Surface Soil Moisture Estimation: Significance, Controls, and Conventional Measurement Techniques

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2.1 Soil Moisture: Definition and Significance

Soil moisture is generally defined as the water contained in the unsaturated soil surface of the Earth, derived from rainfall, from snowmelt, or by capillary attraction from groundwater. Soil moisture content (SMC) is a significant component of climatological, hydrological, and ecological systems. Classic estimates of global soil moisture are approximately $70 \times 10^3 \text{ km}^3$ (0.005% of the Earth’s total volume of water; Jones 1997), with a renewal time of 280 days (Wetzel 1983). It has long been recognized as a key state variable of the global energy and water cycle due to its control on exchanges of energy and matter and physical processes, in particular, the partitioning of available energy at the Earth’s surface into latent (LE) and sensible (H) heat exchange with the atmosphere. SMC also directly impacts the exchanges of trace gases on land, including carbon dioxide (Seneviratne et al. 2010), and strongly influences feedback between the land surface and climate, which, in turn, influences the dynamics of the atmosphere boundary layer and thus weather and global climate (Patel et al. 2009).

Hydrologically, the water stored on land is a key variable controlling numerous key land surface and feedback processes within the climate system. The degree of prior saturation is an important control on river catchment response to rainfall or snowmelt and subsequent flood generation, primarily by partitioning rainfall into infiltration and runoff (Zribi et al. 2005; Penna et al. 2011; Radatz et al. 2012) and also by contributing to runoff itself (Jones 1997). Overland flow will be larger and will occur more quickly on wetter soils and in catchments where areas of saturated soils (e.g., in topographic lows and near watercourses) are more extensive. Knowledge of the spatial distribution of soil moisture can therefore aid us in determining the potential for infiltration, overland flow, floods, and erosion as well as the resultant impacts on streams, reservoirs, infrastructure, and, most importantly, human life (Hebrard et al. 2006). In addition, it can inform sustainable water resources management, the study of ecosystems and ecological processes (Choi et al. 2009), plant water requirements, plant growth and productivity, as well as irrigation management and deciding when to carry out cultivation procedures (e.g., Glenn et al. 2007; Yang et al. 2010). This is particularly true in ecosystems of many arid and semiarid regions in which water is a limiting resource (Mariotto and Gutschick 2010). In a period in which climatic changes are leading to significant changes in the hydrological cycle, which, in turn, impacts on the quantity and quality of food and water available to human society, knowledge of such an important store of freshwater is essential.

SMC is most commonly expressed as either a dimensionless ratio of two masses or two volumes or given as a ratio of a mass per unit volume. These dimensionless ratios can be reported either as decimal fractions or percentages. Soil moisture has traditionally been considered to exist in an unsaturated zone of aeration in which soil pores contain more air than water (Jones 1997). Water enters this zone as a result of the processes listed above through infiltration and capillary action and exits via evapotranspiration or by vertical percolation across the water table into a zone of saturation or groundwater (Jones 1997). Although SMC tends to refer to water in storage, water can drain laterally through the zone of aeration via a process called throughflow.

SMC can also be characterized as a combination of surface SMC (defined as the water contained within the first 5 cm of the soil depth) and root zone SMC (defined as the water content contained below 5 cm of soil depth; e.g., Hillel 1998; Seneviratne et al. 2010; Figure 2.1). In practice, often only a fraction of soil moisture is relevant or measureable, as it exists in a heterogeneous matrix of solid material, both organic and inorganic (Shaw 1994). Thus
Surface Soil Moisture Estimation

soil moisture needs to be considered with regard to a given soil volume. One measure commonly used is volumetric soil moisture $\theta$ (m$^3$ H$_2$O/m$^3$ soil) in a given soil volume $V$ (e.g., volumes A or B in Figure 2.1). Two key parameters often used to inform practical applications of SMC (especially in agricultural systems) are field capacity (defined as the maximum volume of water that a soil can hold) and soil moisture deficit (the amount of water required to raise SMC to field capacity).

This chapter aims to first provide an overview of the main parameters controlling SMC variations, as understanding this is essential in order to be able to appreciate the main limitations and challenges in deriving and validating SMC from remote sensing observations. Second, it aims to provide an all-inclusive overview of the conventional SMC estimation methods and to discuss key operational ground-based observational networks that currently provide such data. This allows an appreciation of the absolute accuracy by which SMC can be measured in the field. This is important from the perspective of remote sensing–related dataset validation by using in situ estimates as reference datasets for satellite-derived estimates of SMC. Furthermore, knowledge of available infrastructure providing validated in situ observations of soil moisture and related parameters on a consistent basis is of paramount importance in establishing strategies for validating satellite-derived remote sensing estimates and assessing the performance of relevant operational products available globally.

