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ADVANCES IN SOIL MOISTURE ESTIMATION THROUGH REMOTE SENSING AND GIS: A REVIEW

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ABSTRACT

Soil moisture estimation is a critical component of environmental management and agricultural planning. This review paper explores an extensive array of techniques and methodologies for soil moisture estimation, with a focus on the integration of Geographic Information Systems (GIS) and remote sensing. The review encompasses a spectrum of approaches, ranging from ground-based methods involving in-situ measurements, gravimetric techniques, and electrical measurements to advanced remote sensing technologies such as passive and active microwave remote sensing, optical and thermal remote sensing, and GIS-based integration. The comprehensive analysis includes detailed case studies that demonstrate the practical applications of these methods in diverse geographical regions and environmental conditions. As the world faces increasing challenges related to climate change and water resource management, accurate soil moisture estimation emerges as a vital tool. This review paper not only offers insights into the methodologies but also addresses the challenges and limitations associated with soil moisture estimation. It provides a valuable resource for researchers, environmental scientists, and policymakers working in fields where soil moisture plays a pivotal role in decision-making and resource allocation. The integration of GIS and remote sensing techniques presents a powerful approach for addressing the global demand for precise and timely soil moisture information in a changing world.

Keywords: Soil Moisture Estimation, Remote Sensing, GIS, Water Resource Management, Agricultural Planning

I. INTRODUCTION

Soil moisture is a crucial component of the Earth's hydrological cycle and plays a fundamental role in a wide range of environmental processes, ecosystems, and human activities. Soil moisture is defined as the amount of water present in the soil, typically expressed as a percentage of the soil's weight or as the depth of water in a specific soil layer. Accurate estimation and monitoring of soil moisture levels are essential for various scientific, agricultural, environmental, and engineering applications. Understanding the background and significance of soil moisture estimation is key to appreciating its role in modern research and practical applications.

Agriculture: Agriculture is heavily reliant on soil moisture information. It affects crop growth, yield, and quality. Farmers use soil moisture data to make informed decisions about irrigation, planting, and harvesting. Over-irrigation can lead to water wastage and environmental issues, while under-irrigation can reduce crop productivity. Soil moisture estimation enables precision agriculture, optimizing water use and maximizing agricultural output specifically arid and semi-arid regions like Saurashtra in Gujarat [1,2].

Weather and climate modelling: Soil moisture is a key driver of local and regional weather patterns [3]. Accurate data on soil moisture content are crucial for meteorological and climate models. They influence temperature, humidity, and precipitation patterns, impacting weather forecasts, flood predictions, and climate studies.

Water Resource Management: Water resource managers rely on soil moisture information to allocate water resources efficiently. Accurate data help ensure that water supply is adequate for various uses, such as agriculture water [4,5].

Drought monitoring and management: Droughts have severe socio-economic and environmental consequences. Monitoring soil moisture levels is a critical component of drought early warning systems. Timely data on soil moisture deficits can help authorities implement water conservation measures, manage water resources, and prepare for potential drought-related crises [6,7].

Erosion and Landslide Prediction: Soil moisture is closely related to soil stability. High soil moisture can lead to landslides and soil erosion, which can be hazardous to both the environment and human settlements. Monitoring soil moisture in vulnerable areas helps predict and mitigate such natural disasters and helps in selection of less erosion prone sites for water harvesting structures [8].

Environmental and Ecological Studies: Soil moisture is a critical factor for ecosystem health. It affects vegetation growth, wildlife habitats, and nutrient cycling. Ecologists and environmental scientists use soil moisture data to assess the impact of changing moisture levels on various ecosystems.

In light of these critical applications, the accurate estimation of soil moisture has become a central focus of research in fields such as hydrology, agriculture, environmental science, and geospatial technology.

Geographic Information Systems (GIS) have revolutionized the field of soil moisture estimation by providing a comprehensive framework for data integration, analysis, and visualization. GIS technology leverages spatial data to enable researchers and practitioners to better understand and manage soil moisture dynamics at various scales. One of the primary strengths of GIS is its capacity to integrate diverse datasets from various sources. In the context of soil moisture estimation, GIS facilitates the combination of data from multiple sensors, including remote sensing platforms (e.g., satellites, drones), ground-based measurements (e.g., soil moisture sensors), and meteorological data. Researchers can use GIS to perform spatial interpolation, modelling, and geostatistical analysis to predict soil moisture values at unmeasured locations based on the data available from neighbouring points. This helps create high-resolution soil moisture maps and identify patterns and trends in soil moisture content.

