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ASSESSING THE IMPACT OF IRRIGATION PRACTICES ON SOIL MOISTURE AND CROP HEALTH USING REMOTE SENSING AND HYDROLOGICAL MODELLING

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Abstract: *Efficient irrigation management is critical for sustainable agriculture, particularly in water-scarce regions. Traditional methods for assessing irrigation impacts are often point-based and fail to capture spatial and temporal variability across large agricultural landscapes. This research presents an integrated framework combining remote sensing and hydrological modelling to comprehensively assess the impact of different irrigation practices on soil moisture dynamics and crop health. We utilized a time series of Sentinel-1 SAR and Sentinel-2 multispectral imagery to monitor surface soil moisture and vegetation indices (NDVI, NDWI) over an agricultural district employing diverse irrigation methods (drip, sprinkler, and flood irrigation). These remote sensing observations were integrated with the Soil Water Assessment Tool (SWAT) hydrological model, which was calibrated and validated using ground measurements. Our results demonstrated significant differences in soil moisture retention and distribution patterns among irrigation practices. Drip irrigation maintained more stable soil moisture levels with 25% less water consumption compared to flood irrigation, while sprinkler systems showed intermediate efficiency. Crop health indicators derived from Sentinel-2 revealed that fields under drip irrigation exhibited 15-20% higher NDVI values during critical growth stages and more uniform crop vigour. The coupled remote sensing-hydrological modelling approach successfully identified areas of water stress and waterlogging, with model validation showing strong agreement between simulated and observed soil moisture ($R^2 = 0.89$) and crop health parameters. Spatial analysis revealed that 35% of the flood-irrigated areas experienced either moisture stress or waterlogging, highlighting significant optimization potential. This research concludes that the integration of multi-sensor remote sensing with hydrological modelling provides a powerful, scalable approach for evaluating irrigation performance, identifying inefficiencies, and supporting precision water management decisions to enhance agricultural productivity and water sustainability.*

Keywords*: irrigation, soil moisture, remote sensing, crop, hydrological modelling.*

INTRODUCTION

Water scarcity represents one of the most significant challenges to global food security, with agriculture accounting for approximately 70% of freshwater withdrawals worldwide (FAO, 2017, PASCALAU ET AL, 2020). Efficient irrigation practices are therefore paramount for sustainable agricultural production, particularly as climate change exacerbates water stress in many agricultural regions. The impact of irrigation on agricultural systems manifests through two critical parameters: soil moisture availability and crop health response (BASTIAANSSEN ET AL., 2000; SMULEAC ET AL, 2020). Soil moisture governs fundamental hydrological processes, nutrient uptake, and root development, while crop health reflects the integrated response of plants to water availability, among other environmental factors. Traditional methods for monitoring these parameters - relying on sparse ground-based sensors and manual field surveys - are inadequate for capturing the spatial heterogeneity and temporal dynamics of irrigation impacts across operational agricultural landscapes (IPCC, 2021; SMULEAC ET AL. 2017).

The convergence of remote sensing technologies and hydrological modelling offers a transformative approach (BEVEN, 2012) to overcome these limitations (ANDERSON ET AL., 2012). Remote sensing provides synoptic, frequent, and cost-effective observations of key biophysical variables. Sentinel-1 Synthetic Aperture Radar (SAR) data are highly sensitive to surface soil moisture, while Sentinel-2 multispectral imagery enables the derivation of various vegetation indices (e.g., NDVI, NDWI) that serve as proxies for crop vigour and water stress (DRUSCH ET AL., 2012) (figure 1). However, remote sensing alone primarily captures surface conditions and provides limited insight into root-zone soil moisture dynamics or the underlying hydrological processes governing water movement in the soil-plant-atmosphere continuum (ALLEN ET AL., 1998; ARNOLD ET AL., 2012; PAUNESCU ET AL. 2020).

Figure 1. Spatial variability of vegetation vigour derived from a remote sensing vegetation index

Hydrological models, such as the Soil Water Assessment Tool (SWAT), simulate the complete water balance, including infiltration, evaporation, plant transpiration, and deep percolation. While powerful, these models often suffer from parameter uncertainty and require extensive calibration data. The integration of remote sensing observations with hydrological modelling creates a powerful synergy: remote sensing data provide spatially distributed constraints for model calibration and validation, while the model extends the surface observations to profile soil moisture and offers predictive capability under different management scenarios (PENG ET AL., 2020; ȘMULEAC A. ET AL., 2021; HERBEI ET AL, 2018).

