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Strategic Assessment of Evapotranspiration for Wheat Cultivation in Punjab, Pakistan

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Abstract

The nation's main wheat producing area, namely the province of Punjab, is becoming progressively more susceptible to water constraints brought on by climate change, ineffective irrigation techniques, and inadequate management of water for agriculture. The lack of district-level evapotranspiration (ET) surveillance networks, which are necessary for developing an appropriate water policy, exacerbates these difficulties. The absence of geographically and statistically specified ET data for optimal irrigation planning during wheat farming is an important regulatory gap that this investigation covers. For the 2022-2023 season, the study evaluates ET throughout the five major phenological phases of wheat (sowing, tillering, flowering, grain filling, and harvesting), utilizing Sentinel-2 satellite images and Google Earth Engine. A vegetation-index-driven ET computational method is used to produce high-resolution maps and district-level evaluations that represent variations in water demand within and between seasons. The results show notable spatial differences between districts like Faisalabad and Bahawalpur, with ET peaking at the grain filling stage (~4.09mm/day) and falling during sowing (~1.95mm/day). Presenting a data driven framework for proportionate water distribution, regional irrigation zoning laws, and climate-resilient agrarian management, this study offers plenty to the larger legislative conversation. It makes the case that incorporating remote sensing into policies can improve the allocation of resources and productivity, two essential components of sustainable agriculture strategies in the face of increasing environmental stress.

***Keywords*:** administrative framework, climate adaptation, Google Earth Engine, irrigation planning, irrigation zoning, Sentinel-2 satellite imageries, wheat production

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Introduction

Wheat plays a vital role in Pakistan's agricultural sector, serving as a staple crop that significantly contributes to rural livelihoods and national food security. Considering more than 75% of the nation's wheat is produced in the province of Punjab alone, the area is vital to maintaining both the nation's food supply and its financial wellness (Ahmad et al., 2022). Nevertheless, global warming, unpredictable precipitation trends, warmer temperatures, and diminishing water supplies pose a growing threat to Punjab's wheat production (Zakir-Hassan et al., 2022; Zhao et al., 2024). Moreover, outdated methods used for irrigation and imprecise transportation of water have exacerbated these challenges, resulting in inefficient usage, excessive consumption, and inappropriate utilization of already depleted clean water supplies (Wu et al., 2023).

The primary issue driving this work is the lack of stage-specific, regional evapotranspiration (ET) data that aids decision-making for irrigation governance. An important biophysical indication of agricultural water requirements is ET, particularly combining soil moisture loss and transpiration from plants (Allen et al., 1998). There still exists a significant gap in converting this ET knowledge into useful policy instruments at the subnational level, especially in poor nations, despite the fact that several international studies have emphasized the significance of ET in agricultural simulation and adaptation to climate change (Ren et al., 2021; Yang et al., 2022). The capacity of authorities to assign priority to water distribution, depending on its effectiveness or necessity, is limited in Punjab. This is because there is minimal regulatory structure in place to track ET differences between districts and crop stages.

The incorporation of hi-tech instruments including remote sensing into the governance framework has become more and more imperative in public policy discourse on sustainable agriculture (Pei et al., 2023). However, empirical integration of satellite-derived ET data into irrigation planning remains limited within Pakistani agricultural policy frameworks. This discrepancy hinders the attempts to ensure fair and effective water usage and reduces the possibility of adaptive governance. Hence, this study utilizes Sentinel-2 satellite images processed by the Google Earth Engine to provide spatially precise ET estimates across wheat's five crucial phenological stages, namely sowing, tillering, flowering, grain filling, and harvesting. For near real-time water demand monitoring, NDVI-driven ET modeling offers a scalable and reproducible method.

Based on a wider collection of research on precision farming and climate resilient governance, this study provides a workable solution to integrate geospatial intelligence into district level frameworks for resource allocation and irrigation zoning. It makes the case that, in addition to being a scientific tool, satellite-based ET monitoring may be used as a policy tool to calculate infrastructure expenditure, inform irrigation schedule, and support climate adaptation in the agriculture sector (Nagappan et al., 2020; Xie et al., 2023). Furthermore, the research intends to facilitate a shift from reactive to proactive water governance by placing it at the nexus of environmental monitoring and public policy. In Pakistan's agricultural policy environment, it promotes data driven planning procedures that acknowledge the regional variability of crop water requirements and match irrigation efforts with real demand, supporting the more general objectives of sustainability, equality, and resilience.

