Vol 8, Issue 11, 2025 **Impact Factor: 8.535** DOI: https://doi.org/10.31426/ijamsr.2025.8.11.8916

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**International Journal of
Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281**

# Monitoring Soil Quality Using Microwave Remote Sensing Technologies

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**ABSTRACT**

Monitoring the quality of soil is essential for the purpose of sustainable land management and maximizing agricultural productivity. This research examines the current state of microwave remote sensing methods (both active and passive) for evaluating soil quality parameters, including soil salinity, soil erosion, soil physical qualities (such as soil texture and hydraulic capabilities, as well as drainage condition), and soil surface roughness. Microwave remote sensing provides distinct benefits, including the ability to operate in all weather conditions and the capacity to detect soil moisture and texture. These advantages make it an indispensable instrument for monitoring soil quality. The study investigates the integration of microwave data with other remote sensing modalities and ground-based measurements to improve precision and dependability.

***Keywords:*** *Soil, Microwave, Texture, Salinity, Roughness.*

## I. INTRODUCTION

A non-invasive, efficient, and accurate way to monitor and analyze diverse soil parameters, microwave remote sensing has emerged as a vital technique in soil quality evaluation. Using microwaves, which are a part of the electromagnetic spectrum and usually range from 1 GHz to 100 GHz, this method may go into the soil and get useful information about its makeup, moisture level, and other important properties. Soil scientists, agronomists, and environmentalists now have access to cutting-edge tools that have the potential to transform our understanding of soil health, agricultural output, and ecological sustainability. Among microwave remote sensing's many benefits is its capacity to see through surface materials and plants to the soil below. This is especially helpful in areas where there is a lot of vegetation, as regular optical remote sensing techniques might not be able to collect good soil data. Continuous soil monitoring is made possible by microwave sensors like Synthetic Aperture Radar (SAR), which can function in a variety of weather situations, including cloud cover and rainfall. Soil quality evaluation relies on accurate and consistent data, and its all-weather capacity makes sure that data collection doesn't be stopped by bad weather.

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Nutrient availability, microbial activity, and plant development are just a few of the soil qualities and activities that are affected by soil moisture content, making it an important metric for evaluating soil quality. Because microwaves are very sensitive to the dielectric characteristics of water, they have shown to be an excellent tool for monitoring soil moisture by remote microwave sensing. Microwave sensors are able to detect changes in soil moisture content, which occur at a rapid rate of change in the dielectric constant. Soil moisture estimations derived from active microwave sensing (e.g., SAR) and passive microwave radiometry are widely utilized in agricultural management, drought monitoring, and hydrological modeling. Microwave remote sensing can learn more than just soil moisture; it can also tell you about the structure, texture, and surface roughness of the soil. A soil's capacity to hold water and nutrients is influenced by its texture, which is defined as the relative amounts of sand, silt, and clay particles. Microwave backscatter and polarization analysis can help classify and map different types of soil by inferring its structure and texture. Planning land use, choosing crops, and soil conservation all rely on this data.

Another crucial soil component that affects microwave signal scattering is surface roughness. Soil erosion, tillage methods, and land degradation can all be revealed by changes in surface roughness. Soil management techniques and their effects on soil health can be better understood by tracking these variations over time and evaluating changes in microwave backscatter. For precision agriculture, where better use of resources and less impact on the environment can result from up-to-the-minute data on soil conditions, this skill is invaluable. To further improve its applicability in soil quality evaluation, microwave remote sensing may be integrated with other remote sensing technologies and ground-based measurements. By integrating microwave data with multispectral and hyperspectral imaging, a thorough comprehension of soil processes and characteristics may be achieved. For example, optical sensors may gather data on the condition of the plant, the organic matter in the soil, and the mineral composition, whereas microwave sensors are great at gauging soil moisture and texture.