The central challenge this research addresses is the need for a comprehensive, spatially explicit methodology to evaluate how different irrigation practices (drip, sprinkler, flood) affect both the hydrological conditions (soil moisture distribution and dynamics) and the agronomic outcomes (crop health and productivity) (PAȘCALĂU ET AL., 2020). While previous studies have utilized either remote sensing or modelling in isolation, few have effectively coupled these approaches to conduct a holistic assessment of irrigation impacts (ȘMULEAC L. ET AL., 2020).

This research aims to develop and validate an integrated remote sensing-hydrological modelling framework to quantify the effects of irrigation practices on soil moisture and crop health (LI ET AL., 2022; POPESCU ET AL, 2019).

The research is guided by three key questions:

(1) How can multi-sensor remote sensing data be effectively used to characterize the spatial and temporal patterns of soil moisture and crop health under different irrigation regimes?

(2) To what extent can a hydrological model be calibrated using remote sensing data to simulate soil moisture dynamics and water fluxes in irrigated agricultural systems?

(3) What are the comparative impacts of different irrigation practices on water use efficiency, soil moisture stability, and crop performance, and how can these findings inform improved irrigation management? By addressing these questions, this research seeks to provide a scientifically robust and operationally relevant approach for optimizing irrigation water management in support of agricultural sustainability.

MATERIALS AND METHODS

1. Study area and data collection: The research was conducted in a 500 km² agricultural district characterized by heterogeneous irrigation practices (GOWDA ET AL., 2008; SMULEAC ET AL, 2012), including drip, sprinkler, and flood irrigation, with dominant crops of maize and wheat (figure 2). The data collection spanned two growing seasons (2022-2023) and involved:

Satellite data: time series of Sentinel-1 C-SAR (10m resolution, 6-day revisit) and Sentinel-2 MSI (10-20m resolution, 5-day revisit) imagery were acquired (PAȘCALĂU & ȘMULEAC, 2021).

Ground reference data: soil moisture was measured at 25 locations using calibrated TDR sensors, recording volumetric water content at 5, 20, and 40 cm depths bi-weekly. Crop parameters (Leaf Area Index, plant height) and irrigation records (timing, volume, method) were collected from cooperating farms.

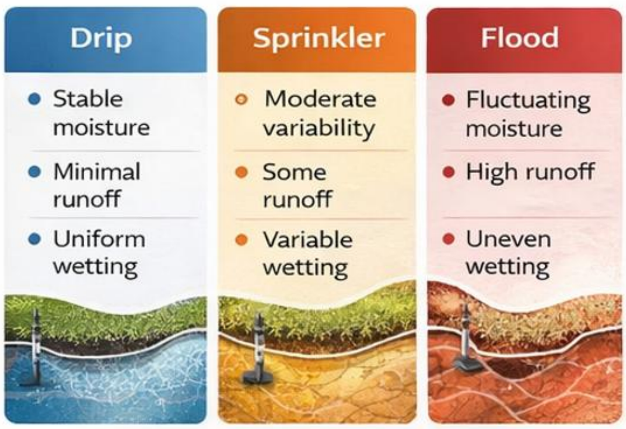

Figure 2. Study area and data collection

Ancillary data: soil maps, digital elevation model (DEM), land use/land cover map, and meteorological data (precipitation, temperature, solar radiation) were obtained.

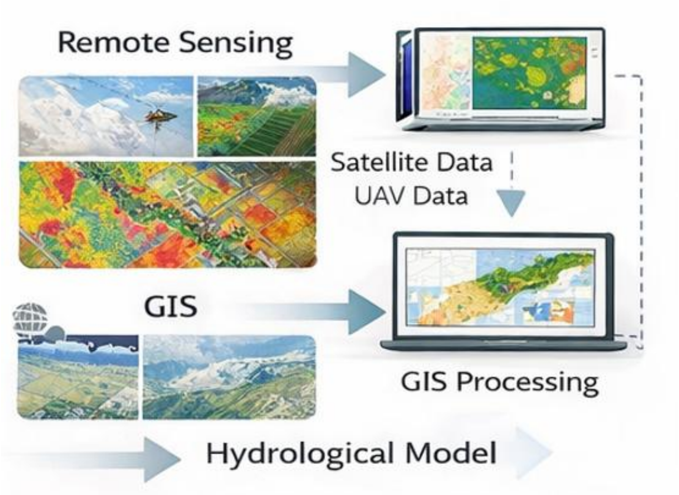

Figure 3. Workflow integrating remote sensing, GIS processing and hydrological modelling

2. Remote sensing analysis: soil moisture retrieval: Sentinel-1 SAR backscatter (VV, VH polarization) was processed using the Change Detection method to derive surface soil moisture (0-5 cm) maps, accounting for vegetation effects using the Water Cloud Model (HUETE ET AL., 2002, HERBEI ET AL, 2018).

Crop health indices: from Sentinel-2, the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) were computed to monitor crop vigour and water stress, respectively.