Method

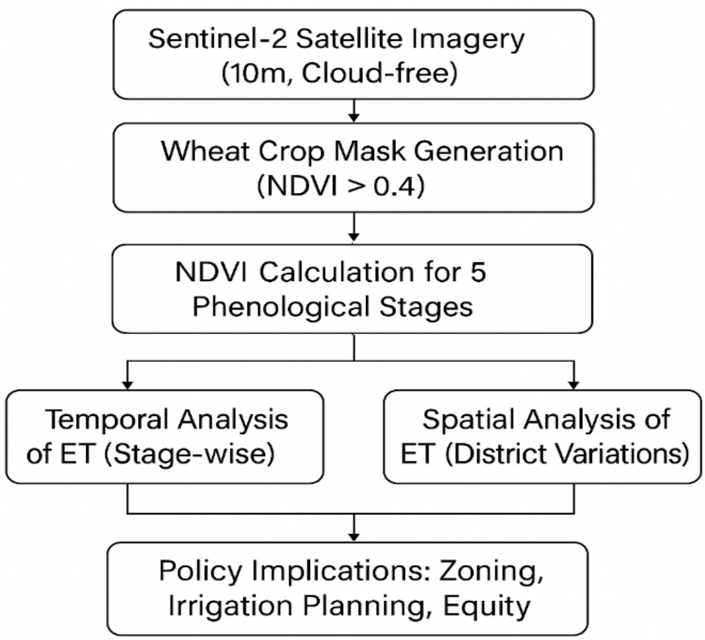
Study Area

The Punjab province of Pakistan is crucial to the national agricultural economy and is the subject of the current research. Punjab, which covers an area of around 205,000 square kilometers, has a variety of agro-climatic zones that enable the year-round cultivation of various crops including sugarcane, wheat, and rice. The province produces around 75% of the country's total wheat (Ahmad et al., 2022). The deliberate selection of Punjab to examine the effects of factors influencing ET is supported by the fact that 60% of the nation's total exports are from the agriculture sector (Pakistan Institute of Development Economics [PIDE], 2025), with Punjab accounting for 60% of these exports. Furthermore, the government of Punjab has been working for many years to address the issues of food security; as a result, it is crucial to evaluate how the climate affects crop productivity in such an agriculturally dense area. Additionally, precise ET estimation in this area can help with scheduling irrigation, allocating water to various crops, and planning other agricultural tasks (Nagappan et al., 2020).

The districts of Punjab can be categorized into multiple regions using a variety of methods, such as splitting rural Punjab into north and south or breaking the province into three areas: north, center, and south. Amjad et al. (2008) divided the rural areas of Punjab into five agro-climatic or agricultural zones using Pinckney's (1989) technique. These agro-climatic zones were categorized according to the criteria of International Food Policy Research Institute. The province offers a very important and complicated terrain for assessing ET-based irrigation governance because of its socioeconomic importance and vulnerability to institutional and meteorological hazards. The administrative division of the province at the district level also allows for the geographical disaggregation of outcomes. This facilitates targeted public policy interventions, such as drought contingency planning and irrigation zoning, particularly in area and subsidy allocation.

Figure 1

Workflow of NDVI-Based ET Estimation and Policy Integration for Wheat Cultivation in Punjab, Pakistan



In order to produce useful information for irrigation governance, this research estimates stage-wise evapotranspiration for wheat production throughout Punjab, Pakistan using a policy-oriented geospatial technique. The method is intended to overcome current institutional constraints in localized ET monitoring by combining remote sensing techniques with spatial analysis. In line with the contemporary policy literature supporting evidence-based agricultural water management, the said technique emphasizes both scientific validity and practical application (Elnmer et al., 2019; Nagappan et al., 2020).

