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Abstract

Soil moisture is an important state variable in the terrestrial system because it controls the exchange of water and energy between the land surface and the atmosphere. In this paper, we review recent advances in non-invasive techniques that allow continuous non-invasive and contactless measurements of soil moisture dynamics at the field to basin scale. In particular, we report on 1) cosmic-ray neutron probes, 2) GNSS reflectometry, 3) ground-based microwave radiometry, 4) gamma-ray monitoring, 5) terrestrial gravimetry and 6) low-frequency electromagnetic surface waves. Each method is described in terms of its basic principle, measurement scales, calibration issues, measurement accuracy, and applications. We hope that this review will further stimulate the community to invest in the continued development of novel soil moisture sensing methods that

address the need for large-scale soil water content measurements with sufficiently high temporal resolution.

Introduction

Soil moisture is an important state variable in the terrestrial system because it controls the exchange of water and energy between the land surface and the atmosphere. Soil moisture is highly variable in space and time with characteristic length scales ranging from a few centimetres up to several kilometres and characteristic time scales ranging from minutes up to years[1]. Information on soil moisture dynamics is important for optimizing agricultural management[2], and to improve our understanding of biogeochemical processes[3], vadose zone processes[4], and atmospheric processes[5]. Many studies have analysed spatial variability of soil moisture at a range of scales, including the field scale[6, 7], the catchment scale[8, 9] the regional scale[10, 11], and the continental scale[12, 13].

The spatial characteristics of soil moisture data can be characterized using the "scale triplet" proposed by Blöschl and Sivapalan (1995)[14], encompassing support, spacing and extent. The support refers to the integration volume of the measurement methods, the spacing to the distance between single measurements, and the extent to the area over which measurements are available (e.g. area of measurement network). In a similar manner, we can define a scale triplet for time series of soil moisture[5]: 1) the integration time of the measurement, e.g. continuous, intermittent, day and night (equivalent to support in the spatial sense); 2) the measurement frequency (equivalent to spacing); and 3) the time period of the measurements (equivalent to extent).

Soil moisture is most commonly measured using in-situ electromagnetic (EM) soil moisture sensors with rather small support (typically smaller than 100 cm^3)[1]. EM sensors measure the dielectric permittivity of the soil and empirical or semi-theoretical models can be used to convert dielectric permittivity estimates into soil moisture[15, 16]. For instance, time domain reflectometry (TDR) sensors determine dielectric permittivity from the velocity of an EM wave that is emitted by a pulse generator and passed along a waveguides of the TDR probe[16]. Capacitance sensors are less expensive and easier to operate. They determine the soil permittivity by measuring the charge time of a capacitor[17]. Another cost-effective EM sensor type is the time domain transmission (TDT) sensor, which measures the propagation velocity of an EM wave along a closed transmission line[18, 19]. On the other hand, large scale soil moisture estimates with a larger support and extent can be acquired from microwave sensors on board of airborne or spaceborne platforms[20]. However, soil moisture obtained by remote sensing typically suffer from limitations related to spatial averaging, dense vegetation and small penetration depths[4].

An important problem in soil moisture assessment is the space-time trade-off. As the spatial support and extent of the soil moisture observation increases, the temporal measurement frequency typically decreases[21]. This problem is important because the behaviour of the entire system is not simply the sum of its parts in most environmental systems. Recently, Robinson et al. (2008)[21] analysed the spatial and temporal scales of existing geophysical methods to infer processes at the watershed and basin scale. They argued that considerable gaps exist beyond the measurement capabilities of current technologies and they made a plea for new technological developments to obtain measurements at larger scales, while still maintaining a sufficiently high temporal resolution.

In recent years, several new measurement technologies have emerged that attempt to address this need, including hydrogeophysical methods, in-situ sensor technologies, and distributed sensor networks[22-24].

In this paper, we aim to review recent advances in the development of non-invasive and contactless measurement techniques that allow the continuous determination of soil moisture dynamics at the field to catchment scale. In particular, we will focus on cosmic-ray neutron monitoring, GNSS (Global Navigation Satellite Systems) reflectrometry, ground-based microwave radiometry, gamma-ray monitoring, terrestrial gravimetry, and low-frequency electromagnetic surface waves. We selected these measurement techniques because they are particularly well-suited to fill the space-time scale gap in measurement capability. They have the following important advantages compared to other soil moisture sensing methods not reviewed here: i) soil structure remains undisturbed by the measurements, ii) the measurement device can be operated continuously (e.g., also during tilling operations), iii) and the soil moisture measurements integrate large areas (i.e. larger than 100 m^2).

The remainder of this review is organized as follows. In section 2, we present an overview of the selected methods for soil moisture determination in terms of their basic principle, measurement scales, calibration issues, measurement accuracy, and existing applications. In section 3, we discuss the development status and future prospects for all presented techniques.

Emerging non-invasive methods for soil moisture determination

Cosmic-ray neutron monitoring

Cosmic-ray neutron probes (CRNP) count secondary fast neutrons near the soil surface that are created by primary cosmic-ray particles in the atmosphere and in the soil[25, 26]. Hydrogen atoms in the soil, which are mainly present as water, moderate the secondary neutrons on the way back to the surface. Therefore, fewer neutrons escape when soil moisture content is high, whereas more neutrons are able to escape from a dry soil (Figure 1).

[Insert Figure 1 Approximately Here]

Figure 1: Schematic drawing showing that the emission of fast neutron (red dots) from the soil is controlled by soil water content (lower fast neutron intensity in case of higher hydrogen contents in the soil and vice versa).