2.2 Environmental Variables Controlling SMC

SMC is generally a highly variable parameter both temporally and spatially, especially at the soil surface. Previous studies have noted that the most important parameters influencing the spatial variability of SMC are topography, soil properties, vegetation type and density, mean moisture content, depth to water table, precipitation depth, solar radiation, and other meteorological factors (e.g., Famiglietti et al. 1998; Herbrard et al. 2006). Soil moisture variability, however, always reflects a combination of the effects of more than one of the above factors and the dominant parameter(s) vary according to the soil wetness state (e.g., Grayson et al. 1997; Gomez-Plaza et al. 2001; Herbrard et al. 2006; Liancourt et al. 2012). The
significance of the exact relationship between SMC and the different factors is variable and difficult to quantify precisely. This section aims to briefly discuss the effect of each of the different factors affecting surface soil moisture. Detailed discussions on the topic can be found, for example, in the works of Famiglietti et al. (1998) and Herbrard et al. (2006).

2.2.1 Climatological and Meteorological Factors

Variability in surface SMC at a catchment scale is strongly influenced by a variety of climatological and meteorological factors, including incoming solar radiation, wind, humidity, and, most importantly, precipitation. Variations of incoming solar radiation and wind can both influence the rate of evapotranspiration from soils, either increasing or decreasing SMC. At its most simple state, the characteristics of surface runoff, subsurface flow, and soil moisture depend on the characteristics of precipitation (phase, intensity, duration, etc.; Sivapalan et al. 1987; Famiglietti et al. 1998; Salvucci 2001). Reynolds (1970c) was the first to propose that variability in surface SMC might be largest after rainfall because the effects of soil heterogeneity would be at their maximum, whereas the opposite would occur after a prolonged dry period.

A significant number of studies have examined the complex interrelationships between and cumulative effects of multiple climatological and environmental factors on the distribution of surface SMC (Bell et al. 1980; Robinson and Dean 1993; Nyberg 1996; Famiglietti et al. 1998; Western et al. 1999; Wu et al. 2012). These climatological factors, of course, strongly influence the dominant vegetation and soil type and the type of land use that can be utilized in that location and are, in turn, themselves influenced by those factors as well as by topography. In general, precipitation patterns (in conjunction with other meteorological factors) will dominate patterns of SMC at the watershed scale, but other factors will become more important at smaller scales (Vinnikov et al. 1996; Crow et al. 2012).

2.2.2 Topography

Topography-related parameters that affect the distribution of SMC in the top soil layer include slope, aspect, curvature, specific contributing area, and relative elevation. Slope influences processes such as infiltration, subsurface drainage, and runoff. Aspect and slope have been shown to have a direct control on the solar irradiance received, which, in turn, affects the rate of evapotranspiration from the land surface and, as a result, soil moisture (Hills and Reynolds 1969; Moore et al. 1988; Nyberg 1996; Huang et al. 2011). Land surface curvature is a measure of the landscape convexity or concavity and influences the convergence of overland flow. Areas characterized by high curvature tend to be characterized by a larger heterogeneity in SMC than areas in which plan curvature is low (Moore et al. 1988). The specific contributing area is defined as the upslope surface area that drains through a unit length of contour on a hill slope. This parameter controls the potential volume of subsurface moisture that flows from a particular point on the land surface, affecting the distribution of soil surface moisture (e.g., Nyberg 1996). Generally speaking, locations with larger contributing areas are expected to be wetter in comparison to areas of smaller contributing areas (Famiglietti et al. 1998). Last but not least, relative elevation (so-called slope location) affects soil surface moisture directly by affecting the degree to which orographic precipitation contributes to SMC as well as indirectly due to its effect on soil water redistribution (Famiglietti et al. 1998). Many studies have shown an inversely proportional relationship between soil moisture and relative elevation (e.g., Crave and Gauscuel-Odoux 1997). For example, Hawley et al. (1983) examined the influence of variations in vegetation, soil properties, and topography on the distribution of soil
moisture. Their results indicated that relative elevation was the dominant control on local soil moisture variability, whereas the presence of vegetation cover tended to decrease the variations in SMC explained by topography. In another study, Nyberg (1996) evaluated the relationship between surface SMC and a number of parameters including relative elevation and slope. Their study only reported high positive correlations between soil moisture and slope and elevation.

2.2.3 Soil Properties

The composition of soils varies enormously both spatially and temporally but almost always includes material in the solid phase (including both organic and inorganic material), liquid phase (including solutes), and gaseous phase (including oxygen, carbon dioxide, and nitrogen in varying proportions) (Smithson et al. 2008). These solid organic and inorganic components of the soil form the soil structure. The inorganic solid matter of soil is composed of various rock decompositions, clasts, and minerals in different sizes and composition. The diameters of sand particles range between 2 and 0.02 mm, those of silt particles between 0.02 and 0.002 mm, while those of clay particles have diameters smaller than 0.002 mm (Kuruku et al. 2009). A number of studies have documented that surface SMC is closely correlated to the soil properties (e.g., Niemann and Edgell 1993; Crave and Gauscuel-Odoux 1997; Gao et al. 2011; Atchley and Maxwell 2011). Key soil surface properties influencing the concentration and spatiotemporal distribution of moisture in the soil include the soil texture, organic matter content, and soil macroporosity. Texture, in particular, can control the nature of water transmission and retention in the soil. Coarsely textured soils with a high proportion of sand will drain better than finely textured soils such as clays, and as such, will have a lower water-holding capacity and lower SMC. This influence has been shown to occur in large-scale studies in the United States (Panciera 2009) where soil moisture patterns reflect varying soil texture.

