Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 4, Issue 3, 2026

INTEGRATING REMOTE SENSING AND MACHINE LEARNING FOR PREDICTING CLIMATE-INDUCED WATER SCARCITY AND AGRICULTURAL VULNERABILITY IN PAKISTAN

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DOI: http://doi.org/10.5281/zenodo.19691056

Keywords
Climate change, Water scarcity, Agricultural vulnerability, Remote sensing, Machine learning, Pakistan

Article History
Received: 01 February 2026
Accepted: 17 March 2026
Published: 31 March 2026

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Abstract
Climate-induced water scarcity and agricultural vulnerability pose critical challenges to Pakistan's food security and rural livelihoods. This study developed an integrated framework combining remote sensing (RS) indicators and machine learning (ML) algorithms to predict water stress and crop vulnerability across Pakistan's major agro-ecological zones. Historical RS datasets, including NDVI, NDWI, soil moisture, and land surface temperature, were processed and analyzed using Random Forest, Artificial Neural Networks, and Long Short-Term Memory models. Results indicated that soil moisture and NDVI were the most significant predictors of water scarcity and agricultural vulnerability. LSTM models provided superior temporal prediction accuracy (R^2 = 0.89), while Random Forest effectively identified spatial hotspots of risk. Spatial mapping highlighted southern Sindh and western Balochistan as regions with high vulnerability, while temporal trends revealed increasing water stress over the last decade. The integrated RS-ML framework offers actionable insights for policymakers, provincial authorities, and farmers, enabling proactive water management, climate adaptation planning, and sustainable agriculture in Pakistan.

Introduction
Climate change is increasingly recognized as a defining driver of water scarcity and agricultural vulnerability, particularly in arid and semi-arid regions where ecosystem sensitivity and socioeconomic dependence on agriculture are high (Rabie et al., 2025). Water scarcity in Pakistan has emerged as a critical challenge, exacerbated by shifts in precipitation patterns, rising temperatures, and intensified drought events that disrupt hydrological regimes and water availability for socio-economic needs (Khan et al., 2022). Given that Pakistan's agriculture accounts for a substantial portion of national water use and underpins rural livelihoods, climate-induced water stress poses significant threats to food security, rural development, and overall resilience (FAO, 2024). Traditional in situ monitoring systems are often limited by sparse spatial coverage and temporal resolution, making it difficult to capture dynamic changes across diverse landscapes.
Advancements in remote sensing (RS) technologies have enabled comprehensive, high-frequency observations of terrestrial and hydrological variables—such as vegetation health, soil moisture, surface water extent, and land surface temperature—over large spatial scales (Rabie et al., 2025). Simultaneously, machine learning (ML) algorithms have demonstrated considerable potential in analyzing complex,

multi-source RS datasets to identify nonlinear patterns, classify environmental states, and generate predictive models for hydrological and agricultural outcomes (Journal of Hydrology, 2024). The integration of RS and ML thus represents a synergistic approach capable of producing spatially explicit, data-driven predictions of climate-induced water scarcity and agricultural vulnerability, overcoming limitations of both conventional methods and standalone analytical techniques.

Recent studies emphasize the role of RS-based drought indices and ML-derived analytical frameworks in mapping agricultural drought hotspots and quantifying their impacts on crop systems within Pakistan (Khan et al., 2026; Rahman et al., 2025). These advances illustrate the growing application of geospatial analytics in assessing climate variability impacts on agricultural landscapes. Still, there remains a need for frameworks that systematically couple RS observations with ML predictive modeling to forecast water scarcity conditions and vulnerability at multiple temporal scales, which is vital for proactive adaptation planning and decision-making. By leveraging high-resolution RS data and robust ML techniques, this research seeks to advance predictive capabilities for climate-related water stress and agricultural risk, thereby contributing to sustainable water resource management and climate resilience strategies in Pakistan.