## II. REVIEW OF LITERATURE

M. Vreugdenhil, et al., (2022) Agricultural droughts are severe occurrences that frequently arise from the interactions of several hydro-meteorological phenomena. Thus, evaluating the presence, magnitude, length, and severity of drought is intricate and necessitates the simultaneous use of several factors, including temperature, precipitation, soil moisture (SM), and vegetation condition. The advantage of utilizing data on social media and vegetation condition is that they incorporate information on precipitation, temperature, and evapotranspiration, rendering them direct indicators of the availability of water for plants and the productivity of vegetation. Microwave remote sensing allows for the collection of both soil moisture (SM) and vegetation data. Satellite-based SM and vegetation products are readily accessible and provided at no cost on a regional or global level, with updates available daily. Consequently, microwave remote sensing solutions are becoming increasingly crucial in applications related to monitoring drought. In this article, we present a summary of the latest advancements in utilizing microwave remote sensing to monitor agricultural drought on a broad scale. Our main focus is on closely monitoring the intricate process of drought development by analyzing different variables. Initially, we provide a concise explanation of the basic

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**International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281**

principles of microwave remote sensing, along with a summary of current advancements, progress, and practical uses of drought indicators obtained from satellite-based soil moisture and vegetation observations using microwave technology. Subsequently, a comprehensive examination of the existing research deficiencies and obstacles in integrating microwave-based soil moisture (SM) and vegetation measurements with hydro-meteorological data sets is presented. The efficacy of utilizing microwave remote sensing for drought monitoring is exemplified through a case study conducted in Senegal, employing several satellite- and model-derived datasets pertaining to rainfall, soil moisture, vegetation, and their respective combinations. The case study illustrates the enhanced use of microwave-based soil moisture (SM) and vegetation observations in the context of drought monitoring applications. Lastly, we present a perspective on possible advancements and prospects.

Xie, Qiuxia et al., (2021) The SMAP (Soil Moisture Active and Passive) satellite, with a grid resolution of 9 km, the ASCAT (Advanced Scatterometer) satellite, with a grid resolution of 0.1D (Degree), and the FY-3B and ESA-CCI (European Space Agency-Climate Change Initiative) satellites, with a grid resolution of 25 km, are commonly utilized for various applications such as drought monitoring and evapotranspiration estimation. Prior to use, it is crucial to assess these satellite SM products. This study utilized both point-scale in-situ soil moisture measurements and area-scale airborne soil moisture data with a grid resolution of 1 km to evaluate the performance of SMAP, ASCAT, FY-3B, and ESA-CCI satellite soil moisture products in the Shandian river basin of Inner Mongolia in September 2018. The evaluation was conducted using various assessment indices such as RMSE (Root Mean Square Error), R (Correlation Coefficient), MAE (Mean Absolute Error), Bias, and ubRMSE (unbiased Root Mean Square Error). This study successfully conducted an evaluation process that involved transitioning from point-scale in-situ soil moisture (SM) measurements to area-scale (1 km×1 km) airborne SM data, and further to area-scale (9 km×9 km, 0.1 D×0.1 D, 25 km×25 km) satellite SM products. The airborne SM data served as a bridge between the in-situ SM measurements and the satellite SM products. The findings indicated that in areas with bare soil, the airborne soil moisture (SM) measurements were more closely aligned with the in-situ SM measurements. The root mean square error (RMSE), mean absolute error (MAE), bias, unbiased root mean square error (ubRMSE), and correlation coefficient (R) values were 0.033 $cm^3/cm^3$, 0.030 $cm^3/cm^3$, -0.004 $cm^3/cm^3$, 0.033 $cm^3/cm^3$, and 0.474, respectively. The SMAP satellite SM product exhibited greater consistency with in-situ SM measurements compared to ASCAT, FY-3B, and ESA-CCI satellite SM products. The RMSE, MAE, Bias, ubRMSE, and R values were 0.037 $cm^3/cm^3$, 0.032 $cm^3/cm^3$, -0.008 $cm^3/cm^3$, 0.036 $cm^3/cm^3$, and 0.507, respectively.