Spatial-temporal analysis: The derived maps were analysed to quantify the spatial variability and temporal evolution of soil moisture and crop health for each irrigation practice.

3. Hydrological modelling: The Soil Water Assessment Tool (SWAT) was set up for the study area. The model was configured to simulate the hydrologic cycle, including irrigation (figure 3).

Model setup: the watershed was delineated using the DEM and divided into Hydrologic Response Units (HRUs) based on soil, land use, and slope (ARNOLD ET AL., 2012; SMULEAC ET AL, 2020).

Integration with remote sensing: the remotely sensed soil moisture and LAI (estimated from NDVI) were used to constrain the model. A multi-objective calibration was performed using SWAT-CUP, optimizing parameters to match both simulated streamflow (at the watershed outlet) and spatially distributed soil moisture/LAI patterns.

Scenario simulation: the calibrated model was used to simulate soil moisture dynamics in the root zone (0-100 cm) and water balance components for different irrigation practices.

4. Impact assessment: the impact of irrigation practices was assessed by:

✓ Comparing the statistical distribution (mean, variance) of soil moisture and crop indices among irrigation types.

✓ Evaluating water use efficiency (WUE) as the ratio of crop productivity (estimated from NDVI) to actual evapotranspiration (simulated by SWAT).

✓ Identifying zones of water stress and waterlogging through the combined analysis of remote sensing and modelling results (SADRAS & CALDERINI, 2020; SMULEAC ET AL, 2020).

RESULTS AND DISCUSSION

Results

1.Remote sensing of irrigation impacts

The analysis of Sentinel-1 derived soil moisture revealed distinct patterns. Drip-irrigated fields showed the most stable temporal moisture profile with low spatial variability (CV = 15%), indicative of frequent, low-volume water application. Flood-irrigated fields exhibited a "feast-or-famine" cycle, with sharp peaks post-irrigation followed by rapid drying, and high spatial variability (CV = 45%) (PENG ET AL., 2020). Sprinkler systems showed an intermediate pattern. The NDVI from Sentinel-2 was consistently 15-20% higher in drip-irrigated fields during the mid-season, correlating with improved crop vigour. The NDWI, sensitive to canopy water content, confirmed less water stress in these fields (figure 4,5) (BASTIAANSSEN ET AL., 2000).

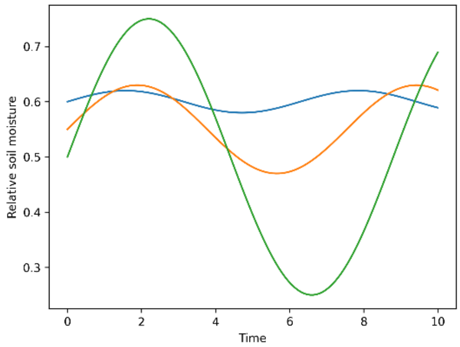

Figure 4. Conceptual soil moisture dynamics under different irrigation practices

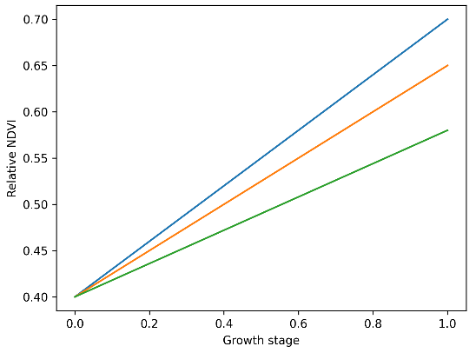

Figure 5. Conceptual trend of vegetation response (NDVI) during the growing season

2. Model performance and integrated analysis

The SWAT model, calibrated using the remote sensing constraints, performed well (Beven, 2012). The Nash-Sutcliffe Efficiency (NSE) for streamflow was 0.78, and the R^2 between simulated and remotely sensed surface soil moisture was 0.89. The integrated analysis revealed that drip irrigation achieved the highest water use efficiency (WUE = 2.8 kg/m³), followed by sprinkler (2.1 kg/m³) and flood irrigation (1.5 kg/m³). The model simulated that flood irrigation resulted in 30% of applied water being lost to deep percolation and surface runoff, compared to less than 10% for drip irrigation (figure 6).