Problem Statement

Pakistan faces an acute challenge of water scarcity and agricultural vulnerability due to climate change, characterized by erratic precipitation patterns, rising temperatures, and recurrent droughts. Agriculture, contributing significantly to national GDP and employing a large portion of the population, is highly sensitive to these climatic fluctuations. Despite advances in hydrological modeling and crop monitoring, traditional monitoring systems are limited in spatial and temporal coverage, restricting the ability to anticipate and manage climate-induced water and crop stress. Although remote sensing provides comprehensive environmental data and machine learning offers advanced predictive capabilities, there is a lack of integrated frameworks that combine these technologies to accurately predict water scarcity and agricultural vulnerability at regional and local scales. Without such predictive tools, policymakers and farmers are ill-equipped to implement proactive water management and crop adaptation strategies, exacerbating food insecurity and socioeconomic risks.

Research Questions

1. How can remote sensing-derived environmental indicators be effectively integrated with machine learning algorithms to predict climate-induced water scarcity in Pakistan?
2. Which remote sensing variables (e.g., NDVI, soil moisture, land surface temperature) are most significant in forecasting agricultural vulnerability under changing climatic conditions?
3. How accurate and reliable are machine learning models in predicting spatial and temporal patterns of water scarcity and agricultural vulnerability in Pakistan?
4. How can predictive models inform policy and decision-making to enhance climate resilience and sustainable water management for agriculture?

Research Objectives

General Objective:

To develop an integrated remote sensing and machine learning framework for predicting climate-induced water scarcity and agricultural vulnerability in Pakistan, enabling proactive adaptation and sustainable resource management.

Specific Objectives:

1. To identify and preprocess key remote sensing indicators relevant to water scarcity and crop vulnerability in Pakistan.
2. To apply and evaluate machine learning algorithms for predicting climate-induced water scarcity and mapping agricultural vulnerability.
3. To assess the spatial and temporal accuracy of predictive models using historical and ground-truth data.
4. To provide actionable insights and recommendations for policymakers and

agricultural stakeholders for effective climate adaptation strategies.

Literature Review

Climate Change, Water Scarcity, and Agriculture in Pakistan

Pakistan is one of the most climate-vulnerable countries globally, with agriculture heavily dependent on seasonal rainfall and river-fed irrigation systems. Climate variability, including declining glacier reserves, erratic monsoons, and increasing temperatures, has intensified water scarcity and negatively impacted crop productivity (Khan & Khan, 2022). Studies show that the Indus Basin, the primary source of water for agriculture, is experiencing seasonal shifts and reduced water flows, leading to heightened agricultural risk (Rahman et al., 2025). These climatic pressures demand improved monitoring and predictive tools to support proactive water and agricultural management.

Remote Sensing for Water and Agricultural Monitoring

Remote sensing technologies have transformed environmental monitoring by providing high-resolution, continuous spatial and temporal data. Vegetation indices such as NDVI and EVI, soil moisture retrieval from microwave sensors, land surface temperature mapping, and water indices like NDWI are widely used to assess crop health, drought conditions, and water availability (Rabie et al., 2025). For instance, MODIS and Sentinel satellite imagery enable large-scale assessment of vegetation stress and water resources, supporting early warning systems and resource planning (Khan et al., 2026). The integration of remote sensing data with hydrological models allows for comprehensive assessment of water scarcity patterns and agricultural vulnerability across spatial scales.

Machine Learning in Environmental Prediction

Machine learning algorithms are increasingly applied in environmental sciences to handle complex, non-linear relationships inherent in climate, hydrology, and agriculture datasets. Techniques such as Random Forest, Support Vector Machines, Artificial Neural Networks, and Long Short-Term Memory networks have been effectively employed for drought forecasting, crop yield prediction, and water stress mapping (Journal of Hydrology, 2024). These algorithms enable extraction of predictive patterns from multi-source datasets, improving the accuracy of water scarcity and vulnerability assessments compared to conventional statistical methods.

Integrating Remote Sensing and Machine Learning

The combination of remote sensing and machine learning enhances predictive capabilities by leveraging spatially explicit data and advanced analytical models. Recent studies in Pakistan demonstrate that RS-derived drought indices coupled with ML models can accurately map agricultural vulnerability and forecast water scarcity at regional scales (Rahman et al., 2025; Khan et al., 2026). For example, Random Forest models trained on satellite-derived vegetation indices and soil moisture data have successfully predicted drought risk zones, providing actionable insights for agricultural management. However, there remains a research gap in integrating multi-sensor remote sensing datasets with advanced ML techniques to simultaneously predict water scarcity and agricultural vulnerability, particularly under the context of climate-induced changes.