In addition, the organic matter content of soils directly influences soil albedo and dielectric properties. Soils with a smaller proportion of decomposed organic substances are characterized by a higher albedo (and thus reflectance) especially in the near-infrared and visible parts of the electromagnetic spectrum, whereas soils with a higher proportion of decomposed organic matter have a lower albedo in all wavelengths ranging between 0.5 and 2.3 mm (Kuruku et al. 2009). Thus, by controlling soil albedo, soil organic matter influences evaporation rates from the soil surface and hence the SMC of the surface layer (Famiglietti et al. 1998). Analysis of soil color can provide information about numerous other soil characteristics (texture, organic matter content, natural drainage condition, aeration, and the phenomena of washing and accretion; Kuruku et al. 2009) and as such is commonly used as a morphological specification for characterizing soils.

2.2.4 Vegetation

The influence of vegetation cover, especially its type, density, and uniformity (Crow et al. 2012), on surface SMC variability is another parameter that has been extensively documented since as early as the 1950s when an experimental study by Lull and Reinhart (1955) underlined the strong effect of vegetation cover in the regional variability of surface SMC, which increased as a function of decreasing vegetation cover. Since then, other authors have investigated the bidirectional relationship between vegetation cover and SMC (e.g., Hawley et al. 1983; Francis et al. 1986; Liancourt et al. 2012). The presence and amount of vegetation influence the concentration of surface SMC by adding organic
matter to the soil surface layer and also by extracting water from the soil to be used for vegetation transpiration. Furthermore, the presence of vegetation cover influences soil moisture via the throughfall pattern and shading of the soil layer that is imposed by the vegetation canopy, which, in turn, influences the rate of evaporation from the soil and soil hydraulic conductivity via the impact of root activity (Famiglietti et al. 1998; Atchley and Maxwell 2011).

2.2.5 Land Use

Land use is also very influential in determining the spatial variability of SMC, mainly because of its influence on vegetation cover and associated impacts on infiltration and runoff rates and evapotranspiration processes, with a more pronounced effect exhibited during the growing season (e.g., Fu and Gulinck 1994; Fu and Chen 2000; Qiu et al. 2001; Zhao et al. 2011). Furthermore, many studies have shown that the influence of land use on surface SMC, expressed mainly via transpiration, can even eliminate the effects of topography-related parameters (i.e., aspect; e.g., Ng and Miller 1980; Herbrard et al. 2006). Land use also influences the spatiotemporal variations of key soil surface characteristics, such as topsoil structure, soil crusting, and soil cover by vegetation and other materials, which, as previously mentioned, strongly affect the spatial variation of SMC (Le Bissonnais et al. 2005).

2.3 Conventional Approaches for the Measurement of Soil Moisture

Given the importance of soil moisture in such a wide variety of physical processes and in the management of resources and land use, various methods have been developed for directly measuring this parameter in the field or by analyzing soil samples under laboratory conditions. Overviews of these different techniques have been given by Robock (2000), Robinson et al. (2008), Verstraeten et al. (2008), Dorigo et al. (2011a) and Dobriyal et al. (2012). Some of these works (e.g., Robock 2000; Verstraeten et al. 2008) have classified the existing methods into the following broad categories: gravimetric, nuclear-based, electromagnetic, tensiometer-based, hygrometric, and emerging techniques.

This section aims to provide an overview of the conventional techniques currently available for measuring soil moisture and also to present a few promising emerging measurement techniques. Examples of instruments used, based on the different techniques reviewed herein, are presented in Figure 2.2. For efficiency, and in common with the reviews mentioned above, this overview will follow the categorization adopted previously by others. Each of the techniques is reviewed herein by means of a simple description, outlining its relative advantages and disadvantages. Understanding these not only provides a good basis for understanding estimates of SMC obtained using remote sensing techniques reviewed herein, but also allows appreciating the potential limitations when validating the satellite-derived estimates. Verstraeten et al. (2008) in their recent overview of the available conventional methods employed in estimating soil moisture concluded that even today there is not a single, clearly superior method suitable under all circumstances for measuring SMC.

As Dorigo et al. (2011a) noted, even when one technique is consistently employed, SMC measurements can be strongly influenced by several other factors including, for example,
instrument calibration, the installation conditions (e.g., installation depth and sensor placement), as well as the spatial resolution, geographical coverage, and representativeness of the measurements obtained. When the aim is to validate regional estimates of SMC derived, for example, from remote sensing observations, given the high spatiotemporal variability of SMC, a large number of SMC measurements from different points are required in order to obtain a value of SMC representative of the study area (Robock 2000). Strategies of upscaling point measurements of SMC to validate large-scale estimates derived from remote sensing have been described by Crow et al. (2012). Alternatively, one or a few sensors can be placed at locations that are representative for the area covered by the satellite footprint (Brocca et al. 2010a,b).