This results in a negative correlation between near-surface fast neutron counts and soil moisture content and enables the use of the CRNP to sense soil moisture. In order to detect neutrons in the fast energy range, a detector tube filled with ^{3}He and shielded with polyethylene is used. The polyethylene shielding moderates fast neutrons to thermal neutrons before they enter the detector tube. Within the tube, neutrons that collide with ^3He atoms will produce electrons that induce pulses of electrical current that are counted by the detector.

Initial simulations with neutron interaction models have suggested that the horizontal footprint of the CRNP has a radius of about 300 m that is almost independent of soil moisture[26]. More recently, it was reported that the footprint is inversely proportional to air density and linearly proportional to the height of the sensor above the ground for heights up to 125 m[27]. The footprint also depends on atmospheric humidity (it decreases by 40 m for every 0.01 kg kg^{-1} increase in specific humidity). The measurement depth is strongly dependent on soil moisture (~70 cm for dry soils and ~12 cm for wet soils). In addition, the penetration depth will further decrease in the presence of further belowground hydrogen pools, e.g. organic matter, lattice water, root biomass[28].

Three parameterization methods have been suggested to convert neutron intensity into soil moisture: i) the site-specific N_0-method[29], ii) the universal calibration function (hmf-method)[30] and iii) the COsmic-ray Soil Moisture Interaction Code (COSMIC)[31]. The site-specific N_0-method requires intensive soil sampling to adequately estimate the N_0-calibration parameter. The universal calibration function was developed to overcome the necessity of local calibration campaigns and to allow measurements with a moving CRNP[32]. COSMIC attempts to reproduce the interaction between neutrons and soil moisture in a simplified way and requires site-specific calibration of three parameters. Recently, the performance of these three methods was compared at ten different sites in Germany and it was found that they performed equally well when uncertainty of neutron intensity measurements was considered[33]. However, sensor-to-sensor variability in counting efficiency should be considered to improve comparability between CRNP within a network[34]. In addition, Baatz et al. (2015)[34] presented a vegetation correction for CRNP applications and Franz et al. (2015)[35] demonstrated the use of cosmic-ray for monitoring soil moisture at 12x12 km spatial scale.

The CRNP counting rate precision is governed by Poisson statistics, which means that the standard deviation of counts depends on the total number of counts[36]. Thus, the measurement uncertainty decreases with increasing counting rates. High neutron counting rates can be expected for locations of high altitude and latitude because of higher incoming cosmic-ray intensity[37]. The uncertainty of the soil moisture measurement depends on the accuracy of the neutron count measurements[26] (~ 2%), which corresponds to a soil moisture content of ~0.01 m^3/m^3. However, the measurement accuracy also depends on other factors, such as the accuracy of the calibration procedure and the need to account for additional sources of hydrogen (e.g. above- and below-ground biomass, humidity of the lower atmosphere, lattice water of the soil minerals, organic matter and water in the litter layer, intercepted water in the canopy, and soil organic matter).

The most attractive feature of the CRNP is its ability to measure integral soil moisture at the field-scale with an acceptable temporal resolution (e.g. hourly). The applicability of the CRNP has been demonstrated for several different environmental settings. Franz et al.[38] found a soil moisture RMSE of 0.017 m^3/m^3 using a standard CRNP at a desert site (CRS-1000, Hydroinnova LLC, Albuquerque, NM, USA). For a location with high biomass and soil moisture contents, Bogena et al.[28] were still able to obtain daily mean soil moisture estimates with a RMSE smaller than 0.04 m^3/m^3. Recently, Lv et al. [39] showed that recalibrated CRNP output was able to capture soil moisture dynamics in a heterogeneous forest site in Utah, USA, with a RMSE of 0.011 m^3/m^3. In the past years, several networks of CNRP have been established in the USA[26], Germany[33], and Australia[40].

GNSS reflectrometry

Global Navigation Satellite Systems (GNSS) were originally used for positioning and navigation. However, GNSS signals can also be used to infer soil moisture[41]. The retrieval algorithm for soil moisture from single GNSS receivers is based on the power variations of the GNSS signal[42]. The direct signal from the GNSS satellite and the signal reflected at the land surface are simultaneously received at the antenna and add up to the observed signal power (Figure 2). The simultaneous reception of the direct and reflected signals causes an interference pattern in the signal power due to the different travel distances from the satellite to the antenna. The amplitude and phase of the interference pattern are affected by the soil permittivity, which is linked to the soil moisture content[43]. GNSS signals comprise two L-band frequencies with wavelengths of 19.05 and 24.45 cm. For soil moisture estimation, both dual frequency GNSS sensors that are permanently installed in geodetic networks as well as lower cost sensors that receive one frequency only can be used.

[Insert Figure 2 Approximately Here]

Figure 2: GNSS reflectometry consists of receiving the direct and the reflected GNSS signal by the GNSS antenna. When the satellite is approaching the horizon, the signal is reflected at a larger distance to the GNSS antenna.