In addition to spatial analysis, GIS supports temporal analysis of soil moisture data. Time-series analysis is crucial for tracking changes in soil moisture over days, months, and years. Researchers can create models that incorporate a wide range of variables, including land cover, topography, precipitation, and temperature, to predict soil moisture content. These models aid in understanding the factors influencing soil moisture and can be used for forecasting and decision-making in agriculture, water resource management, and environmental conservation.

GIS has emerged as powerful tools for integrating and analyzing soil moisture data from various sources, making it possible to model and visualize soil moisture patterns at different spatial and temporal scales. As GIS technology advances, it provides researchers and decision-makers with new insights into soil moisture dynamics, offering opportunities to improve water resource management, enhance environmental conservation efforts, and better prepare for the challenges posed by a changing climate. This review paper will explore these advancements and their significance in the context of soil moisture estimation using GIS.

II. SOIL MOISTURE ESTIMATION METHODS

Ground-based methods

Ground-based methods involve the direct measurement of soil moisture at specific locations, providing accurate and reliable data for various applications. These methods are essential for validating and calibrating remote sensing data and for obtaining high-resolution information in areas of interest. Here's an overview of some commonly used ground-based soil moisture estimation methods:

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a. Gravimetric Method:

The gravimetric method is a direct and accurate way to measure soil moisture content. It involves collecting soil samples from the field, drying them in an oven, and weighing them to calculate moisture content. While this method provides precise measurements, it is labor-intensive and not suitable for continuous monitoring.

b. Tensiometers:

Tensiometers measure soil water tension, which is the negative pressure that plants need to overcome to extract water from the soil. This method is especially useful in agriculture for understanding the availability of water to plants. Tensiometers consist of a water-filled tube with a porous ceramic tip that is inserted into the soil. Tensiometer is shown in Figure 1. The tension in the tube is measured and used to determine soil moisture potential.

c. Soil Moisture Sensors:

Soil moisture sensors are devices designed to measure the volumetric water content of the soil, typically expressed as a percentage. These sensors are inserted into the ground at various depths and can be either invasive or non-invasive.

Invasive sensors, such as time domain reflectometry or frequency domain reflectometry (FDR), require direct contact with the soil and send electromagnetic signals to determine soil moisture. Non-invasive sensors, like capacitance sensors, measure soil moisture without physically contacting the soil and are often used for remote or continuous monitoring.

d. Time Domain Reflectometry (TDR):

TDR sensors measure soil moisture by sending electromagnetic pulses into the soil and analysing the time it takes for the pulses to travel through the soil. TDR provides accurate measurements at different depths and is widely used in research and environmental monitoring. Figure 2 demonstrates TDR meter.

e. Dielectric Sensors:

Dielectric sensors, such as capacitance and impedance probes, measure soil moisture by assessing the dielectric constant of the soil, which is related to its moisture content. Typical dielectric sensor is shown in Figure 3. These sensors are non-invasive, easy to install, and suitable for continuous monitoring.

f. Neutron Probe:

Neutron probes are used to measure soil moisture by emitting fast neutrons into the soil. The return of thermalized neutrons is detected and used to estimate soil moisture content. Neutron probes can measure soil moisture at various depths and are particularly useful in research and agricultural applications. Neutron probe in action measuring soil moisture is shown in Figure 4.

g. Cosmic-Ray Neutron Probes:

Cosmic-ray neutron probes measure soil moisture indirectly by detecting neutrons produced by cosmic rays interacting with the Earth's atmosphere. These probes are capable of providing soil moisture information over large areas and have gained popularity in agricultural and environmental studies.

Figure 1: Tensiometer

Figure 2: TDR

Figure 3: Dielectric sensor

Figure 4: Neutron probe

Ground-based methods for soil moisture estimation offer advantages in terms of accuracy and validation of remotely sensed data. However, they have limitations, including the need for local installation and the challenge of obtaining data over larger spatial scales. Often, these ground-based methods are integrated with Geographic Information Systems (GIS) to provide a comprehensive understanding of soil moisture dynamics at different depths and locations.