Generally, required accuracy in the measurement of SMC is subject to the application considered each time. Yet an absolute accuracy of about 4% volume by volume (vol vol$^{-1}$) in SMC is generally satisfactory for a large range of applications (Engman 1992; Walker and Houser 2004; Sequin and Itier 1983; Calvet and Noilhan 2000). Even though most sensor manufacturers claim to achieve this accuracy requirement, these specifications are usually made for a default calibration, which is only valid for “typical conditions” achieved under laboratory conditions. A field-specific calibration and accuracy assessment is indispensable to exploit the potential quality of the sensor and to quantify the actual accuracy. Table 2.1 summarizes the advantages, disadvantages, cost, possible scale of operation, response time, and examples of instruments used to measure soil moisture.

### 2.3.1 Gravimetric Methods

Gravimetry [sometimes referred to as the (thermo-) gravimetric method] refers to the measurement of soil water content by measuring the difference in weight between a soil
### TABLE 2.1
Overview of Conventional Methods for Measuring Soil Moisture in the Field

<table>
<thead>
<tr>
<th>Method</th>
<th>Strengths</th>
<th>Limitations</th>
<th>Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetry</td>
<td>High level of accuracy</td>
<td>Destructive</td>
<td>24 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repeat sampling not possible</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time and labor intensive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>High level of possible uncertainty</td>
<td></td>
</tr>
<tr>
<td>Nuclear methods</td>
<td>Neutron scattering</td>
<td>Radiation hazard</td>
<td>1–2 min</td>
</tr>
<tr>
<td></td>
<td>Straightforward implementation</td>
<td>Time intensive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nondestructive</td>
<td>Low sensitivity in upper 20 cm soil profile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Enables measurement at several depths</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High level of accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma attenuation</td>
<td>Nondestructive</td>
<td>Low accuracy</td>
<td>Instantaneous</td>
</tr>
<tr>
<td></td>
<td>Operation can be automated</td>
<td>Requires high level of expertise</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restricted to soil depth of 2.5 cm</td>
<td></td>
</tr>
<tr>
<td>Nuclear magnetic resonance</td>
<td>As for neutron scattering</td>
<td>As for neutron scattering</td>
<td>Instantaneous</td>
</tr>
<tr>
<td>Electromagnetic methods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistive sensors</td>
<td>Enables measurement of SMC over extended time periods</td>
<td>Low accuracy</td>
<td>2–3 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Requires individual calibration</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited lifespan of instrument</td>
<td></td>
</tr>
<tr>
<td>Capacitive sensors</td>
<td>High level of accuracy</td>
<td>Questionable long-term stability</td>
<td>Instantaneous</td>
</tr>
<tr>
<td></td>
<td>Enables SMC measurement at any soil depth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDR</td>
<td>Nondestructive</td>
<td>Environment-sensitive, especially in saline soils</td>
<td>Instantaneous</td>
</tr>
<tr>
<td></td>
<td>Easy to use</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operation can be automated at multiple points</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High level of accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDR</td>
<td>Nondestructive</td>
<td>Environment-sensitive</td>
<td>Instantaneous</td>
</tr>
<tr>
<td>Tensiometer techniques</td>
<td>Nondestructive</td>
<td>Only allow indirect estimation of SMC</td>
<td>2–3 h</td>
</tr>
<tr>
<td></td>
<td>High level of accuracy</td>
<td>Only allow indirect estimation of SMC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Easy to install, operate and maintain for extended periods</td>
<td>Fragile</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Automated operation impractical</td>
<td></td>
</tr>
<tr>
<td>Hydrometric techniques</td>
<td>Low maintenance</td>
<td>High level of calibration</td>
<td>&lt; 3 min</td>
</tr>
<tr>
<td></td>
<td>Operation can be automated</td>
<td>Sensors deteriorate with time as they interact with soil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Only provides estimation of SMC</td>
<td></td>
</tr>
<tr>
<td>Emerging techniques</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>Nondestructive</td>
<td>Requires measurement of meteorological variables and calibration</td>
<td>Instantaneous</td>
</tr>
<tr>
<td>Distributed temperature sensing</td>
<td>Can be used in remote environments</td>
<td>Difficulty of installing at consistent depths</td>
<td>Instantaneous</td>
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<td></td>
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</tbody>
</table>
sample before and after drying. This is the oldest and most direct method currently used for SMC measurement and remains the standard against which other methods are calibrated and compared (Zazueta and Xin 1994; Verstraeten et al. 2008; Huang et al. 2011). Implementation of this technique is based on extracting a soil sample from the field which is then transferred to a soil analysis laboratory, where it is put into a drying oven at 105°C for a period of 24–48 h. The concentration of water in the soil is determined by subtracting the oven-dry weight from the initial field weight. The difference in mass gives the total soil moisture in the sample, which is converted to volumetric units using the density of the soil. Details of the principles and implementation of this technique are given by Reynolds (1970a,b).