The effective measurement depth of GNSS reflectometry strongly depends on soil moisture. For wet soils, the GNSS signal is reflected within the first millimeters below the land surface while for dry soils the signal penetrates deeper into the soil and is reflected within a near-surface layer of up to 7 cm depth[43]. The reflections start at a distance of 70 m from the GNSS antenna and approach the antenna until 2 m for a satellite pass from 5° to 30° elevation. The satellite needs about one hour for this passage. Within this time soil moisture information is obtained over a ground track about 70 m long and 4 m wide. The radius of the area that is scanned around a GNSS antenna varies from 50 m for an antenna installed at 1 m height to 330 m for an antenna installed at 20 m height. Naturally, the footprint is reduced if the line of sight from the antenna to the satellites is obstructed by trees, buildings, or mountains. The increasing number of GNSS satellites within the upcoming Satellite Navigation Systems Galileo, Beijdou and QZSS in parallel with the modernization of the U.S. GPS and the Russian GLONASS system will increase the temporal and spatial resolution of the soil moisture estimates obtained with GNSS reflectometry. While each GPS satellite has a revisit time of one day at any antenna location, this large number of satellites potentially allows for sub-daily resolution of soil moisture monitoring.

Empirical studies have shown that the amplitude, frequency, and phase of the interference pattern are affected by soil moisture[41, 43]. Chew et al.[44] found a linear relationship between soil moisture and the phase of the interferogram based on both field data and electro-dynamic forward modelling, with negligible variations of the slope of this relationship as a function of soil texture. Thus, relative soil moisture changes can be directly inferred from the GNSS signal. In order to obtain absolute soil moisture values, local calibration campaigns with in-situ soil moisture sensors are necessary for each site. Another approach is the calibration of absolute soil moisture by assuming that the minimum value seen in a sufficiently long GNSS time series corresponds to a plausible texture-dependent estimate of the residual soil moisture.

The accuracy of soil moisture estimates from GNSS reflectometry depends on (1) the vegetation cover of the ground, (2) the type of the GNSS signal, (3) the sampling rate, and (4) the calibration. Rodriguez-Alvarez et al.[45] showed that soil moisture derived from GNSS over bare soil agreed well with in-situ data (RMSE of 0.03 m^3/m^3). Soil moisture estimation in a corn field using a specifically designed GNSS receiving system of two antennas resulted in differences of less than 0.04 m^3/m^3 to in-situ data[46]. A sampling rate of 30 sec which is the standard for GNSS positioning reduces the accuracy of soil moisture estimates slightly, but Vey et al.[47] showed that the precision is still better than 0.02 m^3/m^3.

The application of GNSS reflectometry for soil moisture estimation has been successfully demonstrated for a few sites with different soil type, climate, and vegetation cover in Uzbekistan[41], Northern America[42, 48], and South Africa[47]. The direct surrounding of existing permanent GNSS stations is not always suitable for soil moisture estimation, especially if the stations are installed in urban areas with sealed surfaces. The method requires bare soil or sparse vegetation cover and wide open space without obstructions like trees or buildings. For the stations of the plate boundary observatory in North America, soil moisture is successfully estimated at 59 sites in near-real time[22].

Ground-based L-band microwave radiometry

Since the 1970s, L-band microwave radiometry has been recognized as an operational tool for soil moisture estimation because the microwave emissivity of soil is directly dependent on moisture content. At microwave frequencies, the measured radiance is proportional to the physical temperature and emissivity of the soil (Rayleigh–Jeans approximation of Planck's Law) and referred to as brightness temperature (T_B [K])[49]. A simple zero-order radiative transfer approach called the Tau-Omega model is classically used to model microwave emission[50]. In this approach, vegetation effects are parameterized by tau, the vegetation opacity, and omega, the single-scattering albedo. However, for dense vegetation, such as forest or mature corn, more physically-based approaches have to be used to better account for vegetation canopy scattering[51]. For smooth soil surfaces and homogeneous soils, the soil emissivity is usually computed from the soil dielectric permittivity using the Fresnel equations. More sophisticated models are used to account for soil surface roughness and layering in the soil[52, 53]. Finally, soil dielectric permittivity is related to soil moisture using dielectric mixing models[54].

The horizontal footprint of a ground-based L-band radiometer depends on the height of the antenna, the observation angle, and the antenna characteristics. Ground-based instruments are typically placed from a few meters to more than 20 m above the surface, which results in radiometer footprint on the order of tens of square meters. For example, if we consider an L-band radiometer (1.4 GHz) with a horn antenna fixed on a tower at 18 m above the ground, with an observation angle of 40° relative to nadir, and characterized by a -3 dB full beamwidth of 12°, the -3 dB footprint will be approximately 25 m^2 (elliptic footprint with half axes of about 3.2 and 2.5 m). The measurement depth depends on the soil moisture (between 2 and 5 cm).

Radiometer calibration generally requires both internal and external calibration[55]. The internal calibration consists of performing measurements with hot and cold internal noise reference sources connected to the radiometer input. From the known noise temperature of the calibration sources and the corresponding measured receiver output voltage, a linear calibration curve can be derived that is used to obtain the antenna temperature by linear interpolation. In addition, external calibration is realized by pointing the antenna to specific targets with well-known brightness temperatures, such as the sky (cold target: T_B ~5K) or a microwave absorber (hot target: T_B is equal to the physical temperature of the absorber). The external calibration is performed to correct the antenna temperature for the noise added by lossy feed cables connecting the receiving antenna with the radiometer unit and the noise added by the antenna itself. Internal calibration is typically performed before each measurement, while the external calibration is performed about once per day during continuous monitoring.