Conceptual Framework and Policy Alignment

The main premise is that fairer and effective irrigation practices may be informed by the temporal and geographical variability in ET among the various districts of the Punjab province. This idea is consistent with theories of adaptive governance and sustainable development, which stress that policymakers should be sensitive to local environmental circumstances (Pei et al., 2023; Xie et al., 2023). The goal of the current study is to assist in the creation of irrigation zoning, drought contingency planning, and subsidy targeting by producing district-wise ET estimation over five wheat phenological phases.

Data Collection

Sentinel-2 imagery, which is cloud-free, was selected owing to its superior spatial accuracy and the ability to capture vegetation-related metrics, such as NDVI. It was also chosen because of its high spatial resolution (10 m). Data was collected during the entire wheat growing season (October 2022-April 2023), with distinct time frames for each developmental stage:

Sowing: October 20 to November 10, 2022

Tillering: December 1 to December 31, 2022

Flowering: January 20 to February 10, 2023

Grain Filling: March 1 to March 31, 2023

Harvesting: April 1 to April 27, 2023

Wheat Crop Mask Generation

NDVI readings over 0.4, a threshold signifying active vegetation, were used to create a crop mask representing a high coverage of vegetation associated with wheat throughout the optimum photosynthesis activity. This mask was applied to NDVI composites, calculated for each stage, in order to identify wheat growing locations (Allen et al., 1998). Cloud masking utilizing Sentinel-2's QA60 band ensured precise NDVI computation. To identify the wheat growing regions, the resultant NDVI composite was cropped to the boundaries of the province using the official administrative shape file. The baseline for the ET estimate was this crop mask.

Estimation of Evapotranspiration

In accordance with methods confided in earlier research, ET was calculated by employing Sentinel-2 imagery-derived NDVI composites for each developmental stage (Elnmer et al., 2019; Karbasi et al., 2022). Since NDVI can measure surface moisture and canopy growth, it has a favorable correlation with real ET. Using calibrated scaling factors derived from related agro ecological research, composite NDVI measurements for each stage were converted into ET proxies. At the provincial level, this method provided computational efficiency and useful policy information, although it did not replace a complete energy balance model, such as SEBAL or METRIC. Higher ET readings presumably indicate areas that consume more water. Color gradients were used to illustrate the geographical heterogeneity among the districts of Punjab districts on ET maps.

Spatial and Temporal Analysis

To identify the geographic differences in water demand, ET maps were created for every step and examined at the district level. Similarly, to identify areas with high demand, statistical summaries comprising mean ET per district at each stage were computed and illustrated. Critical times for irrigation treatment were evaluated by comparing temporal trends across phases. The outcomes' policy implications, such as setting infrastructure, investment priorities, or creating stage-specific irrigation advice, were assessed in addition to their environmental value. A systematic and reproducible strategy for incorporating remote sensing into subnational agricultural policy systems was established by using this technique. It allowed for tailored responses regarding crop vulnerability and water shortages in Pakistan's most important agrarian region by bridging the gap between the availability of climatic data and efficient governing systems.

Figure 2

ET Map during Sowing Stage (Oct–Nov 2022)

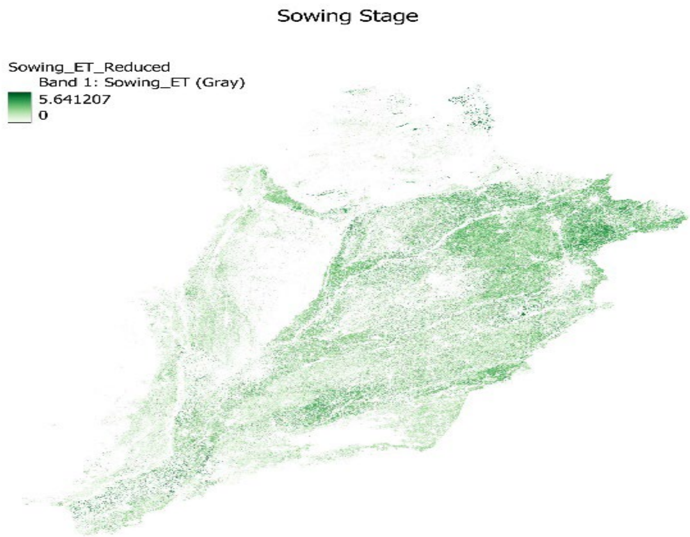


Figure 3

ET Map during Tillering Stage (Dec 2022)

