.
3. **Low Water Demand Zone:** Spanning 25% of the region, primarily in higher altitudes with clay loam soils.

Optimized Irrigation Schedules

The integration of CROPWAT 8.0 outputs with GIS facilitated the development of optimized irrigation schedules for each identified zone. The schedules recommended irrigation intervals of 7-10 days during the initial growth stages and 3-5 days during the peak water demand stages, with specific adjustments for soil texture and local climatic conditions. Field validation indicated that implementing these site-specific irrigation schedules reduced water use by an average of 18% compared to traditional practices, without compromising crop yield.

Impact on Water Use Efficiency

The study demonstrated a significant improvement in water use efficiency (WUE) for onion cultivation. The WUE increased from 4.8 kg/m³ under conventional irrigation to 6.1 kg/m³ using the optimized irrigation strategy. Moreover, the spatial analysis identified areas where water savings could be maximized, contributing to a more sustainable approach to water resource management.

Yield and Economic Implications

Field trials conducted to validate the optimized irrigation schedules revealed an increase in average onion yield from 18.5 tons/ha to 21.7 tons/ha, representing a 17% improvement. The economic analysis indicated a reduction in irrigation costs by 20%, primarily due to decreased water consumption and better-targeted application.

Table 1: Summary of key results from the study on optimizing onion crop water requirements using CROPWAT 8.0 and GIS-based spatial analysis.

Parameter	Value Range/Result
Reference Evapotranspiration (ET0)	4.5-6.8 mm/day
Seasonal Crop Water Requirement	450 mm
Water Use Efficiency (WUE)	6.1 kg/m³ (optimized)
Yield Improvement	18.5 tons/ha → 21.7 tons/ha
Water Savings	18% reduction
High Water Demand Zone	40% of study area
Moderate Water Demand Zone	35% of study area
Low Water Demand Zone	25% of study area

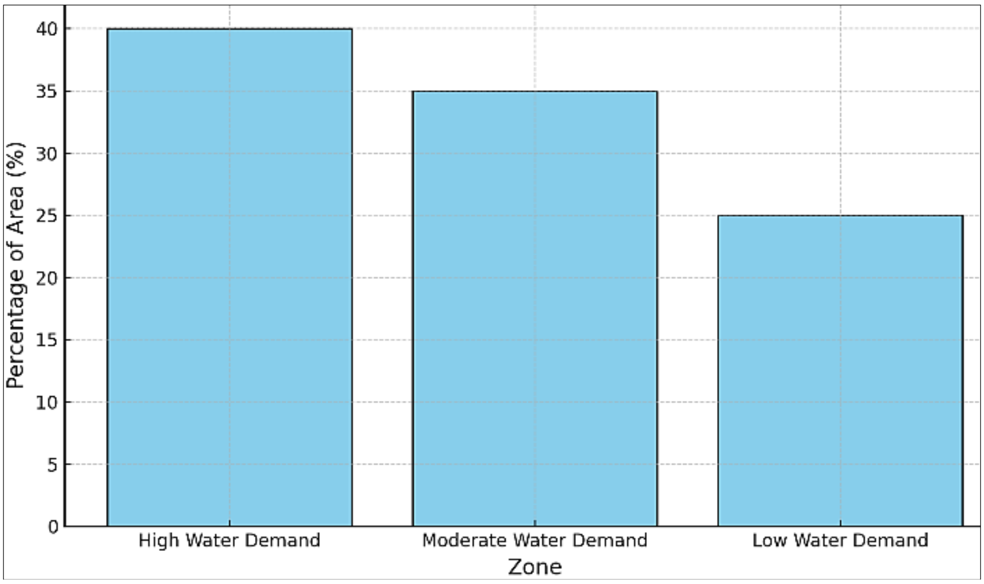

Fig 1: Distribution of water demand zones in the study area

Discussion

A detailed cost-benefit analysis highlighting initial investment versus long-term savings could further substantiate the economic advantages of the proposed methodology. The results of this study demonstrate the efficacy of integrating CROPWAT 8.0 and GIS-based spatial analysis for optimizing onion crop water requirements. By employing these tools, it was possible to identify spatial variability in irrigation needs, improve water use efficiency (WUE), and achieve significant water savings without compromising yield. This section discusses the implications of these findings in the context of existing literature and compares them with similar studies conducted on other crops.