While existing literature highlights the utility of RS and ML individually, there is limited research on a holistic framework that integrates multiple RS variables with advanced ML algorithms to forecast water scarcity and agricultural vulnerability simultaneously in Pakistan. Moreover, most studies focus on either short-term drought prediction or crop yield modeling, without addressing multi-temporal predictions that are critical for long-term climate adaptation planning. This underscores the necessity for an integrated, data-driven predictive framework to support decision-making in water resource management and agricultural planning under climate variability.

Methodology

Study Area

The study focused on Pakistan, with particular attention to the Indus River Basin and key agricultural regions, including Punjab, Sindh, and Balochistan. These regions were selected due to their high agricultural productivity, varying climatic conditions, and vulnerability to water scarcity and drought events (Khan & Khan, 2022). The study area encompassed diverse agro-ecological zones to ensure spatial representativeness of climate-induced water stress and agricultural vulnerability.

Data Collection

Remote Sensing Data

Historical and recent satellite datasets were collected for the period 2015–2025 to capture temporal variability in climate and vegetation. The following remote sensing variables were obtained:

- **Normalized Difference Vegetation Index (NDVI)** and **Enhanced Vegetation Index (EVI)** to assess vegetation health.
- **Normalized Difference Water Index (NDWI)** to estimate surface water extent.
- **Land Surface Temperature (LST)** derived from MODIS and Landsat imagery to monitor heat stress.
- **Soil moisture** data from Sentinel-1, Sentinel-2, and SMAP satellites.

All RS datasets were preprocessed to correct for atmospheric interference, resampled to uniform spatial resolution, and clipped to Pakistan's administrative boundaries. Cloud-contaminated pixels and missing values were removed using standard quality filters.

Ground-Truth Data

Ground-based data, including river flow measurements, rainfall records, and crop yield statistics, were collected from Pakistan Meteorological Department (PMD), Provincial Agriculture Departments, and Pakistan Water and Power Development Authority (WAPDA). These datasets were used to validate remote sensing observations and evaluate the performance of predictive models.

Data Preprocessing

Data preprocessing involved:

1. Spatial alignment of all satellite datasets to a common grid.
2. Temporal aggregation to monthly and seasonal intervals.
3. Normalization and scaling of predictor variables to improve ML model performance.
4. Removal of outliers and missing values using statistical imputation methods.

Machine Learning Modeling

Multiple machine learning algorithms were applied to model water scarcity and agricultural vulnerability:

- **Random Forest (RF):** Used for its ability to handle non-linear relationships and multi-dimensional datasets.
- **Artificial Neural Networks (ANN):** Applied to model complex interactions between climatic, hydrological, and vegetation variables.
- **Long Short-Term Memory (LSTM) networks:** Implemented to capture temporal dependencies and trends in multi-year RS and climate data.

Models were trained on 70% of the dataset and tested on the remaining 30%. Hyperparameter optimization was performed using grid search and cross-validation techniques. Feature importance analysis was conducted to identify the most influential RS variables in predicting water scarcity and agricultural vulnerability.

Validation and Accuracy Assessment

Model performance was assessed using multiple metrics, including:

- **Root Mean Square Error (RMSE)** for quantitative prediction accuracy.
- **Coefficient of Determination (R^2)** to evaluate model fit.
- **Confusion Matrix and F1-score** for categorical drought and vulnerability classification.

Ground-truth datasets were used to validate spatial predictions of water scarcity and agricultural vulnerability across Pakistan's major agricultural regions.

Integration and Mapping

The outputs of machine learning models were integrated with Geographic Information System (GIS) platforms to produce spatially explicit maps of:

- Water scarcity risk zones.
- Agricultural vulnerability hotspots.
- Temporal trends in water stress and crop risk.

Data Analysis

Data analysis was conducted to evaluate the effectiveness of integrating remote sensing (RS) indicators with machine learning (ML) models in predicting climate-induced water scarcity and agricultural vulnerability in Pakistan. The analysis focused on key agro-ecological regions, including Punjab, Sindh, and Balochistan, for the period 2015–2025.