Verma, Ashish et al., (2017) Discussed in this study is the topic of microwave remote sensing. Specific soil properties for agricultural use. The interplay between the soil's physical, chemical, and biological components determines the soil's quality. Soil is composed of various physical, chemical, and electrical properties. Physical properties include things like color, texture, grain size, bulk density, etc. Chemical properties include things like nutrients, organic matter, pH, and so on. Meanwhile, electrical properties include things like dielectric constant, electrical conductivity, and permeability. As more is known about soils and the characteristics that make them good for gardening, the idea of soil health and quality has developed over time. The scattering cross-section

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grows larger with increasing frequency and shrinks with decreasing visibility. Radiation intensity from soil is exactly proportional to stimulating field frequency, as has also been shown. As a result, the total loss of energy varies as the frequency increases due to the rise in scatters and radiation.

Das, Kousik & Paul, Prabir. (2015) Soil moisture distribution in space and time is an important parameter in hydrology and meteorology because it affects the fluxes of water and energy at the interface between the land surface and the atmosphere. For many large-scale environmental research, it is crucial to have an accurate assessment of the spatiotemporal fluctuations of soil moisture. Soil moisture may be monitored using a number of remote sensing techniques, each with its own strengths and weaknesses, which minimizes the ill-posed traditional difficulties. This has been demonstrated by recent technical improvements in satellite remote sensing. Soil moisture assessment at the field and catchment size is still a challenge for SAR, but new methods and technologies like multi-configuration radar and upcoming SAR constellations are helping to address this. This study provides an in-depth analysis of a handful of chosen soil moisture inversion methods, with an emphasis on the methodology behind active and passive microwave measurements, as well as the variables that influence the microwave return. A synopsis of the underlying physical and theoretical concepts, as well as the present state of fundamental retrieval methods, is provided. We have addressed the limitations of the existing algorithms for soil moisture estimate and analyzed the important parameters that influence the backscattering coefficient, such as radar configurations (polarization, incidence angle, and frequency of bands) and soil surface properties.

Lakhankar, Tarendra et al., (2009) Most of the freshwater resources are used for agricultural irrigation, accounting for 80% of the total. Making the most efficient use of water resources while simultaneously boosting agricultural output is crucial in light of the growing demand for freshwater. This may be achieved with the use of objective and precise data collected by remote sensing. In this study, we take a look at the possible uses of microwave remote sensing for agriculture, specifically looking at soil moisture and vegetation. Because there is a significant difference between the dielectric constant values of dry and wet soils, microwave remote sensing can be utilized to determine soil moisture. Preventing water stress and increasing production during crop growth phases can be achieved by monitoring the water availability at the soil root zone in real time. Precision agriculture makes greater use of high-resolution soil moisture data for irrigation scheduling at field sizes. On a bigger scale, low-resolution soil moisture data may be utilized to track and forecast crop yield in place of vegetation index. To monitor the distribution, health, and water demands of plants for agricultural purposes, microwave remote sensing might be a viable alternative to VIS/IR hyper spectral data, as microwaves can penetrate clouds.

## III. ASSESSMENT OF SOIL QUALITY PARAMETERS

### Soil Salinity

One of the main issues with soil deterioration that affects crop development and yields is soil salinity. In order to recover salt-affected soils, it is essential to determine their location, extent, type, and severity. Optical remote sensing data can be used to demarcate salt-affected soils, but this becomes more challenging in coastal and desert regions, as well as in the black clay-rich soils region, due to spectral mixing with sand and poor spectral contrast.