The key advantages of this approach are that it is easily and straightforwardly implemented using low cost technology and equipment. Nevertheless, the method has several disadvantages. It is a destructive method (because soil samples must be removed from the field) that precludes repeat sampling from exactly the same point. Furthermore, its implementation is generally time consuming and labor intensive, requiring the availability of sampling equipment, weighing scale, and an oven, and is difficult to use in rocky environments (Dobriyal et al. 2012). Last but not least, some authors (e.g., Baker and Allmaras 1990) have identified that uncertainty can be introduced in soil moisture estimation by this technique, because of the very precise determination of sample volume required in the conversion from gravimetric to volumetric water content.

2.3.2 Nuclear Techniques

2.3.2.1 Neutron Scattering

In this method, the amount of water in a volume of soil is estimated by measuring the amount of hydrogen it contains, expressed as a percentage. Because most hydrogen atoms in the soil are components of water molecules, the backscatter of the thermalized neutrons from a radioactive source emitted and measured by a detector in the probe directly corresponds to water content in the soil. A neutron probe can measure total soil water content if it is properly calibrated by gravimetric sampling. Depth probes and surface probes are available that measure the SMC at the required depth, or in the uppermost layer, respectively (Dobriyal et al. 2012). More details on this technique implementation can be found, for example, in the works of Goodspeed (1981) and Robock et al. (2000).

The key advantages of this method are that it is relatively easy and straightforward to use. Furthermore, it is a nondestructive technique that enables the measurement of soil moisture distribution profiles at several depths. The method is also accurate—a properly calibrated instrument is capable of an accuracy of better than ±0.02 in volumetric water content (Baker and Allmaras 1990)—and capable of measuring surface SMC in real-time conditions (Dorigo et al. 2011a). Disadvantages of this technique include the high cost of equipment purchase and the radiation hazard involved. Additionally, neutron probes require proper calibration according to each soil type in which they will be used, which, in practice, increases the time it takes to collect data. Furthermore, and perhaps most importantly, they have been shown to be insensitive in measuring soil moisture near the surface (top 20 cm) (Zazueta and Xin 1994) because fast neutrons can escape into the atmosphere (Luebs et al. 1968). This technique is not common when frequent and automated observations are required, and its use has been proven most useful in measuring relative soil moisture differences rather than absolute SMC (Dorigo et al. 2011a).
2.3.2.2 Gamma Attenuation

Another radioactive technique employed in field-based estimation of SMC includes the use of gamma attenuation. The operation of this technique is based on the assumption that scattering and absorption of gamma rays are correlated in their path to the matter density and also that the specific gravity of the soil remains relatively constant as soil moisture changes (Zazueta and Xin 1994). This technique takes measurements in the soil profile and requires two parallel access tubes, one for the radioactive source and one for the detector of primary photons, in order to measure wet density changes in soil from which it is possible to determine SMC. A number of radioisotopes have been used for this purpose, with 137 Caesium being the one most commonly used (Baker and Allmaras 1990). A more detailed discussion on the operation of this method and its principles can be found in the works of Gardner (1986) and Nofziger (1978).

The key advantages of this technique include the fact that it is a nondestructive method that is able to provide the average water content for the profile depth. Furthermore, the operation of the method can be easily automated allowing the user to map the temporal changes in soil water content. Additionally, this technique is much easier to calibrate as it does not have to be site specific. However, its implementation requires the use of relatively expensive instrumentation and a greater level of user expertise. In addition, the use of this method is restricted to estimating SMC of a 2.5-cm-thick sample of soil thickness (but at a very high resolution) and measurements are affected by bulk density changes (Dobriyal et al. 2012; Pires et al. 2005).

2.3.2.3 Nuclear Magnetic Resonance

Nuclear magnetic resonance is another technique used for measuring the volumetric soil water content based on the use of radioactivity. This technique subjects water in the soil to both a static and an oscillating magnetic field perpendicular to each other. A radio frequency detection coil, turning capacitor, and electromagnetic coil are used as sensors to measure the spin echo and free induction decays. This technique can discriminate between bound and free water in the soil. Stafford (1988) provides more details concerning the method’s operation principles as well as its relative strengths and weaknesses. Generally, advantages and disadvantages of this technique are similar to those of the neutron scattering technique discussed earlier.

