Remote sensing of soil moisture: implications for groundwater recharge

Thomas J. Jackson

Abstract Remote sensing provides information on the land surface. Therefore, linkages must be established if these data are to be used in groundwater and recharge analyses. Keys to this process are the use of remote sensing techniques that provide information on soil moisture and water-balance models that tie these observations to the recharge. Microwave remote sensing techniques are used to map the spatial domain of surface soil moisture and to monitor its temporal dynamics, information that cannot be measured using other techniques. The physical basis of this approach is presented with examples of how microwave remote sensing is utilized in groundwater recharge and related studies.

Résumé La télédétection fournit des informations sur la surface du sol. C'est pourquoi des liens doivent être établis lorsque ces données sont utilisées dans l'étude des eaux souterraines et de leur recharge. Les clés de cette démarche sont l'utilisation des techniques de télédétection qui informent sur l'humidité du sol et les modèles de bilan hydrologique qui associent ces observations à la recharge. Les techniques de télédétection dans le domaine des micro-ondes sont mises en œuvre pour cartographier l'humidité du sol en surface dans l'espace et pour suivre sa dynamique dans le temps, informations qui ne peuvent pas être obtenues par d'autres techniques. La base physique de cette approche est présentée avec des exemples d'utilisation de la télédétection micro-onde pour la recharge de nappes et dans les études associées.

Resumen La teledetección proporciona información de la superficie terrestre. Por ello, se debe establecer vínculos si se pretende utilizar dichos datos para análisis de aguas subterráneas y recarga. Son factores clave en este proceso el uso de técnicas de teledetección para recoger información sobre la humedad del suelo y los modelos de balance de agua que ligan estas observaciones con la recarga. Las técnicas de teledetección por microondas se emplean con el fin de cartografiar el dominio espacial de la humedad superficial del suelo y controlar su dinámica temporal, cosa que no se puede lograr con otros medios. Se presenta el fundamento físico de este enfoque mediante ejemplos de cómo la teledetección por microondas es aplicada en estudios de recarga y trabajos relacionados.

Keywords Groundwater recharge · Remote sensing · Soil moisture

Introduction

Quantitative information on groundwater recharge rates is important in planning and managing use and maintaining the quality of groundwater supplies (Bouwer 1989). Recharge can be determined at a point given an adequate representation of the soil column's physical characteristics and the forcing variables. However, like most hydrologic processes, it becomes problematic to perform analyses over large regions. Principal techniques for estimating recharge include monitoring the water balance, modeling, and tracers. In modeling or point-scale monitoring of the water balance, an estimate of the downward flux (recharge) to the water table is made.

In modeling approaches, it is usually difficult to describe the soil system a priori. Providing an accurate estimate of evapotranspiration (ET) for modeling and water-balance studies is also a problem. As noted by Bouwer (1989), the greatest need for information on recharge is in arid and semiarid regions, where ET is usually a significant component of the water-balance equation.

Remote sensing has the general advantage of providing a spatially distributed measurement on a temporal basis. However, remote sensing only observes the surface of the Earth. Therefore, a link must be established between the surface observation and the subsurface (groundwater) phenomena.

Photography and visible and near-infrared satellite observations are widely used in groundwater exploration

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(Waters et al. 1990; Engman and Gurney 1991; Meijerink 2000). Physical features of the landscape such as lineaments are detected in these images, and these provide valuable information for groundwater investigations.

An alternative approach is microwave remote sensing. At these lower microwave frequencies (<20 GHz), a layer of soil contributes to the microwave sensor measurement and, most importantly, it is the water content of this contributing thickness that determines the magnitude of the microwave signal. The contributing thickness is small, typically several centimeters, except under some rather specific conditions that are described in a later section. Therefore, for these data to be of value in assessing groundwater recharge, a relationship must be established between the surface and the soil moisture profile.

In this paper, the basic principles of microwave remote sensing of surface and soil profile moisture are presented. Included is a review of techniques that have been developed and demonstrated for (1) estimating the soil moisture profile from surface observations (with and without models), (2) measuring of the depth to shallow water tables, and (3) inferring hydraulic characteristics of the soil profile from surface observations. The use of microwave remote sensing as a groundwater exploration technique is also presented.

