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Estimation of soil moisture content by remote sensing methods: A review

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Abstract
Understanding the spatial and temporal variations of soil moisture is crucial for the land surface processes and their management. The soil moisture content in the surface layers of the soil is an important parameter for many applications in hydrology, horticulture, geotechnical, agriculture and meteorology. Hence accurate estimation of spatial and temporal variation in soil moisture content is important. Recently, remote sensing techniques have been used to estimate soil moisture. Estimation of soil moisture by remote sensing techniques provides only surface layer information and is unable to observe the entire soil column. On the other hand field measurement provide valuable information regarding both surface and subsurface soil moisture, but are insufficient to characterize the spatial and temporal variability of soil moisture at larger scale. Therefore, remote sensing methods have an edge over field methods in terms of spatial and temporal scale. This paper presents a comprehensive review of the progress in remote sensing or soil moisture studies.

Keywords: Soil moisture content, remote sensing techniques

Introduction

Soil moisture content plays a key role in the crop production as it act as a nutrient and serves as solvent for other nutrients. Soil moisture has very important implications for agriculture, ecology, wildlife, and public health and is probably (after precipitation) the most important connection between the hydrological cycle and life-animal, plant, and human. In agriculture point of view, soil moisture information is essential for many applications like irrigation scheduling, plant stress and improving crop yield. It makes a significant impact on plant growth, percolation, and evaporation, microbiological decomposition of the soil organic matter and also on heat exchange. Soil moisture also determines the partitioning of net radiation into latent and sensible heat components in the field of meteorology. Thin layer of soil water may seem as insignificant as compared to the global soil water but it is of fundamental importance to many hydrological, biological, and biogeochemical processes. The role of soil moisture in the top 1 to 2 m of the Earth's surface has been widely recognized as a key variable in numerous environmental studies (Walker, 1999) [66], including meteorology, hydrology, agriculture, and climate change (Topp *et al.*, 1980; Jackson *et al.*, 1987; Fast and McCorcle, 1991; Engman, 1992; Saha, 1995;) [60, 31, 22, 54]. Therefore, it is important to accurately monitor and estimate spatial and temporal variations of soil moisture

In recent decades, different methods are available to estimate soil moisture content which can be categorized into classical and modern techniques for both the laboratory and in situ measurements. Classical soil moisture measurement involves removing moisture from the soil sample by evaporation or chemical reaction comprises of thermo-gravimetric and calcium carbide techniques. Modern soil moisture measurement techniques employ electrical properties of the soil (viz., dielectric constant, impedance, and capacitance and soil resistivity), neutron scattering, gamma attenuation and optical techniques. Now, emerging technique is remote sensing technique in which soil moisture estimation depends upon the measurements of electromagnetic energy that has either been reflected or emitted from the soil surface. Remote sensing has the ability to collect information from various samples over a large area in a short time and repeated time intervals, especially with recent developments in sensor functionality and both temporal and spatial image resolution. Technological advances in satellite remote sensing have offered a variety of techniques for measuring soil moisture across a wide area continuously over time (Engman, 1990) [20]. Quantitative measurements of soil moisture in the surface layer of soil have been most successful using passive remote sensing in the microwave region. The primary difference among these techniques are the wavelength region of the electromagnetic spectrum used, the source of the electromagnetic energy (Walker, 1999) [66], the signal received by the sensors, and the relationship between the retrieved signal and the soil moisture.

2. Remote sensing and moisture content determination

Compared with in-situ methods, satellite remote sensing provides soil moisture observations globally and at larger footprints. Soil moisture estimation from the remote sensing techniques only provides surface layer information and is unable to observe the entire soil column. On the other hand the in-situ measurements provide valuable distributed point measurements, but are insufficient to characterize the spatial and temporal variability of soil moisture at larger scale. Therefore observations that are made by remote sensing techniques have an edge over the conventional data collection methods in terms of the spatial and temporal scale. Soil moisture estimation by means of remote sensing depends upon the measurements of electromagnetic energy that has either been reflected or emitted from the soil surface.