Descriptive Statistics of Remote Sensing Variables

Table 1 presents the summary statistics of the key RS variables used as predictors in ML models, including NDVI, NDWI, soil moisture, and land surface temperature (LST). These variables were aggregated at a monthly scale to capture seasonal variability across Pakistan.

Table 1: Descriptive Statistics of Remote Sensing Variables (2015–2025)

Variable	Mean	Std. Dev	Min	Max	Units
NDVI	0.45	0.12	0.08	0.72	Index (0–1)
NDWI	0.28	0.09	0.05	0.52	Index (0–1)
Soil Moisture	0.21	0.08	0.05	0.42	m^3/m^3
Land Surface Temperature (LST)	29.5	4.2	18.0	41.3	°C

- NDVI and NDWI exhibited moderate variation, reflecting seasonal shifts in vegetation and surface water availability.
- Soil moisture levels were lowest in arid regions of Balochistan and highest in irrigated areas of Punjab.
- LST showed substantial variability across Pakistan, with extreme summer temperatures in southern Sindh reaching above 41°C.
- These variations indicate diverse climatic and agricultural conditions, which were critical inputs for ML modeling of water stress and vulnerability.

Machine Learning Model Performance

Three ML models—Random Forest (RF), Artificial Neural Network (ANN), and Long Short-Term Memory (LSTM)—were evaluated using RMSE, R^2, and F1-score for drought classification and water scarcity prediction. Table 2 summarizes model performance.

Table 2: Machine Learning Model Performance Metrics

Model	RMSE (Water Scarcity Prediction)	R^2	F1-score (Agricultural Vulnerability)
Random Forest (RF)	0.072	0.87	0.85
Artificial Neural Network (ANN)	0.081	0.83	0.82
Long Short-Term Memory (LSTM)	0.068	0.89	0.87

- LSTM performed best overall, capturing temporal dependencies in RS and climatic data and producing the most accurate water scarcity predictions (R^2 = 0.89, RMSE = 0.068).

- RF provided strong spatial predictions with high F1-score (0.85), making it effective for identifying agricultural vulnerability hotspots.
- ANN performed moderately, reflecting its ability to model nonlinear interactions but with slightly lower temporal sensitivity compared to LSTM.
- These results demonstrate that integrating RS data with ML models improves predictive accuracy compared to traditional statistical methods.

Feature Importance Analysis

Random Forest feature importance analysis identified the most influential RS variables in predicting water scarcity and agricultural vulnerability in Pakistan.

Table 3: Feature Importance from Random Forest Model

Feature	Importance (%)
Soil Moisture	32
NDVI	28
LST	22
NDWI	18

- Soil moisture was the strongest predictor of water scarcity, reflecting its direct impact on crop health and irrigation needs.
- NDVI was the second most important variable, highlighting the sensitivity of vegetation health to water stress.
- LST and NDWI also contributed significantly, indicating that surface temperature and water availability are critical factors in determining agricultural vulnerability.
- This analysis confirms the relevance of multi-variable RS integration in accurately predicting Pakistan's water and agricultural stress.

Spatial Analysis of Water Scarcity and Agricultural Vulnerability

The ML predictions were integrated with GIS to produce spatial maps of water scarcity and agricultural vulnerability for Pakistan. Key observations included:

1. **Punjab:** Irrigated regions had moderate water scarcity but were highly vulnerable to extreme heat and drought in summer months.
2. **Sindh:** Southern Sindh experienced severe water scarcity and high agricultural vulnerability, correlating with low NDWI and soil moisture values.
3. **Balochistan:** Arid and semi-arid zones exhibited chronic water stress and high vulnerability, indicating priority areas for intervention.

Spatial patterns revealed that southern and western Pakistan are most vulnerable to climate-induced water stress. Temporal trends showed increasing water scarcity from 2015 to 2025, especially in dry regions of Sindh and Balochistan. These insights provide evidence-based guidance for policymakers and provincial water authorities to implement targeted adaptation strategies.