Traditional Applications of Remote Sensing in Groundwater Hydrology

Reviews of applications of remote sensing in groundwater hydrology are presented in Farnsworth et al. (1984), Waters et al. (1990), Engman and Gurney (1991), and Meijerink (2000). All of these reviews note that remote sensing has been widely used as a tool, mostly to complement standard geophysical techniques. Meijerink (2000) suggests two roles for remote sensing: (1) conceptualizing the hydrogeology in order to develop a model, and (2) defining the upper boundary condition in water-balance computations.

The first role, conceptualizing the hydrogeology, has been the traditional role of remote sensing and is widely applied. Aquifer features can be observed in satellite and aircraft images. These features include landforms, drainage patterns and textures, vegetation cover, and lineaments. Waters et al. (1990) categorize these features into two groups, linear features and thematic mapping.

Meijerink (2000) recognizes the value of remote sensing in recharge studies and suggests that this technique can provide both qualitative and quantitative information. Using conventional assessment and modeling techniques, the overall recharge of an aquifer can be quantified. Meijerink (2000) proposes that remote sensing could be used to improve on this average recharge by refining the spatial pattern of the recharge. Observations of the physiography and vegetation, which are readily detected using imagery, can aid in this process.

Vegetation patterns in a particular environment can provide an indicator of recharge. In semiarid and arid environments, it can be inferred that vegetation suggests the presence of soil moisture, some of which may contribute to recharge (Finch 1990). Meijerink (2000) suggests that the accuracy of more quantitative methods is limited by the description of the spatial system (horizontal and vertical), the soil hydraulic properties, the vegetation root network, and the adequacy of the forcing-variable observations needed for modeling.

Microwave Remote Sensing of Surface Soil Moisture

Microwave remote sensing provides a direct measurement of the surface soil moisture for a range of vegetation cover conditions within reasonable error bounds. Two basic approaches are used, passive and active. In passive methods, the natural thermal emission of the land surface (or brightness temperature) is measured at microwave wavelengths, using very sensitive detectors. In active methods or radar, a microwave pulse is sent and received. The power of the received signal is compared to that which was sent to determine the backscattering coefficient.

The microwave region of the electromagnetic spectrum consists of frequencies of 0.3–30 GHz. This region is subdivided into bands, which are often referred to by a lettering system. Some of the relevant bands that are used in Earth remote sensing are: K (18–27 GHz), X (8–12 GHz), C (4–8 GHz), and L (1–2 GHz). Within these bands, only small ranges exist that are protected for scientific applications, such as radioastronomy and passive sensing of the Earth's surface.

A general advantage of microwave sensors (in contrast to visible and infrared) is that observations can be made through cloud cover, because the atmosphere is nearly transparent, particularly at frequencies <10 GHz. In addition, these measurements are not dependent on solar illumination and can be made at any time of the day or night. Instruments can be mounted on trucks, aircraft, and spacecraft for repetitive large-area observations.

Microwave sensors operating at very low microwave frequencies (<6 GHz) provide the best soil moisture information. At low frequencies, attenuation and scattering problems associated with the atmosphere and vegetation are less significant, the instruments respond to a deeper soil layer, and a higher sensitivity to soil water content is present.

Reflectivity and Soil Moisture

Active and passive sensors provide different types of measurements, which are determined by various physical phenomena. However, both types of sensors provide information on the surface reflectivity. The essential relationship needed to utilize microwave remote sensing is a link between reflectivity and soil moisture.

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Assuming that the Earth is a plane surface with surface geometric variations and volume discontinuities much less than the wavelength, only refraction and absorption of the media need to be considered. This situation permits the use of the Fresnel reflection equations as a model of the system (Ulaby et al. 1986). These equations predict the surface reflectivity as a function of dielectric constant and the viewing angle, based on the polarization of the sensor (horizontal or vertical). The Fresnel equations apply when the two media at the interface each have uniform dielectric properties.

From the reflectivity, the dielectric constant of the soil can be estimated. The dielectric constant of soil is a composite of the values of its components: air, soil, and water. Although the dielectric constant is a complex number, for soil mixtures the imaginary part is small and can be ignored for computational purposes without introducing significant error. Values of the real part of the dielectric constant for air and dry soil particles are 1 and 5, respectively. Therefore, a very dry soil has a dielectric constant of about 3. Water has a value of about 80 at low frequencies. The basic reason microwave remote sensing is capable of providing soil moisture information is this large difference between the dielectric constants of water and the other components. Because the dielectric constant is a volume property, the volumetric fraction of each component is involved in the computation of the mixture dielectric constant. The computation of the mixture dielectric constant (soil, air, and water) has been the subject of several studies, and different theories exist as to the exact form of the mixing equation (Schmugge 1980; Dobson et al. 1985).