Direct observations of soil moisture are currently restricted to discrete measurements at specific locations, and such point-based measurements do not represent the spatial distribution because soil moisture is highly variable both spatially and temporally (Engman, 1991; Wood *et al.*, 1992) [21, 72]

Researches in soil moisture remote sensing began in the mid 1970's shortly after the surge in satellite development. Subsequent research were carried out for soil moisture content determination by optical and thermal infrared remote sensing, as well as passive and active microwave remote sensing techniques.

3. Optical remote sensing for soil moisture estimation

Remote sensing of soil moisture content using the solar domain with wavelengths between 0.4 and 2.5 µm measures the reflected radiation of the sun from the Earth's surface, known as reflectance (Sadeghi *et al.*, 1984) [53]. Compared with microwave and thermal infrared domains that have been most commonly used for soil moisture estimation (Price, 1980 [51]; Wuthrich, 1994 [73], Engman and Chauhan 1995 [23], Jackson *et al.*, 1995) [36], little attention hasbeen paid to the use of the solar domain. The effect of soil moisture on its reflectance has longbeen recognized by many scientists.

Early in 1925, Angstrom (1925) [1] found a decrease in reflectance when soil moisture increases in his measurements. Thereafter, familiar darkening of soil on wetting has been reported by other researchers (Curcio and Petty, 1951; Bowers and Hanks, 1965; Stoner and Baumgardner, 1980; Ishida *et al.*, 1991) [10, 5, 58, 28].

Bowers and Smith (1972) [6] observed a linear relationship between the absorption in water absorption band and soil water content. A factor of about 2 for all soils except sands was employed by Jackson *et al.* (1976) [29] to account for the reflectance reduction due to the increase of soil moisture content.

Dalal and Henry (1986) [13] by using absorbance values measured in the near infrared, estimated soil moisture with accurate results over a range of soil samples. These empirical approaches, however, provide only a poor indication of soil moisture content, since the spectral characteristic of a soil also depends on numerous other factors, such as mineral composition, organic matter, soil texture, and surface roughness (Asner, 1998; Ben-Dor *et al.*, 1999) [4], causing wide variations when they are applied to other localities outside the calibration conditions.

Lobell and Asner (2002) [41] developed a physical model to explain the soil reflectance variations due to moisture change based on their analysis of the reflectance for four different soils at various moisture contents.

Liu *et al.* (2003) [40] analyzed 18 different soils that represent a large range of permanent soil characteristics and investigated the potential of estimating soil moisture from reflectance measurements in the solar domain.

Wang and Qu (2007) designed the normalized multiband drought index (NMDI) for remotely sensing both soil and vegetation water content from space based on the soil and vegetation spectral signatures.

4. Thermal infrared remote sensing for soil moisture determination

Thermal infrared remote sensing measures the thermal emission of the Earth with an electromagnetic wavelength region between 3.5 and 14 µm (Curran, 1985). The estimation of surface soil moisture utilizing remotely sensed thermal wavebands essentially depends on the utilization of soil surface temperature estimations, either separately like the thermal inertia method or in mix with vegetation files as the temperature/vegetation file method.

4.1 Thermal inertia method

The amplitude of the diurnal range of soil surface temperature has been observed to be profoundly corresponded with the surface soil moisture content (Schmugge, 1978; Friedl and Davis, 1994). Territories having higher soil moisture content are cooler amid the day and hotter during the night. (van de Griend and Engman, 1985) [63].

Verstraeten *et al.* (2006) observed that when soil water content increases, thermal inertia (resistance to temperature variation) proportionally increases as well, thereby reducing the diurnal temperature fluctuation range.

The thermal inertia method, straightforward and simple to utilize, has clear physical importance and can accomplish high exactness in assessing soil moisture conditions. Nonetheless, it is just appropriate in the areas with no or little vegetation cover. (Xue and Ni, 2006).