L-band (1-2 GHz) has been identified as the optimal frequency band for soil moisture estimation using radiometers because of the lower attenuation and scattering in soils and vegetation. Radiometer sensitivity is in general less than 1K[49], which should then result in a soil moisture estimation accuracy of better than 0.01-0.02 m^3/m^3. However, the soil moisture retrieval is also affected by soil surface roughness, vegetation cover, and soil heterogeneity, which can significantly reduce the accuracy of the estimation. The quality of the calibration as well as the dielectric mixing model will also affect the measurement accuracy. Over an agricultural bare soil, soil moisture was estimated with a RMSE of 0.02 m^3/m^3 after accounting for soil surface roughness[56]. Pardé et al.[57] carried out L-band measurements over a wheat field and found a RMSE of 0.051 m^3/m^3.

The potential of ground-based microwave radiometry for soil moisture monitoring and mapping at the field scale has been already demonstrated in many different contexts, such as bare agricultural soils[56], grassland[58], crop fields[57, 59], forested areas[60], and freezing soils[61]. A large number of these radiometer studies have been initiated in support of the ESA's Soil Moisture and Ocean Salinity (SMOS) mission launched in 2009 and the NASA's Soil Moisture Active Passive (SMAP) mission launched in 2015 in order to improve the understanding of passive microwave signatures of the Earth's surface and to validate the large-scale remote sensing soil moisture products.

Gamma-ray intensity monitoring

All rocks and soils emit gamma radiation at a range of energies due to the decay of radioactive isotopes (^{40}K, ^{238}U and ^{232}Th) and their progenies in soil[62]. The attenuation of gamma-rays in soil can be approximated by classical radiation intensity laws[63]. Since attenuation in water is higher than in air or solid soil particles, a negative correlation between measured gamma-ray intensity and soil moisture is expected. Gamma-ray intensity can be measured using airborne and ground-based platforms. Although the influence of soil moisture can be detected by airborne surveys[63], it is difficult to quantitatively determine soil moisture from such data because of the unknown spatial distribution of the radioactive isotopes that determine the background radiation intensity. Therefore, a more promising approach for soil moisture estimation from gamma-ray intensity is the use of permanently installed measurement stations that provide temporal changes in spectrometric or the total amount of gamma-ray intensity[64]. Here, the total amount of gamma-ray intensity is of particular interest because it can be measured with relatively cheap Geiger-Müller counters.

Gamma-ray attenuation strongly decreases with increasing energy[62], which means that high-energy gamma-rays travel further than low-energy gamma-rays. At a high-energy of 2.6 MeV, the radius of the horizontal footprint (90% of energy) is on the order of 250 m and independent of soil moisture for an airborne survey at a height of 100 m[62]. This value decreases with decreasing energy and also depends on the angular sensitivity of the detector. For gamma-ray intensity measurements near the surface, the footprint is much smaller. According to the approximate models used for airborne surveys, the radius of the horizontal footprint is on the order of several meters for a sensor height of 1 m at an energy of 2.6 MeV. However, a better assessment of the horizontal footprint using more advanced gamma-ray transport modelling is required to confirm this. The measurement depth similarly depends strongly on the gamma-ray energy[65]. At a high energy of 2.6 MeV, the measurement depth above which 90% of the measured gamma-rays originate is 24 cm in a homogeneous dry soil with a bulk density of 1.0 g cm^{-1}, and 15 cm in a dry soil with a bulk density of 1.6 g cm^{-1}. When these two soils are fully saturated, the measurement depths are reduced to 14 and 12 cm, respectively.

The gamma-ray intensity near the soil surface not only depends on the decay of radioactive isotopes in the soil. There are three main sources of additional gamma radiation: cosmic-rays that enter and interact with the atmosphere, anthropogenic ^{137}Cs from nuclear test and accidents, and atmospheric ^{222}Rn[66]. Therefore accurate soil moisture estimates from gamma-ray measurements can only be obtained when all interfering time-variable, anthropogenic, and non-terrestrial signals have been removed from the data. Loijens[65] provided a simple calibration relationship between the terrestrial component of gamma-ray intensity and gravimetric soil moisture. In principle, a single calibration measurement of gamma-ray intensity for known moisture would be sufficient to parameterize this relationship. However, this has not been extensively validated, and there is considerable need for further studies here.

Only very few studies have attempted to quantitatively relate soil moisture and gamma-ray intensity. Loijens[65] was able to estimate gravimetric soil moisture of the top 25 cm of the soil with an accuracy of 0.025 g g^{-1}. Nevertheless, more studies are required to establish measurement accuracy across a range of soil types with variable bulk density and different amounts of radioactive isotopes. Airborne gamma-ray surveys with low-flying airplanes have been used to determine soil moisture content[67]. However, such airborne surveys can only cover a relatively small area (<100 km^2), and the cost of airborne surveys are nowadays considered to be excessive for most purposes.

Terrestrial gravimetry

Gravimeters measure the strength of gravity, i.e. the sum of gravitational attraction and inertia forces. For a terrestrial instrument at rest, the latter reduces to centrifugal force. The conventional unit in gravimetry is the Gal (1 mGal = 10^{-5} m/s^2). The by far largest time-variable contribution to gravity, several hundred µGal, is caused by the direct (astronomical) tides, solid-Earth tides and ocean tides. Gravity variations induced by soil moisture and groundwater variations may be in the order of up to a few tens of µGal. Gravity variations can thus be converted into changes of volumetric moisture in the unsaturated zone if the depth of storage variations is known, and to water table changes when the specific yield is known. Nowadays, two principles are mostly used to design gravimeters. Relative gravimeters measure the force that is required to keep a test body in rest. While spring gravimeters employ a metal or quartz spring for this purpose, superconducting gravimeters (SGs) keep the test mass levitated within a magnetic field generated by a very stable current flowing through coils. Absolute gravimeters measure the motion path of a free-falling test body by tracking the location of a falling corner-cube reflector with laser interferometry within a vacuum tube.