The dielectric constant of water referred to above is that of free water, in which the molecules are able to rotate and align with an electrical field. However, not all the water in soil satisfies this condition. Schmugge (1980) suggests that some water in the soil has different properties. He proposes that for a given soil these properties could be estimated using soil texture in much the same way that pedo-transfer functions are used to estimate 15-bar and 0.33-bar water contents based on texture (Rawls et al. 1993). Schmugge proposes that the initial water added to dry soil below a "transition" water content is held more tightly by the soil particles and has the dielectric properties of frozen water (~3).

Based upon the discussion above, four components must be considered in computing the dielectric constant of soil: air, soil particles, bound water, and free water. Thus, in order to interpret the data correctly, some knowledge of the soil texture is needed. Dielectric mixing models for soils are presented by Wang and Schmugge (1980), Dobson et al. (1985), and Hallikainen et al. (1985). Based on an estimate of the mixture dielectric constant derived from the Fresnel equations and soil texture, volumetric soil moisture can be estimated using an inversion of the model.

Various theories describe the reflection resulting from a soil profile with uniform or varying properties (Njoku and Kong 1977). The computations involve a nonlinear weighting that decays with depth. Some modeling studies suggest that this dominant depth is one tenth the wavelength (Wilheit 1978). Field experiments (Jackson and Schmugge 1989; Owe and van de Griend 1998) suggest that the contributing depth is about one quarter the wavelength (based on a wavelength range of 2–21 cm).

Passive Microwave Techniques

Passive microwave remote sensing utilizes radiometers that measure the natural thermal radio emission within a narrow band centered around a particular frequency. The measurement provided is the brightness temperature in degrees Kelvin, T_B, which includes contributions from the atmosphere, reflected sky radiation, and the land surface. Atmospheric contributions are negligible at frequencies <10 GHz, and the following section assumes this to be the case. Galactic and cosmic radiation contribute to sky radiation and have a known value that varies very little in the frequency range used for observations of soil water content (T_{sky} ~4 K). The brightness temperature of a surface is equal to its emissivity (e) multiplied by its physical temperature (T). The emissivity is equal to 1 minus the reflectivity, which provides the link to the Fresnel equations and soil moisture for passive microwave remote sensing.

Based upon the above and neglecting atmospheric contributions, the equation for T_B is

$$T_B = eT + [1 - e]\, T_{sky} \tag{1}$$

The second term of Eq. (1) is about 2 K. A typical range of response for a soil is 60 K; therefore, the reflected sky contribution can be dropped for computational purposes. Equation (1) can be rearranged as follows:

$$e = \frac{T_B}{T} \tag{2}$$

If the physical temperature is estimated independently, the emissivity can be determined from T_B. The physical temperature can be estimated using surrogates based on satellite surface temperature, air-temperature observations, or forecast model predictions.

For natural conditions, varying degrees of vegetation type and density are likely to be encountered. The presence of vegetation has a major impact on the microwave measurement. Vegetation reduces the sensitivity of the retrieval algorithm to changes in soil water content by attenuating the soil signal and by adding a microwave emission of its own to the microwave measurement. This attenuation increases with increasing microwave frequency, which is another important reason for using lower frequencies. Attenuation is characterized by the optical depth of the vegetation canopy. Jackson and Schmugge (1991) present a method for estimating optical depth that utilizes information on the vegetation type (typically derived from land cover) and vegetation water content, which is estimated using visible/near-infrared remote sensing.

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After performing the vegetation correction, one can obtain an estimate of the emissivity of the soil surface, which includes the effects of surface roughness. These effects must also be removed in order to determine the equivalent smooth-surface soil emissivity, which is required for the Fresnel equation inversion. A commonly used approach for this roughness correction is a parameterization presented in Choudhury et al. (1979). This technique uses information on surface roughness that is typically described by the standard deviation of the surface heights.