Remote sensing techniques

Soil moisture estimation using remote sensing techniques has become increasingly important in environmental and agricultural research due to its ability to provide valuable spatial and temporal information over large areas. Remote sensing methods allow for the non-invasive measurement of soil moisture from satellites, aircraft, or drones, providing a synoptic view of soil moisture patterns. Here's an overview of some common remote sensing techniques used for soil moisture estimation:

a. Optical and Infrared Remote Sensing:

Optical and infrared sensors on satellites capture data in the visible and infrared spectra, which can indirectly provide information about soil moisture content [9,10]. Vegetation health and land surface temperature are often used as indicators of soil moisture. These sensors are valuable for monitoring vegetation stress and can be combined with other sources of data to estimate soil moisture indirectly.

b. Thermal Infrared Remote Sensing:

Thermal infrared sensors on satellites measure the surface temperature of the Earth. Soil moisture affects the surface temperature, as wet soil cools the surface through evaporation, while dry soil retains heat [11]. Thermal infrared remote sensing can be used to estimate soil moisture indirectly by assessing temperature variations.

c. Hyperspectral Imaging:

Hyperspectral sensors capture a wide range of wavelengths in the electromagnetic spectrum. They can be used to identify spectral signatures associated with soil moisture content. Hyperspectral data can be combined with other information, such as vegetation indices, to estimate soil moisture more accurately.

d. Unmanned Aerial Vehicles (UAVs):

Drones equipped with various sensors, including multispectral and thermal cameras, are increasingly used for high-resolution soil moisture estimation. UAVs can provide flexible and cost-effective data collection for research and applications such as precision agriculture.

e. Passive Microwave Remote Sensing:

Passive microwave remote sensing involves the measurement of natural microwave radiation emitted by the Earth's surface and the interaction of this radiation with the soil. Microwave frequencies are sensitive to soil moisture, and the technique is particularly useful for monitoring soil moisture content at deeper soil layers [12]. Satellites like the Soil Moisture and Ocean Salinity (SMOS) and the Advanced Microwave Scanning Radiometer 2 (AMSR2) are examples of platforms that use passive microwave remote sensing to estimate soil moisture.

f. Active Microwave Remote Sensing:

Active microwave remote sensing systems, like radar and synthetic aperture radar (SAR), emit microwave pulses and measure the backscattered energy. SAR sensors are known for their ability to provide high-resolution images and are used for a wide range of applications, including soil moisture estimation. Radar-based techniques can be sensitive to the surface roughness and vegetation cover, which can complicate soil moisture estimation [13]. However, they are useful for monitoring soil moisture changes over time.

g. L-band Radiometry:

L-band radiometers operate in the microwave part of the electromagnetic spectrum and are sensitive to soil moisture variations in the upper soil layers. The NASA Soil Moisture Active Passive (SMAP) mission uses L-band radiometry to provide soil moisture data at a spatial resolution of about 36 kilometers.

Remote sensing techniques offer several advantages, including the ability to monitor soil moisture over large and remote areas, provide regular and frequent data acquisition, and capture information at various spatial and temporal scales. These methods are especially valuable for applications such as precision agriculture, flood prediction, crop evapotranspiration and environmental management [14,15]. The integration of remote sensing data with Geographic Information Systems (GIS) allows researchers and decision-makers to analyze, visualize, and model soil moisture patterns in a geospatial context, providing valuable insights for a wide range of fields, from agriculture and water resource management to climate studies and disaster preparedness.

III. DATA SOURCES AND INPUT DATA

Various types of data are used for soil moisture estimation, and these data sources are integrated to create comprehensive models and assessments. Here's an overview of the types of data commonly used in soil moisture estimation:

Remote Sensing Data:

- **Optical Imagery:** Optical sensors on satellites provide data on land cover, vegetation health, and other surface characteristics that can be used as indicators of soil moisture.
- **Microwave and Thermal Imagery:** Remote sensing satellites, such as those equipped with synthetic aperture radar (SAR) or thermal infrared sensors, capture data that can be used to estimate soil moisture. Microwave frequencies are sensitive to soil moisture content, while thermal imagery can indirectly provide information about soil moisture through surface temperature analysis.

Meteorological Data:

- **Precipitation:** Precipitation data, including rainfall and snowfall, are critical for understanding the input of water into the soil system.
- **Temperature:** Temperature data influence the evaporation rate, which in turn affects soil moisture levels.
- **Wind Speed and Solar Radiation:** These factors influence evapotranspiration and play a role in the water balance equation.

Land Cover and Land Use Data:

Information on land cover and land use helps characterize the type of vegetation and surface properties in a given area [16]. Different land cover types have varying impacts on soil moisture dynamics.

Topographical Data:

Elevation and slope data are essential for understanding how water flows across the landscape and how it may accumulate or drain in certain areas, affecting soil moisture levels.

Soil Properties Data:

Soil properties, such as soil texture, porosity, and hydraulic conductivity, influence the soil's capacity to hold and transport water. These data are crucial for modeling soil moisture dynamics.