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It is well-known that radar is quite sensitive to a number of surface characteristics, including surface roughness, vegetation, and dielectric constant (e). The real component, the permittivity, and the imaginary component, the loss factor, make up the dielectric constant. Based on the research, it was found that the real component of the dielectric constant (ε') is unaffected by soil salinity, while the imaginary part (ε") is reliant on and grows with increasing salinity for all three types of soil textures. To map soil salinity, Bell et al. (2001) utilized the airborne polarimetric SAR. To improve the estimate of the magnitude of the imaginary part of the complex dielectric constant for soil salinity discrimination, three dielectric retrieval algorithms were used: SPM (Small Perturbation Model), PO (Physical Optics), and DM (Dubois Model). A research case study utilized spatial soil salinity variation mapping in portion of the Unao district of Uttar Pradesh using temporal Envisat polarimetric SAR data (VV & HH). The magnitude of the imaginary component of the complex dielectric constant for soil salinity class discrimination and mapping was retrieved by combining the findings of three dielectric constant retrieval techniques, including SPM and PO DM (Figure 1).

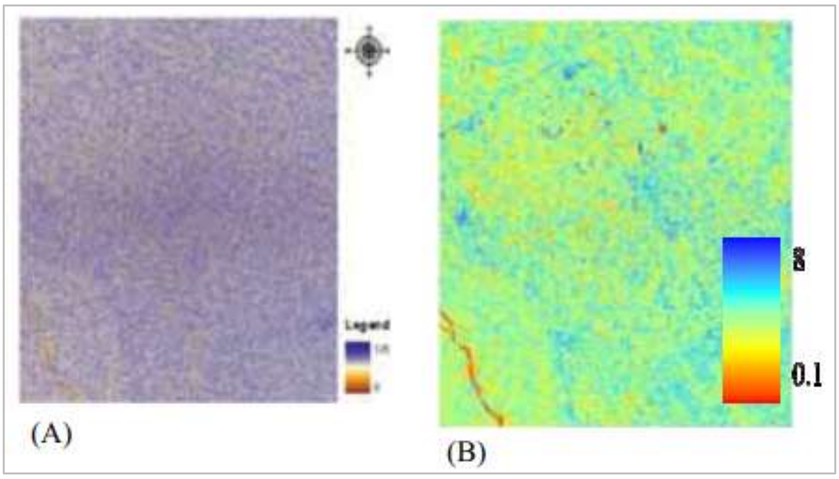


**Figure 1: (A) Imaginary Part of Dielectric Constant (B) Soil Electric Conductivity (EC) Map**

## Ravine Erosion Inventory

Optical multispectral and high-resolution panchromatic data are commonly used to identify and map areas that have been severely eroded, including those damaged by ravines. This mapping involves categorizing the eroded areas into several depth categories, mostly by visual interpretation of the picture properties. Nevertheless, these procedures are of a qualitative character. Microwave synthetic aperture radar (SAR) is highly sensitive to terrain ruggedness and the ability to penetrate vegetation, particularly sparse bushy vegetation and grasses. This makes microwave remote sensing techniques, such as SAR data and interferometric SAR (InSAR), advantageous for accurately mapping and describing ravines in terms of their density, depth, and surface cover.

## Sand Dune Characterization

Many desert regions are covered with sand dunes, which can extend up to a quarter of their whole area. Distributed around the edges of the desert are both permanent and semi-fixed sand dunes, while the movable dunes are generally found in the central region of the deserts. Understanding the dune

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features is crucial for comprehending environmental changes in dry places. Desert environments are often characterized by limited accessibility. Hence, remotely sensed data become highly valuable in monitoring arid settings.