Creutzfeldt et al.[68] found through simulations that a water layer of 1 m thickness, distributed along a realistic terrain with the gravimeter located close to an elevated topographic position in the center of the area, may cause gravity to increase by 52 µGal. Given the inverse distance relationship of gravity to mass sources it can be shown that about 95% of the local signal recorded by a gravimeter is generated within a radius of about 50 meters around the instrument if the mass changes occur at 1 meter below the (flat) terrain surface. A fundamental limitation common to all gravimeters is that an integral signal is recorded; i.e. the depth of soil moisture variation cannot be unequivocally defined by a gravimeter alone. The temporal resolution of gravimetry ranges from minutes in the case of continuous recording with superconducting gravimeters to a user-defined frequency, e.g., daily, monthly or seasonal, in the case of time-lapse monitoring with spring or absolute gravimeters.

The instrument output (e.g. the feedback voltage) is transferred by a calibrated scale factor into units of gravity using vertical baselines or other gravimeters. For superconducting gravimeters, the scale factor usually is nearly constant over time and does not pose a problem for hydrological applications while for spring gravimeters it may need to be determined on a regular basis. In addition, all gravimeters need to be corrected for drift effects. For instance, Reudink et al.[69] found that tilting a relative gravimeter by more than 5-6 degree over more than 20-30 min leads to exponential drifts which may initially amount up to 100 µGal. Superconducting gravimeters are susceptible to drifts in the order of some µGal/a. Drift calibration is commonly achieved by episodic (1-2 per year) comparison to absolute gravimeters. Furthermore, it is important to realize that a vertical motion of the instrument by 1 mm causes gravity changes of up to 0.3 µGal. Therefore, regular height checks are required (e.g. using a differential GPS).

The mere instrument precision is in the range of 0.1 µGal for superconducting gravimeters, which corresponds to a water storage change of 2.4 mm, up to several µGal for relative and absolute gravimeters. However, the accuracy of gravimetric measurements is limited by additional factors, e.g. local stability, ambient (micro-) seismicity (from earthquakes, wind- or sea wave-induced, or traffic). Furthermore, the removal of all other time-variable mass changes is required, and associated errors may lead to a less accurate residual signal for soil moisture estimation. Tidal effects can be removed with comparatively high accuracy using existing tide models. Barometric pressure effects can be accounted for through local admission factors or full-scale 3D atmospheric modelling[70]. Similarly, other environmental corrections, in particular regional and global oceanic and hydrological effects need to be removed both in terms of their mass attraction and loading effect on the gravimeter[71]. Errors in removal of unwanted large-scale signals may be reduced by common-mode rejection of two near-by gravimeters as they show up similarly in both instruments[72].

Example applications include Naujoks et al.[73], who isolated water storage dynamics among different topographic units of a hilly temperate headwater catchment using repeated gravity measurements and a superconducting gravimeter at the reference point. Pfeffer et al.[74] revealed a characteristic organization of spatio-temporal storage variations in the vadose zone of a semi-arid Sahelian hillslope that could be related to surface water infiltration processes. Creutzfeldt et al.[75] demonstrated the inter-annual impact of the Central European drought in 2003 on local water storage. Hector et al.[76] evaluated superconducting gravimeter applications for the case of a sub-humid site in Africa.

Low frequency electromagnetic surface waves

This approach for obtaining large-scale soil moisture estimates is based on a correlation between propagation characteristics of low frequency electromagnetic surface waves and the electrical conductivity and dielectric permittivity of the soil (Figure 3).

[Insert Figure 3 Approximately Here]

Figure 3: Schematic showing simplified low frequency surface radio wave propagation.

Consider an electromagnetic wave that travels from transmitter TX to receivers RX1 and RX2. The amplitude and phase of this wave are altered by the dielectric soil properties. By measuring the amplitude and phase variations, the average soil properties along transects d_1 and d_2, and between receiver RX1 and RX2 can be determined. Both natural sources like lightning strikes[77] and man-made transmitters[78] can be used as an electromagnetic source. The most suited frequency range for man-made sources is in the kHz to MHz frequency range, where radio, navigation and time dissemination transmitters operate. For example, the Normal Time Service Germany transmits at 77.5 kHz with a power of 50 kW, which results in a range of up to 2000 km. Although man-made transmitters can provide continuous measurements in principle, it was found that only selected time intervals are useful for evaluation. The most disturbing factor is the reflection of the emitted waves at the ionosphere boundary, which leads to multipath propagation interference. Typically, the best measurement time is around noon because solar radiation leads to strong ionospheric absorption without reflections.

The receiver distances are between tens of km and a few hundred km which corresponds to the integral lengths for the derived soil properties. The penetration depth of surface waves is variable and strongly depends on the frequency as well as the dielectric soil properties and soil layering. For 77.5 kHz, the typical penetration depths may be from a meter to tens of meters depending on the electrical properties of the critical zone. Soil layers may lead to anomalous propagation effects[79]. The expected temporal resolution is about one day because adequate conditions for radio wave propagation are required.

Wave propagation is primarily dependent on soil electrical conductivity and therefore temperature and salinity. A minor effect is due to dielectric permittivity. Varying groundwater table is a major disturbing influence. So far no stringent calibration method exists. Therefore, empirical or semi-empirical relationships have been developed based on reference point sampling along transects[80, 81].