Active Microwave Methods

Active microwave sensors or radars measure the sent and received power to yield a variable called the backscattering coefficient (σ^o). The backscattering coefficient is related to the surface reflectivity (Ulaby et al. 1986). As described previously, the reflectivity is then used to determine surface soil moisture. For active techniques, the link between the measurement of the backscattering coefficient and the surface reflectivity is more complex than for passive methods. The geometric properties of the soil surface and vegetation have a greater effect on these measurements and simple correction procedures are difficult to develop.

The signals sent and received by a radar are usually linearly polarized, either horizontal (H) or vertical (V). Possible combinations are HH, VV, HV, and VH. Advanced multipolarization systems can make all of these measurements simultaneously.

For bare soils, all models that relate the backscattering coefficient to soil moisture require at least two soil parameters, the dielectric constant and the surface height standard deviation. This means that in order to invert these models, the surface height standard deviation must be accurately estimated.

For a given sensor configuration of frequency and viewing angle, different results are obtained at different polarizations. Therefore, most approaches to determining soil moisture with active microwave methods utilize dual polarization measurements. With two independent measurements of two dependent variables, both the dielectric constant and the surface height standard deviation can be solved for. Algorithms incorporating this approach for bare soils are presented in Oh et al. (1992), Dubois et al. (1995), and Shi et al. (1995). A robust approach to account for vegetation has not yet been developed and validated.

Active microwave sensors on aircraft and spacecraft typically employ synthetic aperture radar (SAR), which utilizes the motion of the platform to synthesize larger antennas. Exceptional spatial resolutions with footprints of about 20 m can be achieved from satellite altitudes.

Available Microwave Remote Sensing Systems

Aircraft platforms

Aircraft-based microwave instruments are especially useful in studies requiring the mapping of large areas. In most cases, they offer better spatial resolution (as low as several meters) than satellite systems, as well as more control over the frequency and timing of coverage.

A challenge facing passive microwave remote sensing from space has been spatial resolution. For a given antenna size, the footprint size increases as frequency decreases and altitude increases. Most of the recent soil moisture studies have considered this issue and have utilized the electronically scanned thinned array radiometer (ESTAR) (Le Vine et al. 1994).

ESTAR is an L-band H-polarized passive microwave instrument that provides image products. It also is a prototype for a new type of sensor system that uses synthetic aperture antenna technology to solve the high-altitude spatial resolution problem described earlier.

Several active microwave aircraft systems are in operation. One of the most widely used for studies related to soil moisture is the AIRSAR, operated by NASA Jet Propulsion Laboratory (Dubois et al. 1995). The AIRSAR flies on a DC-8 aircraft and provides multipolarization data at frequencies of 5.2, 1.2, and 0.4 GHz (C, L, and P-band). It is very efficient for mapping large areas and provides exceptional spatial resolution, on the order of several meters.

Satellite systems

Satellite-based sensors offer the advantages of large-area mapping and long-term repetitive coverage. Revisit time is a critical problem in studies involving rapidly changing conditions, such as the water content of surface soils. With very wide swaths, twice daily coverage can be obtained with a polar orbiting satellite. For most satellites, especially if constant or narrow ranges of the viewing angle are important, the revisit time is much longer. Optimizing the time and frequency of coverage is a critical problem for studies of soil water content.

Currently, all passive microwave sensors on satellite platforms operate at high frequencies (>6 GHz). Of particular note is the Special Satellite Microwave/Imager (SSM/I) package on the Defense Meteorological Satellite Platforms (Hollinger et al. 1990). These satellites have been in operation since 1987 and provide high frequencies and two polarizations (see Table 1). Interpreting data from the SSM/I to extract surface information requires accounting for atmospheric effects on the measurement. When one considers the atmospheric correction, the significance of vegetation attenuation, and the shallow contributing depth of soil for these high frequencies, it becomes apparent that the data are of limited value for estimating soil water content. However, data from the SSM/I can be used under some circumstances, such as in arid and semiarid areas with low amounts of vegetation. Spatial resolution of the SSM/I is very coarse, as shown in Table 1. The SSM/I utilizes conical scanning, which

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Table 1 Passive microwave satellite characteristics