2.3.3 Electromagnetic (or Dielectric Constant) Methods

Some techniques for measuring soil moisture are based on the electromagnetic properties of water. Water's permanent dipole moment (the displacement of positive and negative molecular charge related to the position of the hydrogen atoms relative to the oxygen atoms) is high in comparison with other materials and as such water has a high dielectric constant of \( \approx 80 \) (Robinson et al. 2008). These measurement techniques depend on the effect of water on the bulk dielectric properties of the soil (given that other soil constituents have dielectric constants of less than 5 when measured between 30 MHz and 1 GHz). In a mixture of water and dry soil, the resulting dielectric constant is between these two extremes, thus offering a mechanism for detecting the water content in the soil (Gardner et al. 2001). The dielectric properties of materials such as soil, composed of materials with different dielectric properties, are dependent on frequency, largely due to the fact that more processes occur in such heterogeneous material with different microgeometries, in comparison with homogeneous material.
Values measured in this way are subsequently related through calibration to SMC. A common characteristic of all of these techniques is that they require calibration with gravimetric samples. Broadly speaking, four types of approaches have been developed based on this principle: the resistive sensor (gypsum), the capacitive sensor, the time domain reflectometry (TDR), and the frequency domain reflectometry (FDR). The following sections provide an overview of the operation of those techniques, including a discussion of their advantages and disadvantages. A more detailed discussion on the use of those techniques is given by Verstraeten et al. (2008).

### 2.3.3.1 Resistive Sensor (Gypsum)

Porous blocks of gypsum are used in one of the most common dielectric constant techniques employed for measuring SMC in the field. The device consists of a porous block made of gypsum or fiberglass containing two electrodes linked to a wire lead. When the device is buried into the soil surface, water will enter or exit the block until the matric potential of the block and the soil are the same. Then, the electrical conductivity of the block to the matric potential for any particular soil is calculated using a calibration curve. The main advantage of this technique is that it is a low-cost solution, allowing the measurement of SMC in the same location in the field over extended periods of time, although this is limited by the dissolution and degradation of the block (Dobriyal et al. 2012). Nonetheless, the key disadvantage of this technique is that it requires individual calibration of the porous blocks for each location and for each measurement interval, which limits the gypsum block life span (Zazueta and Xin 1994). The accuracy of this method is affected by both salt and temperature (Dobriyal et al. 2012).

### 2.3.3.2 Capacitive Sensor

Another option for measuring SMC through its effect on the dielectric constant is by measuring the capacitance between two electrodes implanted in the soil using a system of probes (e.g., Dean et al. 1987). A frequency excitation is usually given to the probe installed that enables the measurement of the dielectric constant that is directly proportional to the moisture content in the soil layer. An advantage of the use of this technique is that it can measure water content at any soil depth. Also, it can achieve a relatively high precision in soil moisture estimation when ionic concentration of the soil is constant over time. One of the main disadvantages of this method is that the long-term stability of the system calibration is questionable, as well as its high cost.

### 2.3.3.3 Time Domain Reflectometry

Another technique widely applied for measuring soil moisture based on soil electrical conductivity measurements belonging to the dielectric group of methods is the time domain reflectometer (TDR; Taylor 1955). TDR is a method that uses a device that propagates a high-frequency transverse electromagnetic wave along a cable attached to a parallel conducting probe inserted into the soil. The signal is reflected from one probe to the other before being returned to the meter that measures the time elapsed between sending the pulse and receiving the reflected wave. Assuming that the cable and waveguide length are known, the propagation velocity, which is inversely proportional to the dielectric constant, can be directly related to SMC. This provides a measurement of the average volumetric water content along the length of the waveguide.
Among the most important advantages of this technique are that it is nondestructive to the study site and is not labor intensive (Dobriyal et al. 2012). The ability to automate TDR measurement and to multiplex many waveguides through one instrument (Baker and Allmaras 1990) are further advantages of TDR because they allow unattended measurement at multiple points, either on a scheduled interval or in response to events such as rainfall. When it is properly calibrated and installed, it is a highly accurate method for measuring SMC (Baker and Allmaras 1990; Verstraeten et al. 2008).

### 2.3.3.4 Frequency Domain Reflectometry

FDR is similar to TDR but estimates SMC through measuring changes in the frequency of a signal as a result of soil dielectric properties (Dobriyal et al. 2012). An electrical circuit using a capacitor and an oscillator measures changes in the resonant frequency and indicates variations in SMC. The main advantage of this method is that it is nondestructive, but in comparison with TDR, it can provide less accurate results due to sensitivity to soil characteristics (e.g., salinity and temperature) and also has a limited scale of use (Dobriyal et al. 2012).

### 2.3.4 Tensiometer Techniques

Tensiometers are devices that measure the tension or the energy with which water is held by the soil and are comprised of water-filled plastic tubes with hollow ceramic tips attached on one end and a vacuum gauge and airtight seal on the other. These tubes are installed into the soil at the depth at which the soil moisture measurement is required. At this depth, water in the tensiometer eventually comes to pressure equilibrium with the surrounding soil through the ceramic tip. When the soil dries, soil water is pulled out through the tip into the soil, creating a tension or vacuum in the tube. As the soil is rewetted, the tension in the tube is reduced, causing water to reenter the tip, reducing the vacuum. Tensiometers are available commercially in many different types of configurations and are inexpensive, non-destructive, and easy to install and operate satisfactorily in the saturated range. If properly maintained, they can operate in the field for long time periods. Another important advantage of using tensiometers is that they can allow measurement of the water table elevation and/or soil water tension when a positive or negative gauge is installed. However, they are only able to provide direct measurements of the soil water suction, allowing an indirect estimation of SMC. Furthermore, tensiometers are fragile and require care during their installation and maintenance in the field (Dukes et al. 2010). Automated measurements are possible but at a high cost, and they are not electronically stable.