The uncertainty of soil moisture measurements depends on the accurate determination of amplitude and phase of the electromagnetic waves. A main technical challenge is the GPS-based time synchronization of the widely separated receivers in the nanosecond range. Furthermore, time intervals without multi-path interference have to be selected. An overall accuracy in soil moisture cannot be specified so far, but a realistic operational target would be about 0.05 m^3/m^3 under the assumption that additional information about soil types along the measurement transect are available.

Kiseleva et al.[80] presented a first application of this method, in which a DCF77-time signal from Mainflingen, Germany, was used for a two year period. In their study, three stations were lined up at intervals of 20 km to measure the phase transition of the surface wave. The GPS time signal was used as a reference for the phase transition and several soil moisture and groundwater monitoring stations along the measurement section were used to calibrate and to evaluate the data.

Status and future prospects

In this final section, we discuss the development status and future prospects for all presented techniques. Figure 4 shows a schematic diagram highlighting the gap in measurement capability of classical soil moisture monitoring technologies beyond a certain measurement capability trajectory[21]. We extended this diagram by adding the emerging soil moisture sensing techniques discussed in this review in terms of achievable temporal resolution and spatial scale. For spatial scale, support was used for single instruments, and extent was used for network-compatible instruments. Clearly, the emerging methods are able to fill most of the identified scale gap.

[Insert Figure 4 Approximately Here]

Figure 4: Schematic diagram showing the trade-off of the spatial scale ("support" in terms of single sensors and "extent" in terms of networks) and the temporal resolution of existing soil moisture instruments and the potential of the emerging soil moisture sensing techniques discussed in this review. The acronyms CRNP and LFEMW refer to cosmic-ray neutron probe and low frequency electromagnetic surface waves, respectively.

Ground-based microwave radiometers, cosmic-ray neutron probes, and low frequency electromagnetic surface waves are measurement methods that have been explicitly developed for soil moisture monitoring. Despite their long existence, ground-based microwave radiometers have been typically used in a non-operational mode for the development of transfer algorithms that relate brightness temperature to soil moisture, and the validation of satellite data of brightness temperature. The main obstacles for their operational use are the complex post-processing of the raw data, and the measurement limitations in the presence of dense vegetation. On the other hand, the cosmic-ray neutron probe technology is more straightforward and affordable, which allows the establishment of cosmic-ray neutron probe networks to cover larger areas. To highlight this promising ability for networking, we have opted to represent the spatial scale of the cosmic-ray probe with the potential network extent instead of support in Figure 4. Several cosmic-ray probe networks already exist world-wide. The largest network of cosmic-ray neutron probes is the COSMOS network with more than 50 probes, distributed mainly in the USA[26]. Other operational cosmic-ray neutron probe networks have been set up in Germany[33], Australia[40], and the UK[82]. The neutron count data from these networks is typically freely available, which enables the direct use for environmental modelling activities, such as weather and flood forecasting.

In contrast, the analysis of low-frequency electromagnetic surface waves for the determination of soil moisture is a very new topic and the technique is still under development. Initial results of Kiseleva et al.[80] show considerable potential as well as significant limitations. In the future, it might be a candidate for national or international soil moisture measurement networks operating at scales of around a few tens of kilometers with measurement depths that encompass the critical zone for hydrological, agricultural, as well as meteorological applications. In principle, such networks of transmitters and receivers could allow for an areal estimation of soil moisture fields, in a similar fashion as commercial microwave links are being used to create spatial rainfall distributions[83].

Gravimeters, gamma-ray probes, and GNNS instruments are used for other purposes than soil moisture estimation in the first place. Gravimeters have originally been used for geophysical applications, and the development of high-precision (superconducting) gravimeters as a hydrological field instrument is at an early stage. Currently, the high costs of these instruments also limit their more widespread deployment in hydrological monitoring networks. Monitoring networks measuring outdoor gamma-ray radiation have been established after the nuclear reactor accident in Chernobyl in 1986 in most countries of the European Union (EU); and other international networks exist (e.g. RADNET in the USA). Such networks provide time-lapse measurements of gamma-ray intensity over a broad energy spectrum. Data from the European network have already been used to predict ^{222}Rn flux[84], but not yet to obtain estimates of soil moisture, and this seems a promising research avenue to obtain continental-scale information on soil moisture.

In the past 20 years, the world-wide network of GNSS instruments has increased immensely to obtain highly accurate positional information. For instance, the Plate Boundary Observatory in the US consists of 1100 stations, and its data has already been used to infer soil moisture variability at the continental scale[48]. Clearly, the advantage of using existing global networks of instruments eliminates the need for acquisition and maintenance of soil moisture sensors. However, the location of the instruments may not be representative for the region of interest in all cases (e.g. focus on urban areas), and the required information on influencing factors (e.g. landuse, sources of noise, precipitation etc.) that may be needed to evaluate this may not be available for all sites. In addition, local calibration may still be needed to derive soil moisture estimates with sufficient accuracy. A further limitation has to do with data availability. For instance, GNSS data is often archived only partially (e.g. without signal-to-noise ratio), which currently makes it difficult to extract useful information[48]. Nevertheless, the use of existing gamma-ray probes or GNSS equipment for soil moisture estimation has the potentially large advantage that existing networks can be used to provide soil moisture information in real time at more than thousand sites worldwide[85]. For this reason, we have again opted to represent both GNSS and gamma radiation networks with the spatial extent in Figure 4.