4.2 Vegetation Index Method

Vegetation and land surface temperature (LST) have acomplicated dependence on soil moisture. Cautious examinations of information by Gillies *et al.* (1997) demonstrated that there is a novel relationship some of the time alluded to as the "Universal Triangle" among soil moisture, the normalized difference vegetation index (NDVI), and the LST for a given locale. The outcomes were later affirmed by hypothetical investigations utilizing a soil-vegetation-atmosphere transfer (SVAT) model, which was first named by Gillies and Carlson (1995) and intended to depict the fundamental vanishing forms at the surface, together with the water apportioning between vegetation transpiration, waste, surface spillover, and soil moisture varieties. Wang *et al.* (2007) [68] showed the capability of soil moisture estimation by consolidating in-situ soil moisture estimations and MODIS arrive parameters (LST and NDVI) to accomplish every day soil moisture items with 1 km determination.

Methodologies in light of either the surface temperature or the complimentary temperature-vegetation record are capable and have clear physical importance however have restrictions notwithstanding those normal to every optical system, for example, shallow soil entrance and cloud sullying (Moran *et al.*, 2004). They are regularly experimental and rely upon neighborhood meteorological conditions, for example, wind speed, air temperature, and moistness (Nemani *et al.*, 1993), and hence fluctuate crosswise over time and land cover types (Smith and Choudhury, 1991; Czajkowski *et al.*, 2000) [70].

5. Microwave Remote Sensing

Microwave remote sensing gives an extraordinary ability to soil moisture estimation by estimating the electromagnetic radiation in the microwave area in the vicinity of 0.5 and 100 cm. The principal premise of microwave remote sensing for soil moisture is the vast difference between the dielectric properties of water (~80) and soil particles (< 4). As the moisture builds, the dielectric steady of the soil-water blend increments and this change is perceivable by microwave sensors (Njoku and Kong, 1977; Dobson *et al.*, 1985). Both latent and dynamic microwave remote sensing procedures have exhibited the most encouraging capacity for comprehensively checking soil moisture varieties.

Active sensors provide high spatial resolution, but are more sensitive to different surface feature such as surface roughness, type of vegetation cover and soil wetness conditions. On the other hand, passive radiometers provide high temporal resolution, but are likely to be affected by the near surface soil moisture. The difference between both the sensors is that the passive microwave radiations are less affected by the roughness parameter whereas active microwave radiations have greatly influenced by the surface parameters. The combined use of passive and active sensor observations can provide complementary information included in the land surface microwave signature. (Njoku *et al.*, 2000)

5.1 Passive Remote Sensing

Eagleman and Lin (1976) utilizedpassive microwave remote sensor to screen surface soil moisture over land surface. These sensors measure the force of microwave outflow from the soil, which is corresponding to the brightness temperature, a result of the surface temperature and emissivity.

In an examination led by Kondratyev *et al.* (1977), soil moisture was determined utilizing a calculation that considered moisture slope for each soil compose utilizing emissivity got from radiometer. It has additionally been appeared by different methodologies that microwave discharge from a soil is the consolidated aftereffect of the emanation from all profundities.

Jackson and Vine (1996) [35] assessed soil moisture content amid Washita'92 test utilizing passive microwave radiometry at L-band. A model depicted by Jackson (1993) was connected to get spatially circulated data on soil moisture states and flow utilizing ESTAR instrument.

Past studies (Du *et al.*, 2000) have shown that higher accuracy was observed in there trieval of near surface soil moisture using L-band passive microwave data at low moisture conditions as the backscattering coefficient increases in wet soil condition.

Paloscia *et al.* (2001) examined the affectability of microwave emission to soil moisture at various frequencies utilizing instrument for Radio Observation of the Earth (IROE) and Special Sensor Microwave/Imager (SSM/I) and Scanning Multichannel Microwave Radiometer (SMMR) investigated uncovered and vegetated land. It was observed that the polarization file estimated at C-band gives better aftereffects of soil moisture content in various states of harshness and vegetation impact when contrasted with the estimations at higher frequencies.

Moran *et al.*, 2004 observed emission is related to its moisture content because of the large differences in the dielectric constant of dry soil and water.

To inspect the impact of surface parameters like vegetation cover and soil wetness over the retrieval of soil moisture, Lee and Aagnostou (2004) showed an analysis utilizing 10.7 GHz Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) channel and 13.8 GHz Precipitation Radar (PR) observations from 3 successive years (1999-2001) of warm seasons or the estimation of close surface soil moisture and vegetation properties. It was discovered that the soil moisture retrieval accuracy relies upon the soil wetness conditions and overlying vegetation. The higher accuracy was acquired at a middle of the road wetness condition for direct vegetation cover related with high emissivity with drier soils as the high vegetation cover meddles with the signals.