### 2.3.5 Hygrometric Techniques

Because the thermal inertia of a porous medium depends on moisture content, soil surface temperature can be used as an indication of SMC. For this purpose, electrical resistance hydrometers that utilize chemical salts and acids, aluminum oxide, electrolysis, thermal principles, and white hydrosol are used to measure relative humidity (RH). The resistance of the resistive element measured is a function of RH and allows the SMC to be inferred. More detailed information on the use of these devices can be found in the work of Wiebe et al. (1977). This technique enables SMC measurements to be taken over large areas, and this is perhaps its most important advantage. Important disadvantages
include that hydrometers comprise a very large, complex, and expensive system, making their use impractical.

2.3.6 Emerging Techniques

In addition to the established techniques described above, novel techniques for measuring soil moisture are currently being developed (Ochsner et al. in press). Two of the most important are cosmic ray hydrometeorology (Zreda et al. 2012) and distributed temperature sensing (Gao et al. 2011; Striegl and Loheide 2012). The former utilizes the fact that the density of low-energy cosmic ray neutrons in the atmosphere is inversely correlated with soil moisture and measures the neutrons emitted by cosmic rays in air and soil using a stationary cosmic ray soil moisture probe (neutronavka) (Zreda et al. 2012). This system has the distinct advantage of being able to obtain estimates of soil moisture over areas of a few hundred square meters. Limitations include the need to isolate the signal of SMC from other sources of hydrogen source cosmic rays such as some minerals (e.g., clay), vegetation, and organic matter as well as surface and atmospheric water. Measurements of these variables are required in order to calibrate the soil moisture measurements. Currently, a large monitoring network of cosmic ray probes is being set up in the United States and other parts of the world (Zreda et al. 2012).

Distributed temperature sensing uses fiber optic cables that can extend in excess of 50 km in order to measure changes in soil thermal conductivity, which is a function of soil moisture and ambient temperature. The main advantages are the large spatial extent and resolution (1–2 m) that this technique offers and that low power requirements mean that it can be used in remote environments. Disadvantages include the difficulty of placing the fibers at consistent depths and locations and monitoring diurnal changes in soil temperature (Striegl and Loheide 2012).

2.4 Ground Monitoring Soil Moisture Networks

The important role of ground monitoring networks in further understanding the processes governing the transfer of heat, mass, and energy between the terrestrial ecosystems and the atmosphere and to improve predictions of parameters characterizing surface–atmosphere exchange from remote sensing data was already underlined in Chapter 1. As has already been discussed, the increasing number of Earth Observation (EO) missions with the launch of more and more sophisticated remote sensing radiometers that are continuously becoming available has made developing the necessary infrastructure for validating the remote sensing–derived surface heat fluxes and/or surface SMC data a key priority. In the remainder of this section the currently active global in situ monitoring networks providing appropriate validated ground measurements of soil moisture are briefly reviewed. Knowing this is particularly important from a remote sensing point of view, as availability of validated in situ SMC data is needed to evaluate the performance of EO-based algorithms and operational products that are being developed or offered to the community. Conducting such detailed and thorough benchmarking studies is particularly important for the development and distribution of operational products before those are made available for use to the wider community.
2.4.1 International Soil Moisture Network

The International Soil Moisture Network (ISMN; http://ismn.geo.tuwien.ac.at/) is an international cooperation initiated by the Global Energy and Water Exchanges (GEWEX) project and European Space Agency (ESA) with the purpose of establishing and maintaining a database of harmonized global in situ soil moisture and promoting scientific studies on calibration and validation of satellite based and modeled soil moisture products (Dorigo et al. 2011a,b). The ISMN soil moisture measurement hosting facility is coordinated by GEWEX in collaboration with the Group of Earth Observation (GEO) and the Committee on Earth Observation Satellites (CEOS). The data portal has been implemented by the Vienna University of Technology, who also hosts it.

Within a fully automated process chain, collected data are harmonized in terms of measurement unit, sampling interval, and metadata, and after a basic quality check, they are stored in a database. The ISMN is being made possible through the voluntary contributions of scientists and networks from around the world. The soil moisture and meteorological data sets contained in the ISMN are shared by the different network operating organizations on a voluntary basis and free of cost. In June 2012, the ISMN contained the data of 40 networks, which together contain more than 1600 stations. Available data sets include historical observations as well as near-real-time measurements. Examples of the networks include the US Climate Reference network (United States, 114 stations), SCAN (United States, 182 stations), SNOTEL (United States, 381 stations), UMBRIA (Italy, 7 stations), OZNET (Australia, 64 stations), REMEDHUS (Spain, 18 stations), and SMOSMANIA (France, 21 stations). Apart from several recently established operational networks that share their data with the ISMN, the Global Soil Moisture Data Bank (Robock et al. 2000) merged its historical data collection with the ISMN and has now been closed. A complete list of networks that have already shared their soil moisture measurements with the ISMN are summarized in http://ismn.geo.tuwien.ac.at/networks. A Web interface of the ISMN with a map showing the spatial distribution of the stations as of October 2012 is shown in Figure 2.3. Users are able to access the harmonized data sets easily through this Web portal. A full description of the ISMN was recently given by Dorigo et al. (2011b). Currently, an enhanced quality control is being implemented, which should support the user in filtering the data sets for spurious observations (Gruber et al. 2013).