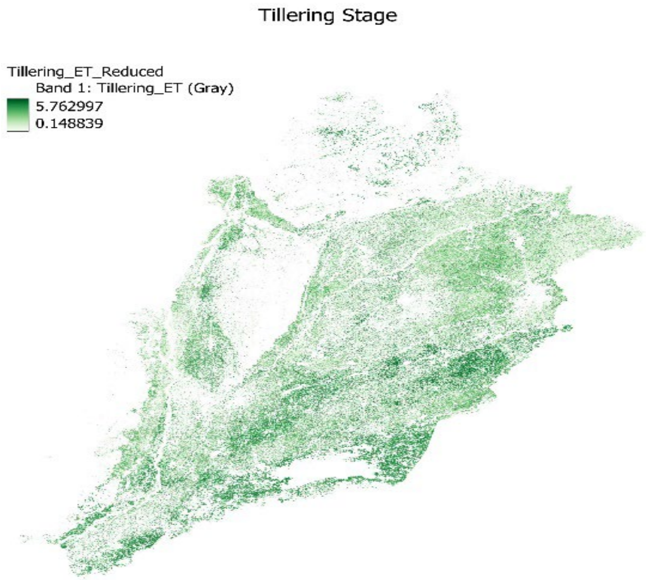


Figure 4
ET Map during Flowering Stage (Jan–Feb 2023)

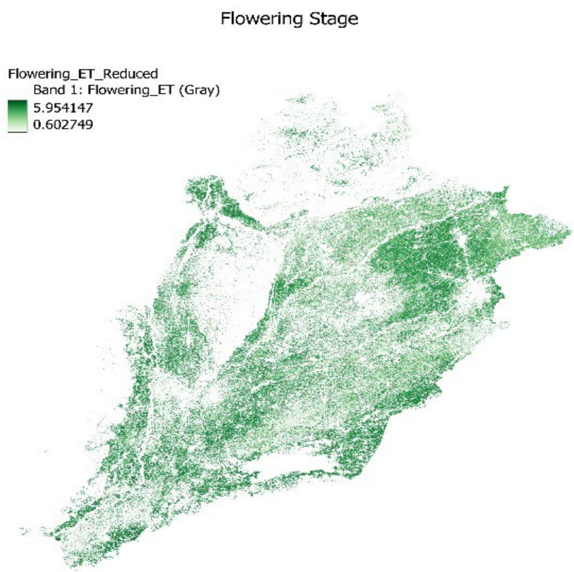


Figure 5
ET Map during Grain Filling Stage (Mar 2023)

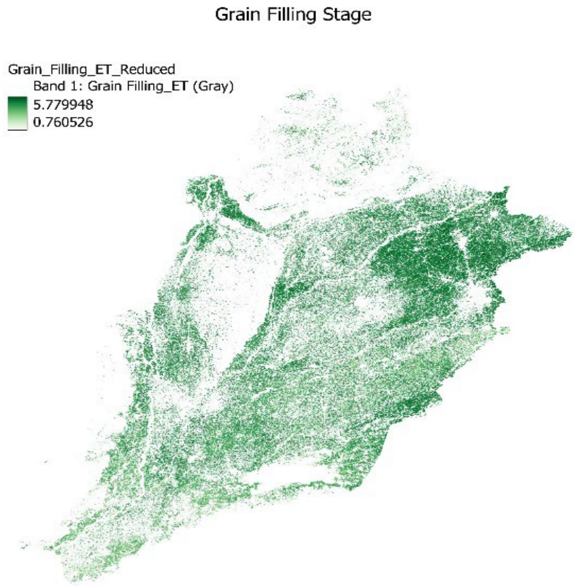
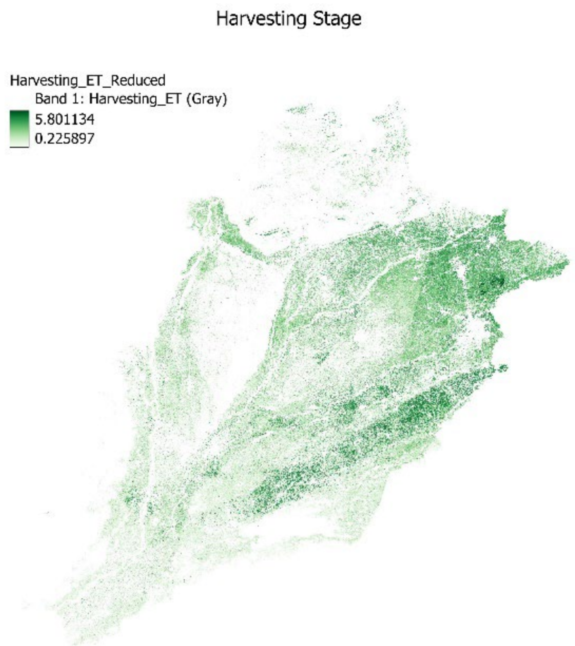