Satellite	Frequency (GHz)	Polarization	Footprint resolution (km)	Incidence angle (°)	Equatorial crossing time (local)
SSM/I	19.4	H and V	69×43	53.1	0922
	22.2	V	60×40		0543
	37.0	H and V	37×28		1000
	85.5	H and V	15×13		
TMI	10.7	V, H	59×36	52.75	Changes
	19.4	V, H	31×18		
	21.3	H	27×17		
	37.0	V, H	16×10		
	85.5	V, H	7×4		
MSMR	6.6	H and V	105×68	49.7	1200
	10.7	H and V	66×43		
	18.0	H and V	40×26		
	21.0	H and V	34×22		
AMSR (NASA)	6.9	H and V	75×43	55.0	1330
	10.7	H and V	48×27		
	18.7	H and V	27×16		
	23.8	H and V	31×18		
	36.5	H and V	16×9		
	89.0	H and V	7×4		
AMSR (Japan)	6.9	H and V	71×41	55.0	1030
	10.7	H and V	46×26		
	18.7	H and V	25×15		
	23.8	H and V	23×14		
	36.5	H and V	14×8		
	89.0	H and V	6×4		

provides measurements at the same viewing angle at all beam positions on a swath. This approach makes data interpretation more straightforward and simplifies image comparisons. As many as four SSM/I satellites are in operation at any given period. Therefore, frequent and even multiple daily passes are typical for most regions of the Earth. Data from the SSM/I are publicly available.

Another option is the Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (TMI) on the TRMM satellite (Kummerow et al. 1998). It is a five-channel, dual-polarized, passive microwave radiometer with a constant viewing angle of 53°. The lowest TMI frequency is 10 GHz (see Table 1), about half that of the SSM/I. The TMI has a higher spatial resolution as compared to the SSM/I. TRMM only provides coverage of the tropics, which includes latitudes between 40°N and 40°S for the TMI instrument. However, a unique capability of the TMI is its ability to collect data daily, and in many cases more often, within some latitude ranges. This capability could facilitate multitemporal and diurnal analyses. Data from the TMI are publicly available.

At the present time, the Indian Space Research Organization is operating a satellite called Oceansat-1 (Sharma 2000). This satellite includes an instrument called the Multifrequency Scanning Microwave Radiometer (MSMR), which has a 6.6 GHz channel (see Table 1). Although this low frequency is an advantage for soil moisture, the very large footprint (>100 km) is a significant problem.

The most recent options are the Advanced Microwave Scanning Radiometer (AMSR) satellite systems that include a 6.9 GHz channel with 60-km spatial resolution (see Table 1). AMSR holds great promise for estimating soil water content in sparsely vegetated regions and is the best possibility in the near term for mapping soil water. Based on published results and supporting theory (Wang 1985; Choudhury and Golus 1988; Owe et al. 1992; Ahmed 1995; Njoku and Li 1999; Koike et al. 2000), this instrument should be able to provide information about soil water content in regions of low vegetation cover, less than 1 kg/m^2 vegetation water content. NASA and Japan each plan to launch one of these instruments in 2002.

A system called the Scanning Multifrequency Microwave Radiometer (SMMR) operated between 1978 and 1987. This system included a 6.6 GHz channel; however, like the MSMR it had coarse resolution (150 km). Several attempts have been made to utilize data from SMMR in soil moisture studies (Owe et al. 1992; Lakshmi et al. 1997; Vinnikov et al. 1999). However, the combination of poor resolution and lack of ground validation limited its use. Data from this instrument are available through NASA.

Research programs are under way to develop and implement space-based systems with a 1.4-GHz channel that would provide improved global soil moisture information. Toward that goal, the European Space Agency is developing a sensor system called the Soil Moisture Ocean Salinity (SMOS) mission (Wigneron et al. 2000).

At present, several radar satellites are in orbit. The European Space Agency (ESA) has operated a satellite SAR series called ERS since 1991, which provides

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C-band VV at a relatively low incidence angle of 23°. Although numerous investigations have been conducted that attempt to utilize ERS data, few results have been reported in the area of soil moisture estimation. This paucity is due to the limitations of using a single short wavelength and a single polarization SAR with an exact repeat cycle of 35 days. With this kind of temporal coverage, the data are of little value in process studies. The next satellite in this series is called Envisat and will include a C-band SAR with multiple polarization capabilities. It will also offer the option of varying the incidence angle to allow for different viewing angles and more frequent coverage if angle is not a critical parameter in the application.