Table 1: Cost estimates for single instruments, approximated number of operational stations and soil moisture measurement accuracy ranges for the different methods

[Insert Table 1 Approximately Here]

Table 1 gives an overview of the instrumental costs, the number of existing operational stations and the measurement accuracy of the different methods. For instance, CRNP and GNSS can be considered as well established and promising approaches, especially CRNP for which a large sensor network is already operating worldwide. Ground based L-band radiometry are potentially useful, but only a couple of studies are available notwithstanding its long heritage. Terrestrial gravimetry has a lower potential to be used operationally for large scale soil moisture monitoring due to its high costs. The use of gamma radiation and low frequency electromagnetic surface waves (LFEMW) for soil moisture monitoring is still in the development phase. For gamma radiation, only a few early studies from the eighties are available, while only one conference paper has been published for LFEMW.

Conclusion

We reviewed recent advances in non-invasive techniques to provide continuous non-invasive and contactless measurements of soil moisture dynamics at the field to basin scale and highlighted their development status and future prospects. We hope that this review will further stimulate the hydrology and soil hydrology science community to continue the development of novel soil moisture sensing methods that address the need for large-scale soil water content measurements with sufficiently high temporal resolution. We are convinced that these techniques will improve the description of local-scale processes related to hydrological fluxes, which is of key importance to reduce the large uncertainties that are still present in large-scale models used to predict these fluxes.

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Table captions

Table 1: Cost estimates for single instruments, approximated number of operational stations and soil moisture measurement accuracy ranges for the different methods.

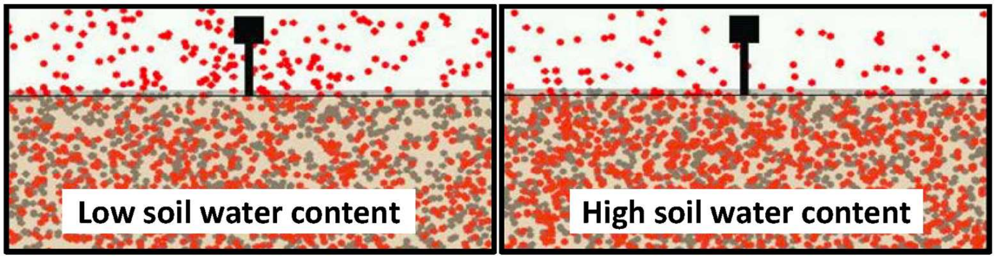
Figure captions

Figure 1: Schematic showing that the emission of fast neutron (red dots) from the soil is controlled by soil water content.

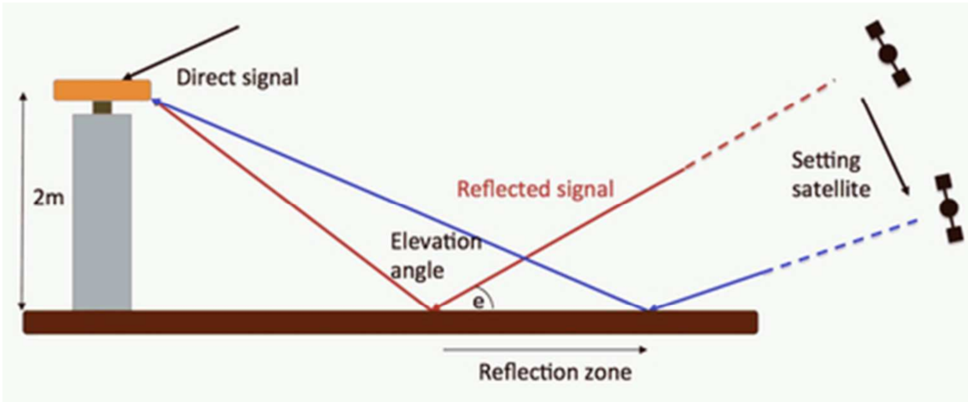
Figure 2: GNSS reflectometry consists of receiving the direct and the reflected GNSS signal by the GNSS antenna. When the satellite is approaching the horizon, the signal is reflected at a larger distance to the GNSS antenna.

Figure 3: Schematic showing simplified low frequency surface radio wave propagation.

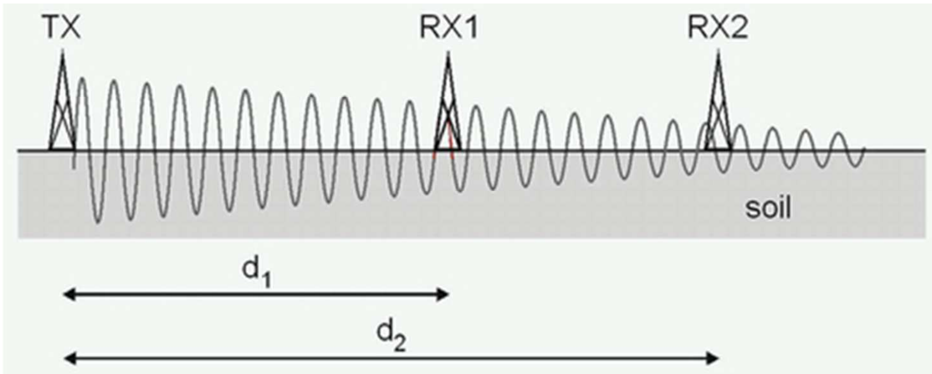
Figure 4: Schematic diagram showing the trade-off of the spatial scale ("support" in terms of single sensors and "extent" in terms of networks) and the temporal resolution of existing soil moisture instruments and the potential of the emerging soil moisture sensing techniques discussed in this review. *The acronyms CRNP and LFEMW refer to cosmic-ray neutron probe and low frequency electromagnetic surface waves, respectively.*