Figure 6
ET Map during Harvesting Stage (Apr 2023)



Results

The ET trends for wheat farming in Punjab at the district and stage levels during the 2022-23 season are shown in this section. The findings are organized to show both geographical differences across districts and temporal changes between wheat development phases, offering an empirical basis for irrigation plans specific to a given location.

Temporal Trends in ET across Growth Stages

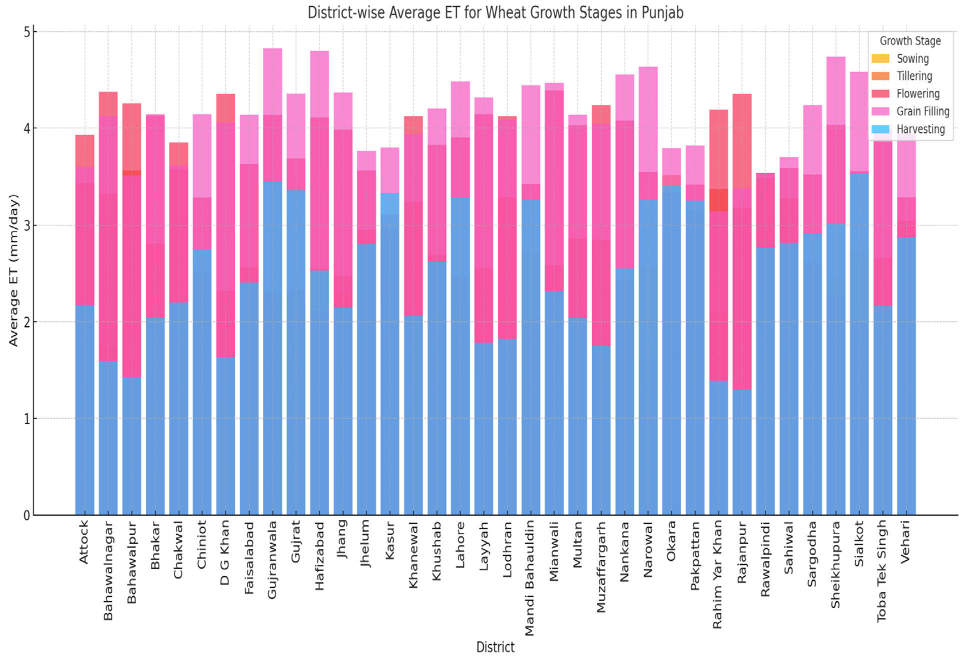
Based on the data, wheat's ET values vary greatly across its five phenological phases, suggesting that the crop's water requirements change over time.

- During the grain filling stage of wheat, the results showed that the demand for ET rose on an average of 4.09 mm per day, in line with the time of significant biomass accumulation and physiological activity. It was also noticed that this stage needed a substantial amount of freshwater during the grain formation process.
- During the sowing stage, it was evaluated that overall, ET accounted for the lowest value at an average of 1.95 mm per day. It implies that during the initial stage, the amount of water used by the wheat crop was the lowest.