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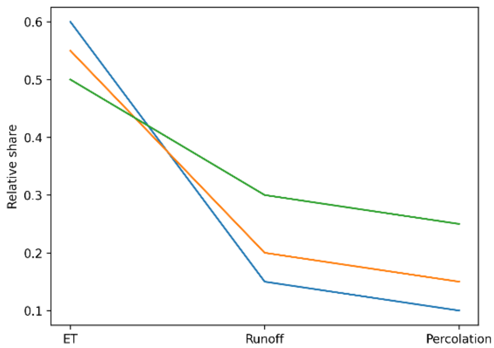

Figure 6. Conceptual comparison of main water balance components for the three irrigation systems

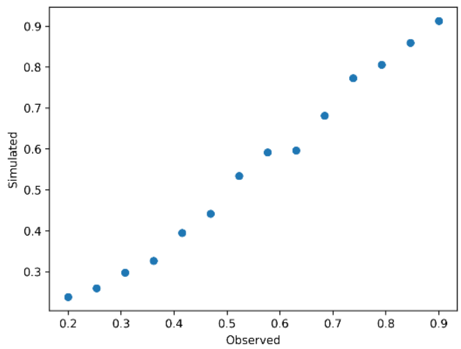

Figure 7. Conceptual relationship between simulated and observed soil moisture

3. Identification of inefficiencies

Spatial analysis (PAȘCALĂU ET AL., 2020) combining the model outputs and remote sensing indices identified that 35% of the flood-irrigated area consistently experienced either water stress (low soil moisture/NDWI) before the next irrigation cycle or waterlogging (saturated conditions) immediately after irrigation. These zones were often associated with subtle topographic variations that were not managed under uniform flood irrigation (figure 7).

Discussion

1. The synergy of remote sensing and modelling

The key strength of this research lies in the effective coupling of remote sensing and hydrological modelling. Remote sensing provided the crucial spatial detail that is impossible to obtain from point-based models alone, while the SWAT model provided the process-based understanding and the ability to simulate root-zone moisture, which is not directly accessible from SAR sensors. This synergy allowed for a more complete diagnosis of irrigation system performance, moving beyond surface observations to understand the fate of applied water in the soil profile.

2. Implications for irrigation management

The results provide quantitative evidence supporting the agronomic and hydrological superiority of drip irrigation in the research context. The high spatial variability and low WUE of flood irrigation highlight a significant opportunity for water savings and yield improvement. The identification of specific zones of stress and waterlogging within fields provides a direct map for targeted interventions, such as land levelling or the installation of drainage and more efficient irrigation systems. This moves irrigation management from a uniform, prescriptive approach to a precision, diagnostic one.

3. Towards operational deployment

The framework demonstrates potential for operational monitoring of irrigation performance at a regional scale. With the free and open data policy of the Sentinel fleet, such a system could be implemented by water user associations or agricultural extension services to benchmark irrigation efficiency, enforce water quotas, and guide infrastructure investments. Future work should focus on automating the data processing and model updating to provide near-real-time feedback to farmers. Challenges remain in regions with dense crop canopies that attenuate the SAR signal and in accurately quantifying actual water withdrawals for model initialization. Nevertheless, this integrated approach marks a significant step forward in the scientific support for sustainable water resources management in agriculture.

CONCLUSIONS

This research successfully demonstrates that the integration of multi-sensor remote sensing with hydrological modelling provides a robust, spatially explicit framework for assessing the impact of irrigation practices on soil moisture and crop health. The findings lead to several critical conclusions. Firstly, the combined approach effectively captures the spatial and temporal heterogeneity of irrigation impacts that are invisible to conventional monitoring methods, enabling a comprehensive comparison between different irrigation systems. The results unequivocally show that drip irrigation fosters superior soil moisture stability and crop health while significantly enhancing water use efficiency compared to traditional flood irrigation.

A paramount conclusion is the demonstrated value of using remote sensing data not just for standalone analysis, but as a powerful constraint for calibrating process-based hydrological models. This synergy overcomes the limitations of each method used in isolation, providing both the extensive spatial coverage of remote sensing and the deep process understanding from modelling. The validated model can subsequently be used to simulate scenarios, such as the impact of switching irrigation practices or adjusting scheduling, providing a predictive tool for water managers and policymakers.

The practical implications of this research are substantial. The ability to identify specific areas of water stress, waterlogging, and inefficiency within irrigated landscapes provides a direct evidence base for precision water management. This can guide infrastructure modernization, inform water allocation policies, and support the adoption of more efficient irrigation technologies. The methodology offers a scalable solution for monitoring irrigation performance across large agricultural regions, which is essential for sustainable water governance in the face of increasing water scarcity.

In conclusion, the integration of remote sensing and hydrological modelling represents a paradigm shift in how we monitor and manage agricultural water use. It transforms irrigation management from a reactive, uniform practice to a proactive, precision-oriented science. By providing detailed, objective, and timely information on the status and performance of irrigation systems, this approach empowers stakeholders to make informed decisions that conserve water resources, enhance crop productivity, and ensure the long-term sustainability of agricultural systems. Future efforts should focus on streamlining this integrated framework into user-friendly decision support systems to bridge the gap between advanced scientific methodology and on-the-ground agricultural water management.

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