Vegetation Indices:

Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), provide information on vegetation health and cover [17], which can indirectly indicate soil moisture levels.

IV. APPLICATIONS AND CASE STUDIES

Remote sensing techniques have become invaluable tools for estimating soil moisture levels. This section showcases practical applications of soil moisture estimation methods, featuring case studies that highlight the real-world significance of GIS and remote sensing techniques in environmental management, agriculture, and resource allocation. Various advancements in soil moisture estimation using remote sensing and GIS are summarised through recent studies in Table 1. These studies offer insights into the operational impact of soil moisture data in diverse contexts and geographical regions.

Table 1. Recent studies in soil moisture estimation using remote sensing and GIS

Ref.	Objectives	Techniques Used	Results	Details
[12]	Explore multiscaling properties of soil moisture fields and compare passive	Passive microwave remote sensing at 200-m resolution	Successful use of passive microwave remote sensing for soil moisture	Unique perspective on soil moisture estimation using passive microwave remote

	microwave remote sensing with field measurements		determination	sensing
[18]	Estimate surface soil moisture using pedotransfer functions (PTF) and spectral indices	11 PTFs combining basic soil properties, machine learning methods (RF, MLR)	RF method had higher accuracy compared to MLR method	Value of combining soil properties and spectral data for improved soil moisture estimation
[17]	Examine trends in NDVI and its correlation with environmental variables using MODIS data	MODIS/TERRA-derived NDVI, observed correlations with LST, soil moisture, and precipitation	NDVI sensitivity to LST (-0.45) compared to soil moisture (r = 0.43) and precipitation (r = 0.341)	Sensitivity of NDVI to LST and its potential as a vegetation index for monitoring environmental variables
[9]	Explore the applicability of spectral indices for soil moisture estimation in farmland	Random forest classifier, spectral bands, red edge, SWIR bands	Red edge and SWIR bands improved soil moisture estimation, SMMI performed the best	Impact of different spectral indices on soil moisture estimation and effective index selection
[19]	Estimate surface soil moisture using supervised machine learning algorithms	Multilayer Perceptron (MLP), Neural Network (NN), linear regression models, Sentinel-1 and Sentinel-2 data	NN yielded the best results, RMSE of 0.0292 (cm3/cm3) and R^2 of 0.92	Demonstrated potential of machine learning algorithms for soil moisture estimation, accurate across different crop types
[13]	Estimate topsoil soil moisture using multi-temporal Sentinel-1 and Landsat 8 satellite images	Backscattering coefficient, NDVI, thermal infrared, Artificial Neural Networks (ANNs)	ANNs yielded R^2 values between 0.7 and 0.9	Showcased potential of remote sensing and ANNs for improved soil moisture estimation
[20]	Develop an integrated methodology for soil moisture estimation in Mongolia	Multispectral satellite data, LST, NDVI, DEM, regression analysis	Good agreement between model output and ground-truth soil moisture data for agricultural area	Effective integration of various satellite data sources and terrain information for soil moisture estimation
[16]	Investigate factors influencing land surface temperature and its relationship with soil moisture	Landsat-8 data, LST, land-use/land-cover, elevation, vegetation coverage	LST influenced by various factors, highlighting complexity of soil moisture estimation	Highlighted importance of considering diverse environmental variables for accurate soil moisture estimation
[21]	Assess flood and drought conditions using remote sensing data and a soil moisture	Soil moisture index (SMI) calculated from multispectral satellite images	Potential of remote sensing in monitoring floods and droughts	Emphasized remote sensing for monitoring extreme weather conditions like floods

	index			and droughts
[22]	Evaluate daily soil moisture simulations and their correlation with Landsat data	Thermal Vegetation Difference Index (TVDI) from Landsat, simple linear regression model	Good agreement between data sources, especially during dry periods	Correlation between remote sensing-based vegetation indices and in-situ soil moisture data
[10]	Investigate soil moisture variability in Alabama using the Moisture Stress Index (MSI)	MSI developed from Landsat 8 OLI and Landsat 5 TM data, simple linear regression model	MSI correlated well with soil moisture at 20 cm depth, efficient soil moisture estimation	Highlighted the correlation between MSI and in-situ data for soil moisture estimation
[23]	Quantify the effectiveness of spectral images for soil moisture estimation	Artificial Neural Network (ANN) model, input variables: visual spectrum, NIR, thermal, vegetation indices	RMSE of 2.0, MAE of 1.8, R^2 of 0.77	Leveraged spectral data and vegetation indices for effective soil moisture estimation
[24]	Estimate soil moisture using MODIS-derived indices	Remote sensing indices (NDVI, NDMI, LST) derived from MODIS data	Reasonable correlation (0.66) with soil moisture	Demonstrated value of MODIS-derived indices for soil moisture estimation, especially with limited ground-truth data

These detailed case studies allow for a comprehensive analysis of the various techniques, objectives, results, and their implications in the context of soil moisture estimation and environmental monitoring. Researchers and practitioners can gain a deeper understanding of the strengths and limitations of different approaches and their potential applications.