The average ET estimates across different developmental phases of wheat in Punjab are represented by bar charts, as illustrated in Figure 7 below. In order to promote the best possible production potential, the graph illustrates the evaluation of water demand and recommends that irrigation resources be concentrated during blooming and grain filling.

Figure 7

Average ET Estimates (mm/day) During the Five Phenological Stages of Wheat Growth across Punjab (Oct 2022-Apr 2023).



The stage by stage understanding highlights the value of phenology-based irrigation planning, which may warrant sufficient supplies throughout crucial developmental stages and minimize water waste during times of minimal demand. It may also help local agricultural administration to create time sensitive irrigation warnings and arrange inputs.

Spatial Variations in District-Level ET

Significant regional variation in crop water requirements was observed in ET distribution across the various districts of Punjab.

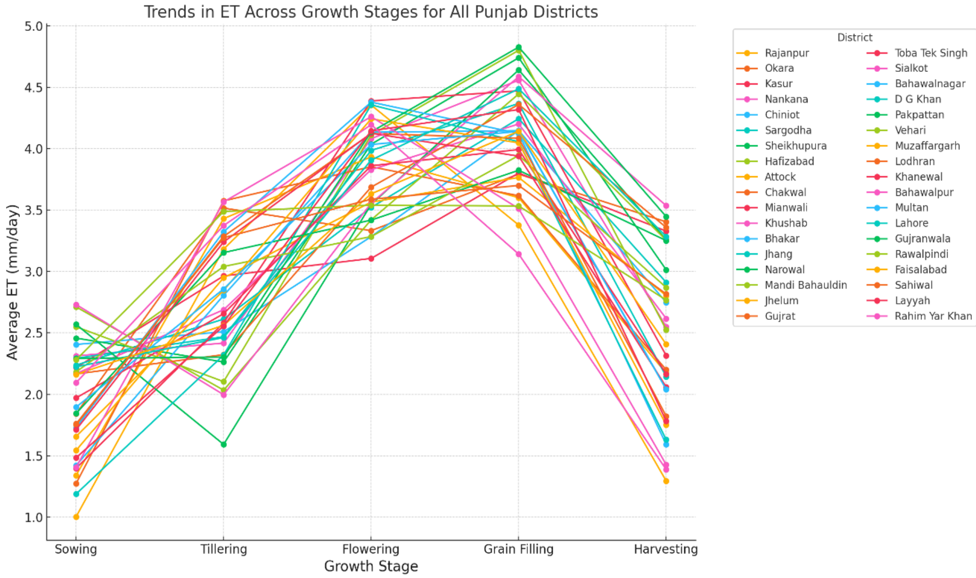
- Faisalabad, Multan, and Bahawalpur were the three districts that consistently displayed high ET values across all the stages, which implies that these districts need the highest amount of water for favorable yield.
- The other regions of Punjab, such as the nethermost areas including Rawalpindi and Chakwal, displayed the lowest ET levels, presumably as a result of shorter wheat growing cycles and colder temperatures. It also shows that these regions needed the lowest amount of water during

all stages. Moreover, it also manifests that decreased irrigation demand can be applied.

The multiline graph below displays the detailed ET patterns for each growth stage across the different districts of Punjab. Regional variations in this chart could help efficiently manage water resources and irrigation water.

Figure 8

A Multiline Graph Displaying the Detailed ET Patterns for Each Growth Stage across the Different Districts of Punjab



Implications

- Stage-specific Irrigation Planning: The necessity of irrigation planning and its variability at the regional level can be regulated by observing ET patterns. Regions that need a high rate of irrigation and those that need the lowest amount of water can be easily regulated by observing their different patterns. Increasing allocation throughout the blooming and grain filling phases can greatly increase crop yield, while avoiding needless consumption during planting or harvesting.
- Spatial Water Governance: Programs aimed at improving irrigation efficiency, maintaining the canal system, and developing real time advisories should be concentrated on districts with a consistently high

ET. On the other hand, adaptive management techniques such as crop diversification or deficit irrigation may be advantageous in regions with a lower ET. By identifying regions where water supplies may be transferred to reduce stress, the results also indicate the potential for effective water management.