The surface emission model is one of the essential components in the applications of microwave remote sensing of soil moisture in the bare or vegetated surfaces (Wang *et al.*, 1983; Mo and Schmugge, 1987; Jackson and Schmugge, 1991; Jackson *et al.*, 1999) [67].

5.1.1 Soil moisture retrieval methods

Many approaches have been developed to retrieve soil moisture from microwave radiometric measurements, which can be grouped into two main categories: statistical techniques and forward model inversion.

5.1.2 Statistical approach

Statistical approaches are simple and efficient, which have demonstrated the capabilities of passive microwave remote sensing techniques for monitoring soil moisture. However, these methods are "these methods site-specific,"

Statistical approaches are generally based on the regression analysis between measured brightness temperature and surface soil moisture. The regression relations are then analyzed in terms of physical variables and parameters, which can be estimated from ancillary data (Wigneron *et al.*, 2003).

5.1.3 Forward Model Inversion

Relating to various types of surface emission models, various reversal strategies have been produced, among which, the statistical inversion approach is the most common algorithm forward models are based on statistical regression analysis. More often than not, the surface soil moisture is factually identified with a mix of microwave emissivity and vegetation records, which are utilized to remedy for the soil harshness and vegetation impacts (Wigneron *et al.*, 2003).

In the statistical retrieval approaches developed by Jackson *et al.* (1982) [34] and Theis *et al.* (1984), the vegetation indices, such as MPDI and NDVI, have been used in the regression function to relate the microwave emissivity to soil moisture. In light of this principle, Choudhury *et al.* (1987) [9] and Choudhury and Golus (1988) [8] did retrievals of soil wetness from space borne radiometer observations (Wigneron *et al.*, 2003).

Compared with conventional statistical algorithms, relatively satisfactory retrieval results have been found for statistical approaches based on forward model inversion by accounting for the vegetation effects (Pulliainen *et al.*, 1993)

Soil moisture retrieval from space-based passive microwave instruments has strong physical premise, and additionally the benefit of every climate perception and better vegetation infiltration particularly at the lower frequencies in the vicinity of 1 and 3 GHz (L band) (Njoku and Li, 1999). Be that as it may, the utilization of passive microwave estimations for the worldwide estimation is restricted for some reasons. To begin with, the spatial resolution is characteristically coarse, which is more often than not in the scope of 10– 20 km. Further, the accessible wavelengths from satellites don't give sufficient soil moisture sensitivity to assorted types and levels of vegetation cover.

5.2 Active microwave remote sensing

Jeffrey P. Walker, *et al.*, used, Active microwave remote sensing observations of backscattering, such as C-band vertically polarized synthetic aperture radar (SAR) observations from the Second European Remote Sensing (ERS-2) satellite to measure soil moisture content at near surface layer of soil and showed that SAR backscattering observations are highly dependent on topography, soil texture, surface roughness and soil moisture.

The most common imaging active microwave configuration is the synthetic aperture radar (SAR), which transmits a series of pulses as the radar antenna traverses the scene (Moran *et al.*, 2004). These SAR systems can provide resolutions in the order of tens of meters over a swath width of 50–500 km.

Although many studies have been conducted to estimate soil moisture in bare soil fields with Synthetic Aperture Radar (SAR) imagery, little success has been achieved in vegetated areas (Wang and Choudhury, 1981) [57].

Many theoretical, empirical, and semi empirical models have been developed since the beginning of SAR studies to relate the SAR backscatter coefficient to soil moisture through the contrast of the dielectric constants of bare soil and water (Fung *et al.*, 1992; Oh *et al.*, 1992). The empirical models are dependent on the site and surfaceproperties and valid only for those regions where they are developed and require a large number of experimental measurements (Oh *et al.* 1992)

5.2.1 Theoretical Approach

Theoretical approaches are usually derived from the diffraction theory of electromagnetic waves and have different ranges of validity, depending on the wavelength and the range of surface roughness (Fung *et al.*, 1992; D'Ursoa and Minacapillib, 2006) [25].