2.4.2 FLUXNET Network

FLUXNET, which was also mentioned in Chapter 1, is a global “network of networks” measuring a number of parameters, including soil moisture. It provides the entire required infrastructure for compiling, archiving, and distributing continuous measurements of soil moisture in different ecosystem conditions, acquired simultaneously to a number of other parameters characterizing land surface interaction processes. An overview of this network was provided in Chapter 1 and will not be included here for brevity. In respect to soil moisture measurement, in particular, at each FLUXNET site, soil moisture is measured at least in two depths (surface and root zone) at half-hourly time intervals. Soil moisture is a core parameter estimated in most, if not all, FLUXNET sites using largely the same type of ground instrumentation. As is also done with all the other parameters, the half-hourly soil moisture data are then passed from each site to their regional networks and then on to FLUXNET.
FIGURE 2.3
(See color insert.) Geographical distribution of the ISMN sites. Place marks indicate the station coordinates of the different networks contained in the ISMN database. The different colors refer to the various networks that provide data.
2.5 Conclusions

In view of the importance of information on the spatial distribution of SMC, its measurement has attracted the attention of scientists from many disciplines and decades of efforts have been dedicated to its estimation. This has led to a relatively mature understanding of the relationships between topographic, climatological/meteorological, hydrological, biotic, abiotic, and anthropogenic factors and SMC at localized scales.

This chapter has provided an overview of the wide variety of approaches available for measuring those parameters directly using ground instrumentation. As has been documented, there are many different options that can be considered, each having distinct practical advantages and disadvantages. Generally, the use of ground instrumentation has certain advantages, such as a relatively direct measurement, instrument portability, easy installation operation and maintenance, the ability to provide measurement at different depths, and also the relative maturity of the methods. However, use of ground measurement techniques has proven very difficult to implement practically over large areas. This is mainly because they can be complex, labor intensive, sometimes destructive to the study site, and not always reliable. Even if dense ground measurements are available, the heterogeneity of the observation site has to be taken into account. Different measurement methods, sensors, calibrations, and installation depths have to be considered as well when comparing measurements from different sites. In addition, the use of ground-based methods often requires the deployment of extensive equipment in the field in order to provide only localized estimates of SMC, making them unsuitable for measuring SMC over large spatial scales. Gravimetric sampling and networks of impedance probes based on dielectric methods appear to be two of the most reliable methods of estimating surface SMC at an accuracy level of ~4% vol vol$^{-1}$ or better, although inaccurate installation can lead to much larger errors than this.

With regard to the availability of ground measurements, an overview of the currently available operational networks showed that the FLUXNET and ISMN networks are currently the densest monitoring networks globally providing *in situ* observations of SMC and other ancillary parameters. One of the key advantages of FLUXNET in comparison to ISMN is that it provides simultaneously to soil moisture archived and new data of a large number of other *in situ* variables characterizing land surface interactions over well-organized ground station networks established in different ecosystems all over the world. One of the key advantages of ISMN includes the fact that it provides easy and rapid access to harmonized and quality-checked SMC ground measurements from a large number of locations distributed all over the world, amalgamating the efforts of different groups attempting to provide long-term measurements of SMC. On both networks the ground data provided are largely based on uniformly adopted and well-established measurement techniques between the sites, allowing data comparability between sites and studies belonging to each network, or even between these two networks. Thus, although FLUXNET and ISMN have two different purposes, they can work complementarily. FLUXNET coordinates the networks and makes decisions of where and which measurements should be taken, whereas the ISMN acts only as a hosting and harmonization facility with the key objective to collect and fuse everything that is available. Therefore it just holds data from important ground monitoring networks.

Clearly, there is a need for efforts such as those of FLUXNET and ISMN to be further supported by the scientific and user community in the future in order to be able to more accurately measure SMC spatially over different ecosystem conditions and to
better understand how the latter interplays with other parameters characterizing land surface interactions of the Earth system. Also, the increasing number of satellite missions related to soil moisture retrieval being placed in orbit has made it indispensable to develop the necessary infrastructure for validating remote sensing–derived estimates of SMC (an overview of methods is provided in Chapter 4). Thus a continuation of the initiatives supporting and expanding such ground observational networks in the future would be a very valuable investment from multiple perspectives, and its importance cannot be overstated.

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