V. CHALLENGES AND LIMITATIONS

Soil moisture estimation using GIS and remote sensing techniques, while valuable, faces several challenges and limitations:

Spatial and Temporal Resolution: Striking a balance between spatial and temporal resolution in satellite data can be challenging, impacting local-scale monitoring.

Inaccurate Ground Truth Data: Limited or inaccurate ground measurements can introduce errors in remote sensing models.

Variability in Land Covers: Diverse land cover types require adaptable models to account for differing relationships between spectral indices and soil moisture.

Vegetation Influence: Dense vegetation can affect optical data, making accurate soil moisture estimation challenging.

Data Fusion and Integration: Integrating data from multiple sources may require complex algorithms for compatibility.

Limited Ground-Based Monitoring: In regions with sparse ground data, model calibration and validation can be hindered.

Model Generalization: Ensuring models perform well across varied conditions is an ongoing challenge.

Climate and Seasonal Variability: Seasonal changes and climate variations impact soil moisture relationships.

Model Complexity: Complex models may require substantial computational resources.

Data Access and Cost: Data accessibility and costs can be limiting factors.

Validation and Ground Truth Data: Collecting accurate ground truth data is labour-intensive and costly.

Cross-Calibration and Data Harmonization: Ensuring compatibility between datasets from different sources can be challenging.

Addressing these challenges is crucial for advancing soil moisture estimation while ensuring its practicality for various applications. Collaboration and data sharing can help overcome some limitations.

VI. INSIGHTS

The wealth of information gathered from these studies allows us to draw several important conclusions and insights:

Multi-Faceted Approach: The studies demonstrate the multi-faceted approach to soil moisture estimation, utilizing a combination of remote sensing data, GIS, and various indices to enhance the accuracy of predictions.

Effective Use of Satellite Data: Satellite imagery, such as Landsat and Sentinel series, plays a significant role in these studies. It offers a rich source of information for assessing soil moisture, especially in large-scale and remote areas.

Integration of Environmental Variables: Many case studies highlight the importance of considering various environmental variables, such as land surface temperature, vegetation indices, and terrain information, in soil moisture estimation models. These variables have a profound impact on soil moisture levels and should not be overlooked.

Machine Learning Techniques: Machine learning algorithms, particularly Artificial Neural Networks (ANNs) and Random Forest, have proven to be effective in enhancing the accuracy of soil moisture estimation models. They exhibit the ability to adapt and learn from complex data relationships.

Role of Vegetation Indices: Vegetation indices, including NDVI and NDWI, have been leveraged in several studies to assess soil moisture levels. These indices, based on remote sensing data, are instrumental in understanding the moisture content of different land covers.

Drought Monitoring and Agriculture: Several case studies emphasize the relevance of soil moisture estimation in the context of drought monitoring and agriculture. The development of location and crop-specific composite drought indices (CDI) demonstrates the practical applications of this research in real-world scenarios.

Advancements in Remote Sensing: The studies showcase the evolution of remote sensing techniques, particularly the use of passive microwave remote sensing for soil moisture determination. These advancements contribute to more accurate and timely monitoring.

Data Integration and Fusion: The integration of various data sources, including satellite images, ground measurements, and environmental data, reflects the importance of data fusion in improving soil moisture estimation models.

Potential for Further Research: The reviewed studies provide a foundation for future research in the field of soil moisture estimation. There is scope for exploring more advanced machine learning techniques, incorporating high-resolution satellite data, and expanding the applications in different regions and land cover types.

VII. CONCLUSION

The review paper has explored a wide array of techniques and case studies related to soil moisture estimation using GIS and remote sensing. In conclusion, the combination of GIS and remote sensing techniques offers a powerful means to estimate soil moisture levels. These techniques are valuable for various applications, including agriculture, drought monitoring, and environmental management. The reviewed case studies shed light on the versatility and advancements in this field, while also indicating the potential for further research to refine and expand these methods. Accurate soil moisture estimation is an essential component of environmental management and plays a vital role in addressing the challenges posed by a changing climate.

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