Blumberg (1998) examined the shape and structure of windblown features in desert environments using polarimetric synthetic aperture radar (SAR). Qong (2000) derived sand dune characteristics using satellite Synthetic Aperture Radar (SAR) data from JERS-1 and ERS-1. This work focused on analyzing the radar backscattering from the surfaces of linear dunes in order to determine dune properties, including dune height, inter dune distance, and dune orientation. These research shown that the height of dunes may be reliably calculated by utilizing the Root Mean Square (RMS) slope parameter generated from Synthetic Aperture Radar (SAR) satellite data. Typically, two methods are used to calculate the RMS slope parameter from SAR backscatter images. The first method involves creating an image that displays the difference in local incidence angle, which corresponds to the variation in backscatter and radar incidence angle. The second method involves using Fast Fourier Transformation (FFT) to generate a power spectrum (Figure 2). The spectrum obtained from the JERS-1 SAR picture had many prominent peaks, and the middle portion of these peaks corresponded to the prevalent wind direction in the area. The distance between the dunes was determined by calculating the wave number k of the spectra. The dune heights obtained from the current technique corresponded rather well with the dune heights observed during the field research.

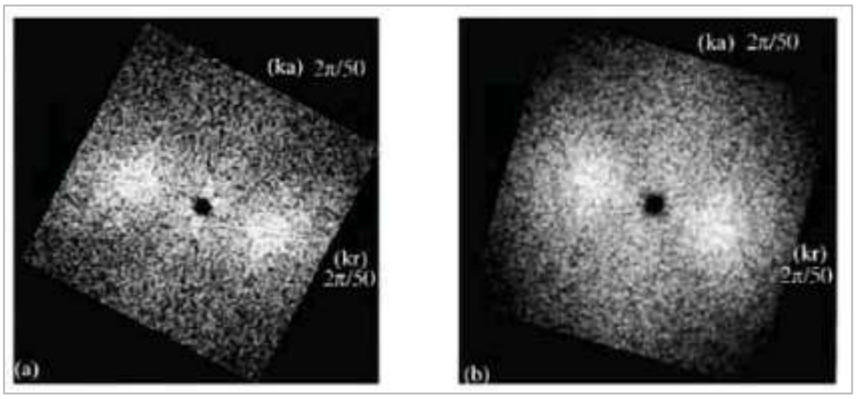


**Figure 2: 2D Linear Dune Wave Number Spectra From JERS-1 SAR and AMI**

**Soil texture and Hydraulic Properties**

Efficient management of soil resources for improving crop productivity, maintaining environmental quality, and developing reliable models of water flow and transport throughout the soil-plant-atmosphere continuum all require an accurate estimation of spatially variable soil physical properties like hydraulic properties and texture. Soil physical property measurements are labor- and cost-intensive. To add insult to injury, their space-time variability cannot be adequately measured without collecting a mountain of data.

One crucial soil parameter, Ksat, or saturated hydraulic conductivity, is notoriously difficult to measure outside of a controlled laboratory setting. Thus, any remote sensing-based approaches that can determine the geographical distribution of Ksat would constitute a crucial data source for

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hydrologic applications. They looked at how variations in microwave brightness temperature affected soil moisture and how that correlated with the harmonic mean Ksat of the soil profile, as predicted by hydrologic models.

Harmonic mean profile Correlation values of 0.77 for a depth of 5 cm, 0.83 for a depth of 30 cm, and 0.68 for a depth of 60 cm indicate a substantial positive link between Ksat and variations in surface soil moisture over two days (Figure 3). The findings showed that total moisture content changes were larger in loam and silt loam soils, and lower in sandy loam and sandy soils. It is possible that the hydraulic qualities of the soil are associated with these features. Loamy soils have a lower hydraulic conductivity and drain more slowly than sandy soils, which have a greater hydraulic conductivity.