The Canadian Space Agency operates a C-band satellite SAR called Radarsat. Radarsat offers HH polarization and has more flexibility in its data-collection modes. Options include a variable viewing angle and a wide swath (large range of incidence angles). These choices offer more frequent temporal coverage of a particular region of the Earth if angle is not important.

Japan will include an L-band SAR called PALSAR on an upcoming satellite, the Advanced Land Observing System (ALOS). The lower frequency will offer information that is different from that offered by other satellite SAR systems operating at C-band. PALSAR will have a multipolarization mode as well as varying incidence angles.

A multifrequency–multipolarization SAR called SIR-C/X-SAR was flown on the Space Shuttle in 1994. This instrument included X, C, and L-band radar sensors. Two missions, one in April and the other in October, provided a large number and variety of observations for selected test sites, some of which focused on soil moisture.

Application Example: Large-Area Multitemporal Aircraft Mapping

Washita'92 was a large-scale study of remote sensing and hydrology conducted using ESTAR over the Little Washita watershed in southwestern Oklahoma, USA (Jackson et al. 1995). Passive and active microwave observations were made over a 9-day period in June 1992. The watershed was saturated with a great deal of standing water at the outset of the study. During the experiment, no rainfall occurred and observations of surface soil water content exhibited a dry-down pattern over the period. Observations of surface soil water content were made at sites distributed over the area. Significant variations in the level and rate of change in surface soil water content were noted over areas dominated by different soil textures.

Passive microwave observations were made on 8 of the 9 days of the study period. The ESTAR data were processed to produce brightness temperature maps of a 740-km^2 area at a 200-m resolution on each of the 8 days. Using the retrieval algorithm of soil water content, these brightness temperature data were converted to images of soil water content. Gray-scale images for each day are shown in Fig. 1. These data exhibit significant spatial and temporal patterns. Spatial patterns are associated with soil textures, and temporal patterns are associated with drainage and evaporative processes.

Surface and Profile Relationships

Information on the state and temporal variation of the unsaturated zone of the soil can be used to estimate recharge. This information is of significant value if the data are provided as a spatially distributed product. Remote sensing satisfies the spatial and temporal needs; however, it cannot be used to directly assess the entire depth of the unsaturated zone without some additional information.

Establishing a link between the easily accessible surface layer and the full soil profile has long been a research goal. A foundation for this endeavor is described in Jackson (1980). In that study, under the assumption of hydraulic equilibrium within a soil profile of known properties, it was shown that a theoretical basis exists for surface-profile relationships and that the chances of success can be improved with additional observations at great soil depths at particular times of the day (early morning/pre dawn).

Arya et al. (1983) examined the correlation between surface observations and the soil moisture profile. They observed that the correlation decreases as depth of the profile being estimated increases. Better results would be expected for vegetated fields than for bare soil, because vegetation tends to make the profile of surface soil moisture more homogeneous with depth. The authors also compared the differences in profile water determined by using this approach and by using the measured net surface flux. In this study, the two were nearly equal, which probably indicates that no recharge or flux was occurring across the lower boundary.

Jackson et al. (1987) combined spatially distributed remotely sensed surface observations of soil moisture over a large area in the Texas High Plains region (USA) of the Ogallala aquifer with limited ground profile observations, in order to produce maps of preplanting soil moisture profiles. The conventional approach to generating the soil moisture product involved sampling the profile at selected locations and then developing a contour map. The accuracy of this product is dependent on the number of points and how well they represent the local conditions at the field scale. In the remote sensing approach, a correlation was established between (1) the surface observation determined using 1.4-GHz passive microwave data and (2) the profile of soil moisture at the observation points. Using this relationship, at each remote sensing data point an estimate of the profile of soil moisture was produced. If repeated on a temporal basis, this technique would provide spatial information on the flux of the soil water profile.