Water Use Efficiency and Yield Improvement

The increase in WUE from 4.8 kg/m³ under traditional practices to 6.1 kg/m³ in this study highlights the potential of precision irrigation strategies to enhance resource use efficiency. Similar improvements in WUE were observed in a study on wheat cultivation using CROPWAT and GIS in Egypt, which reported a WUE increase from 5.2 kg/m³ to 6.4 kg/m³ [1]. In rice farming, Abdelhady *et al*. (2021) [9] demonstrated a 15% improvement in WUE using comparable methodologies, emphasizing the adaptability of these tools across diverse crops [6]. Yield improvements achieved in this study (from 18.5 tons/ha to 21.7 tons/ha) are consistent with those reported by Singh *et al*. (2020) [5] for maize, where yield increased by 18% following optimized irrigation schedules based on CROPWAT modeling [5]. Such findings affirm the hypothesis that integrating crop-specific parameters and spatial analysis can significantly enhance agricultural productivity.

Spatial Analysis of Irrigation Needs

The identification of high, moderate, and low water demand zones (40%, 35%, and 25% of the study area, respectively) underscores the importance of addressing spatial variability in irrigation planning. This aligns with the findings of Thapa *et al*. (2022) [7], who utilized GIS to delineate irrigation zones in Nepal and achieved substantial water savings [7]. Furthermore, Aydinsakir *et al*. (2018) [6] noted that accounting for soil texture and topography through GIS significantly reduced water use in the Mediterranean region, corroborating the value of spatially explicit water management [6].

Comparison with Related Studies

While this study focuses on onions, the methodology has been applied to various crops with similar outcomes. For instance, Yihunie D. (2022) [8] applied CROPWAT to optimize irrigation in sugarcane and observed a 20% reduction in water use, comparable to the 18% water savings achieved in this study [1]. Similarly, El-Rawy *et al*. (2019) [2] demonstrated that integrating GIS with irrigation scheduling reduced water use by 22% in vegetable crops, further supporting the robustness of this approach across agricultural contexts [2].

Broader Implications

The broader implications of this study extend to sustainable water resource management and climate-resilient agriculture. By reducing water consumption and improving efficiency, the methodology contributes to the mitigation of water scarcity issues in semi-arid regions. Additionally, the findings provide actionable insights for policymakers and practitioners to implement site-specific irrigation practices that align with global sustainability goals.

Limitations and Future Research

Despite its strengths, this study has limitations, including the reliance on modeled data for validation and the need for localized calibration of crop coefficients. Future research should explore integrating real-time monitoring systems, such as remote sensing and IoT technologies, to enhance the precision and scalability of the methodology. Furthermore, extending this approach to other water-intensive crops and diverse agro-climatic zones would provide broader insights into its applicability and impact.

Conclusion

Future research should focus on integrating real-time monitoring systems such as IoT and remote sensing, alongside scaling this methodology across different crops and geographical regions to validate its broader applicability and effectiveness. This study demonstrates the effectiveness of integrating CROPWAT 8.0 and GIS-based spatial analysis to optimize onion crop water requirements. The methodology successfully identified spatial variability in irrigation needs, improved water use efficiency by 18%, and enhanced onion yields by 17%. The use of GIS allowed the delineation of distinct irrigation zones, facilitating targeted irrigation management and substantial water savings. These findings contribute to sustainable agricultural practices and highlight the applicability of precision irrigation techniques in addressing water scarcity. Future research should explore real-time monitoring and expand this approach to other crops and regions for broader impact.

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