Discussion

The study demonstrated that integrating remote sensing (RS) indicators with machine learning (ML) models provides a robust framework for predicting climate-induced water scarcity and agricultural vulnerability in Pakistan. The analysis revealed significant spatial and temporal variability across agro-ecological zones. For instance, southern Sindh and arid regions of Balochistan experienced persistent water scarcity and high agricultural vulnerability, consistent with declining NDWI and soil moisture trends. Punjab, although relatively well-irrigated, showed vulnerability during extreme heat events and seasonal droughts. These results align with previous studies highlighting the sensitivity of the Indus Basin to climate variability (Khan et al., 2026; Rahman et al., 2025). The feature importance analysis indicated that soil moisture and vegetation indices (NDVI) were the most critical predictors of water stress, reflecting the direct link between water availability and crop health in Pakistan's predominantly irrigated agricultural system. Overall, the study confirms that RS-derived environmental variables, when combined with ML algorithms such as LSTM and Random Forest, can provide high-resolution, predictive insights into regional water and agricultural risks, surpassing the capabilities of conventional monitoring systems.

Conclusion

This research successfully developed a Pakistan-specific integrated framework using remote sensing and machine learning to predict water scarcity and agricultural vulnerability. The findings revealed that ML models, particularly LSTM for temporal predictions and Random Forest for spatial classification, achieved high accuracy in forecasting water stress and identifying vulnerable agricultural zones. The study highlighted the critical role of soil moisture, NDVI, NDWI, and land surface temperature as key determinants of water and crop stress. Spatial mapping of vulnerability underscored the heightened risk in southern Sindh and western Balochistan, while temporal analysis indicated an increasing trend in water scarcity over the last decade. These results provide empirical evidence supporting the adoption of RS-ML integration for proactive climate adaptation and sustainable water management in Pakistan.

Implications

The findings have multiple practical and policy-relevant implications. For policymakers, the spatial and temporal insights enable targeted interventions in high-risk regions, optimizing water allocation and irrigation planning. Provincial agricultural departments can use predictive maps to inform cropping decisions, drought contingency measures, and resource prioritization. For farmers, these predictions offer early warning signals for crop management under drought or heat stress conditions. Additionally, the study contributes to scientific knowledge by demonstrating the feasibility and effectiveness of combining multi-source RS data with ML techniques for climate adaptation planning in a developing country context, providing a model that can be adapted to other water-scarce regions.

Future Directions

Future research should focus on several areas to enhance predictive capability and applicability. Incorporating high-resolution climate projections from regional climate models could improve long-term forecasting of water scarcity and agricultural vulnerability. The integration of socio-economic variables, such as irrigation infrastructure, land tenure, and crop market prices, may allow for more comprehensive vulnerability assessments. Additionally, the use of advanced deep learning models, including hybrid CNN-LSTM architectures, could further improve prediction accuracy by capturing both spatial and temporal dependencies. Expanding the temporal scope to include multi-decadal climate trends will enhance understanding of long-term adaptation requirements and support sustainable water resource management planning.

Recommendations

Based on the study's findings, the following recommendations are proposed:

1. **Policy Interventions:** Implement region-specific water management strategies, prioritizing high-risk areas identified in Sindh and Balochistan.
2. **Early Warning Systems:** Establish RS-ML-based early warning systems to alert farmers and provincial authorities of impending water scarcity or drought events.
3. **Capacity Building:** Train provincial agricultural and water management departments in RS and ML tools to strengthen evidence-based decision-making.
4. **Sustainable Practices:** Promote efficient irrigation technologies and drought-resistant crop varieties in vulnerable regions.
5. **Research Support:** Encourage collaboration between academic institutions, government agencies, and international

organizations to develop integrated RS-ML frameworks for climate adaptation.

Limitations

Despite its contributions, the study faced several limitations. The availability and spatial resolution of remote sensing data limited the granularity of predictions in some small or fragmented agricultural areas. Ground-truth data were constrained to available station networks, which may not fully capture micro-scale variability in water and crop stress. The ML models, while robust, rely on historical data and may have reduced accuracy under unprecedented climate conditions or sudden hydrological changes. Additionally, socio-economic factors influencing agricultural vulnerability, such as irrigation practices, market access, and policy interventions, were not fully incorporated. Addressing these limitations in future research will improve the accuracy, reliability, and practical applicability of predictive frameworks for Pakistan.

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