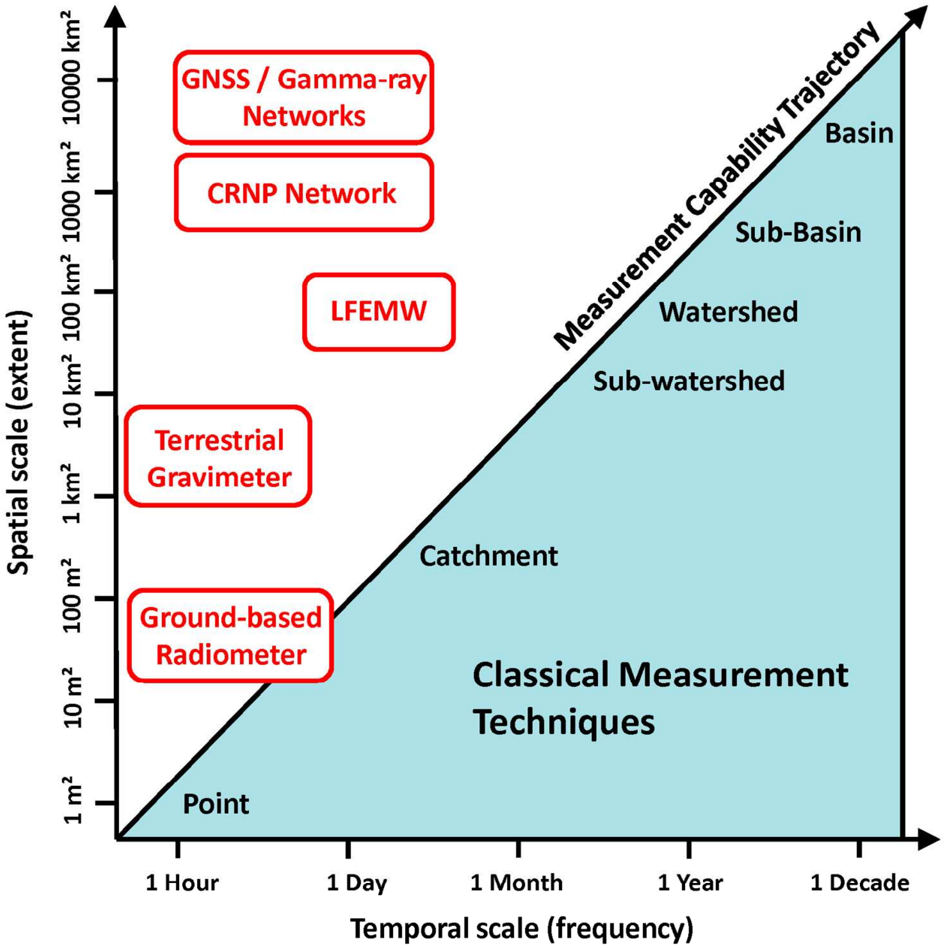
Schematic showing that the emission of fast neutron (red dots) from the soil is controlled by soil water content.
145x37mm (300 x 300 DPI)



GNSS reflectometry consists of receiving the direct and the reflected GNSS signal by the GNSS antenna. When the satellite is approaching the horizon, the signal is reflected at a larger distance to the GNSS antenna.
41x17mm (300 x 300 DPI)



Schematic showing simplified low frequency surface radio wave propagation.
39x15mm (300 x 300 DPI)



Schematic diagram showing the trade-off of the spatial scale ("support" in terms of single sensors and "extent" in terms of networks) and the temporal resolution of existing soil moisture instruments and the potential of the emerging soil moisture sensing techniques discussed in this review. The acronyms CRNP and LFEMW refer to cosmic-ray neutron probe and low frequency electromagnetic surface waves, respectively.
160x160mm (300 x 300 DPI)

Table 1: Cost estimates for single instruments, approximated number of operational stations and soil moisture measurement accuracy ranges for the different methods

Method	Approx. instrument costs [€]	Approx. number of operational stations	Measurement accuracy [Vol.%]
CRNP	10,000 – 25,000	200-300	~2 – 5
GNSS	2,000 – 12,000[a]	~2,000[b]	~3 – 5
Radiometry	50,000 – 100,000	10 – 15	~2 – 5
Gamma-ray	3,000 – 10,000[a]	>4,000[c]	~2 – 5
Gravimetry	~250,000[d]; 50-90,000[e]	~50[d, f]	Not defined[g]
LFEMW	~3,000	-	Target value: ~5

[a]Since operational GNSS and gamma-ray networks already exist, in principle no further instruments need to be purchased.

[b]Potentially usable for operational soil moisture monitoring; at the moment only 132 GNSS sites routinely process soil moisture (http://xenon.colorado.edu/portal).

[c]Potentially usable for operational soil moisture monitoring.

[d]Superconducting gravimeter (~36 Observatory Superconducting Gravimeter (OSG) and 16 Portable Superconducting Gravimeter (iGrav))

[e]Spring gravimeter

[f]This number refers to existing multi-purpose instruments. However, only few are already used in an operational mode for soil moisture monitoring.

[g]See main text for error sources on gravity measurements.