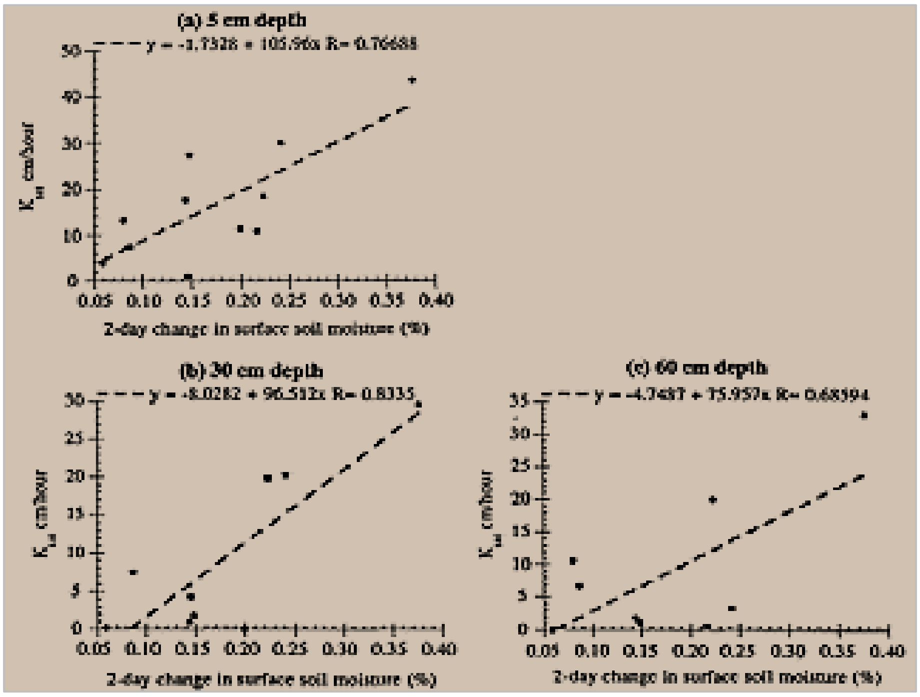


**Figure 3: Relationships Between Profile Harmonic-Mean Ksat Derived from Hydrologic Model Simulations and Two-Day Initial Changes in Surface Soil Moisture Obtainable from Microwave Remote Sensing**

## Soil Drainage

Soil drainage is a crucial soil property because it influences plant development, water movement, and the transfer of solutes in soils. The term "drainage" describes the soil's inherent capacity to let water soak in and seep through. Soil map users typically want data on soil characteristics or soil behavior, not taxonomic groups, when making decisions about land use and management, which is why drainage mapping is interesting. Used in microwave remote sensing. Soil surface roughness and dielectric constant determine the magnitude of radar backscattering from soil surfaces. The dielectric constant, on the other hand, is somewhat affected by the textural composition of the soil and is highly reliant on the soil moisture level. Soil drainage and other soil parameters might be mapped using radar remote sensing.

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**Soil Surface Roughness**

Soil thermal characteristics, infiltration rate, surface runoff, and soil erosion susceptibility are all affected by soil surface roughness (SSR). Natural and man-made processes, such as tillage, erosion, rainfall impact, physical crusting, and other similar events, can cause SSR to vary spatially and temporally. The root-mean-square (rms) standard deviation of surface height defines the vertical scale of roughness and the correlation length (L) represents the horizontal scale over which similar (correlated) roughness conditions are detected. These two parameters summarize the statistical properties of surface roughness for natural surfaces. Both the traditional pin meter and the more modern field-deployed laser scanners are used for this purpose.

## IV. CONCLUSION

Because of its many benefits over more conventional approaches, microwave remote sensing has quickly become an indispensable instrument for soil quality assessments. Its reliability and constant soil monitoring are guaranteed by its all-weather operation and its ability to penetrate surface materials and plants. Its accuracy in measuring soil moisture, structure, surface roughness, and texture makes it a priceless tool for studying soil health. A thorough assessment of soil characteristics is possible by the combination of data from microwave remote sensing with those from other remote sensing methods, such as hyperspectral and multispectral imaging. Together, these fields—agricultural, environmental monitoring, and land management—make better decisions. Recent technological developments in satellites, as demonstrated by missions such as NASA's SMAP, have allowed for high-resolution, global-scale observations, thereby broadening the reach of microwave remote sensing.

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