The standard models are the Small perturbation model (SPM) valid for low frequencyregions and the Kirchoff models (KM) which further consist of Physical optics model (POM) and Geometrical optics model (GOM) and are valid for high frequency regions (Ulaby *et al.*, 1982).

The Integral equation model (IEM was developed by Fung *et al.* (1992) [25], that attempts to combine Kirchhoff and Small perturbation models. Therefore this model is valid for a wide range of surface roughness scale and frequencies.

Bindlish and Barros (2000) applied IEM model in conjunction with an inversion algorithm to retrieve soil moisture using multi-frequency and multi-polarization data from SIR-Cand X-SAR. It was observed that the sensitivity of backscatter to surface roughness decreases asthe rms height increases above 1 cm and this sensitivity was found more in gaussian function than in exponential function.

Satalino *et al.* (2002), who demonstrated that no two-soil moisture classes could bereliably retrieved over smooth bare fields using ERS-1 and ERS-2, support these findings. Theauthors estimated the soil moisture with an overall rms error in the order of ΔMv% = ±6% by inverting the IEM theoretical model using appropriately trained and regularized neural networks. He found that the variable surface roughness is the main source of error, which influences the relationship between the soil moisture and radar backscattering coefficient.

Theoretical models can predict reasonably well the general trend of backscattering coefficient in response to changes in roughness or soil moisture content (Dubois and van Zyl, 1994). However, their complexity and the restrictive requirement for the parameterization of the vegetation and soil surface layer hamper their effective applicability for the soil moisture retrieval (Ulaby *et al.*, 1986).

5.2.2 Empirical Approaches

Empirical models are generally derived from experimental measurements to establish useful empirical relationships for inversion of soil moisture from backscattering observations (Walker *et al.*, 2004) [65]. The main advantage of empirical backscattering models over theoretical backscattering models is that many natural surfaces do not fall into the validity regions of the theoretical backscattering models, and even when they do, the available backscattering models fail to provide results in good agreement with experimental observations (Oh *et al.*, 1992; Walker *et al.*, 2004) [65].

5.2.3 Semi Empirical Approaches

Alternatively, semi-empirical models of backscattering, which represent an acceptable compromise between theoretical and empirical approaches, have been developed based on a theoretical foundation with model parameters derived from experimental data. The main advantage of these backscattering models is that they are not expected to have the site-specific problems commonly associated with empirical models (Walker *et al.*, 2004) [65]. In most cases, these types of models are suited for bare soil surface conditions rather than vegetated surfaces.

Baghdadi *et al.*, 2004 used a semi-empirical calibration of the IEM model. The IEM model was tested over different polarization (HH and VV) and incidence angles ranging from 230 to 570 at frequencies (L, C, and X bands). The fractal function was proved to be optimal for better performance of the IEM out of gaussian and exponential function and the calibration method was found to be dependent on surface roughness. Hence it has been evolved that the calibration version of IEM can be used in the inversion procedures to retrieve soil moisture and the soil surface could be characterize bare agricultural soils using two surface parameters (surface height and soil moisture) instead of three (rms surface height, soil moisture and correlation length).

Conclusion

This paper outlines the basic principles of the satellite based techniques for soil moisture estimation and reviews briefly the status of current retrieval methods. There are a fairly wide variety of approaches, which have been used to retrieve soil moisture from optical, thermal infrared, passive microwave and active microwave satellite measurements. At present, remote sensing methods have not been successful in estimating soil moisture from deep soil layers, such as at the root-zone soil layers. However, the ability to retrieve soil-moisture information from the surface layers in itself needs to be further investigated.

Microwave remote sensing is the most effective technique for soil moisture estimation, with advantages for all-weather observations and solid physics. Soil moisture can be estimated using passive radiometer or active radar measurements. Both radiometer brightness temperature and radar backscattering measurements have been shown to be sensitive to soil moisture. Passive microwave has more potential for large-scale soil moisture monitoring but has a low spatial resolution. Active microwave can provide high spatial resolution but has low revisit frequency and is more sensitive to soil roughness and vegetation.

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