Discussion

The results of this investigation show how useful evapotranspiration (ET) monitoring is as a tool for public policy and decision-making, especially when it comes to agricultural water governance. The study offers practical insights for boosting irrigation effectiveness, advancing water fairness, and strengthening climate resilience in Punjab by exposing both temporal and geographical variability in water demand throughout the wheat producing regions of the province. The key hypothesis is that satellite-derived ET estimates can serve as reliable, evidence-based tools for optimizing irrigation scheduling and guiding equitable water resource distribution across districts. The necessity of stage-specific irrigation planning is shown by consistently high ET values (~4.09mm/day) during the grain filling stage. Farmers run the risk of yield loss from under irrigation or water waste from over irrigation during less crucial phases in the absence of such focused treatments (Allen et al., 1998, Wu et al., 2023). Time sensitive irrigation advice is necessary because the lowest ET levels during sowing (~1.95mm/day) enhance the possibility of input savings early in the growth cycle.

The necessity of distinct water administration techniques is shown by notable regional variations in ET patterns, especially the increased demand in areas like Faisalabad and Multan. These geographical realities are disregarded by uniform irrigation programs, which result in inefficiencies, injustices, and lost chances for focused assistance. By integrating ET measures into district-level irrigation planning, context sensitive policy interventions might be implemented, focusing on infrastructure improvements, water quotas, and subsidies in regions with clearly greater requirements.

These results lend credence to the demand for data driven governance, in which institutional actions are informed by real-time environmental indicators (Pei et al., 2023; Xie et al., 2023). In areas where ground-based monitoring infrastructure is scarce or non-existent, the remote sensing technique employed here provides a scalable and affordable option. Pakistan may transition from a reactive to a preventative paradigm of climate adaptation by incorporating ET monitoring into the operations of the provincial agriculture department.

Furthermore, this study supports a paradigm for sustainable development that emphasizes the equitable distribution of natural resources in the face of climatic stress. Resources can be relocated or supplemented with conservation-focused technologies including crop rotation, deficit irrigation, or rainwater harvesting in regions with consistently low ET, such as Rawalpindi or Chakwal. Lastly, by providing a reproducible technique that connects satellite observations to public sector agendas, the work adds to the larger conversation on science policy integration. Few attempts have been made to incorporate such outputs into practical policy formulation, despite the fact that previous research concentrated heavily on modeling ET for academic research (Karbasi et al., 2022; Zhao et al., 2024). This study fills this gap and offers a model for policy-aligned environmental monitoring by focusing on district-level aggregation and alignment with agronomic phases.

Conclusion

The current study provides beneficial details regarding the significance of remote sensing imagery for correct and detailed ET to cultivate wheat for better yield. By incorporating the Sentinel-2 satellite data and processing through Google Earth, water resource allocation for effective irrigation schemes can be applied. The results facilitate effective and fair water management by supporting the creation of irrigation zone regulations. Keeping in view climate unpredictability, this investigation helps to ensure adequate nutrition and resource effectiveness in forecasting Punjab's agricultural demand by addressing the gap in research policy execution.

Policy Implications

These observations directly relate to policy. In order to help farmers and extension offices optimize water use based on real crop demands, they first assist the formulation of stage-specific irrigation advice. Secondly, district-level irrigation zoning is given a scientific foundation by the designation of high and low ET zones, which promotes fair and effective allocation of water resources.

The absence of data driven tools for subnational water planning is a critical governance issue that this study tackles, in addition to its technical contributions. It bridges the gap between environmental data and institutional decision-making by coordinating remote sensing technology with public sector demands, hence advancing a reproducible paradigm of science policy integration. Resultantly, it adds to the larger conversation on fair resource governance, agricultural sustainability, and climate adaptation.

Future Research Directions

Future studies should focus on combining soil moisture measurements and local meteorological data with real-time ET monitoring devices. Their applicability to agricultural governance may be increased further by broadening the analysis to encompass more crops and geographical areas.

Conflict of Interest

The authors of the manuscript have no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

The data associated with this study will be provided by the corresponding author upon request.

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