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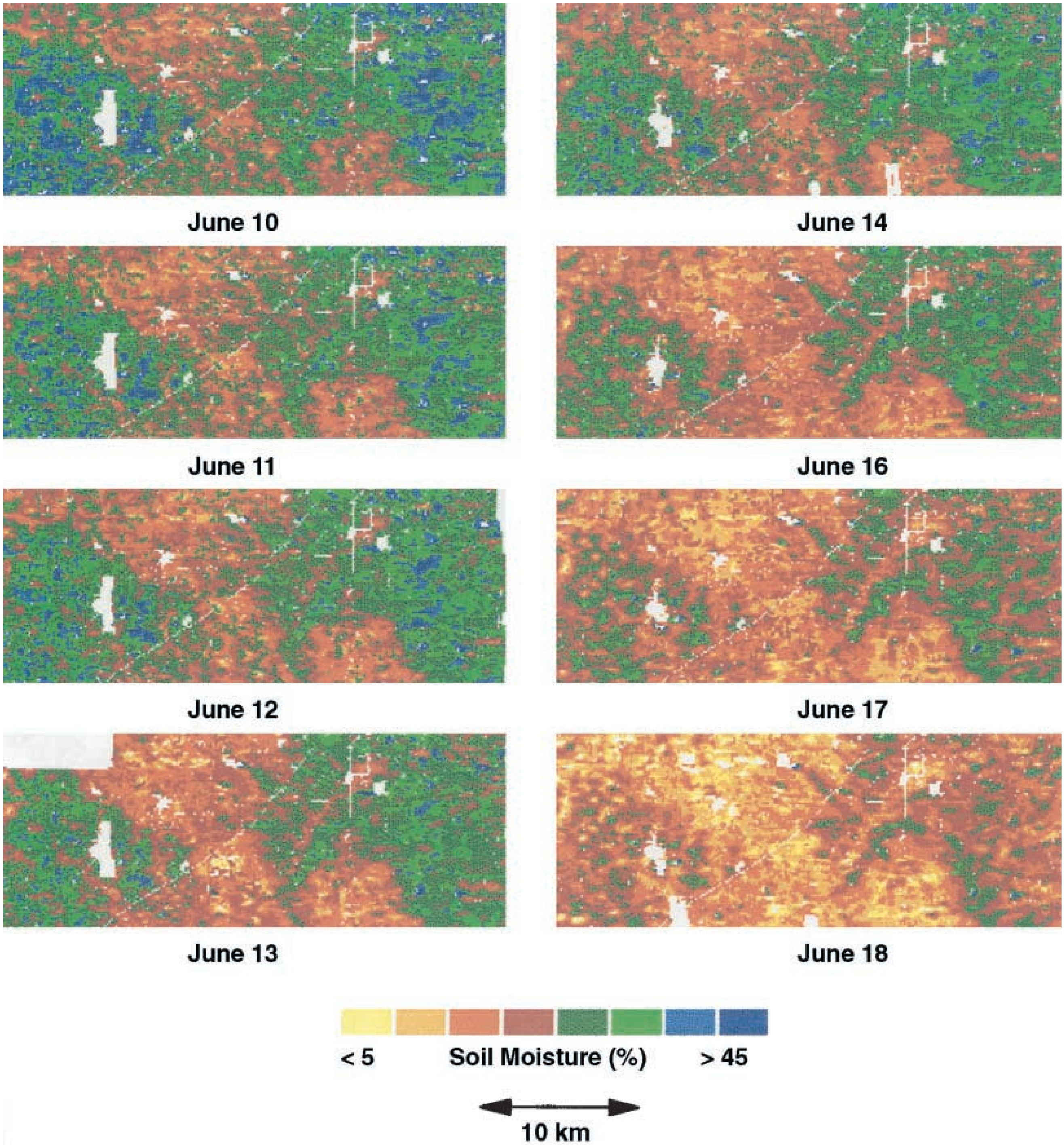

Fig. 1 Maps of soil water content for the Little Washita watershed (Oklahoma, USA) derived from passive microwave data for June 1992. Spatial resolution is 200 m

Hydraulic Properties

Physical and hydraulic properties of soil are of value for water-balance studies and simulations. Although these data can be obtained at the field point scale, the data are not available over large areas, do not take into account spatial variability, and are costly and difficult to obtain.

Temporal observations of soil moisture were used in the work of Ahuja et al. (1993), Hollenbeck et al. (1996), and Mattikalli et al. (1998a). These studies constrained the problem by minimizing the role of the surface flux, or by specifying it, in order to estimate the hydraulic properties of the integrated soil profile.

Studies by Camillo et al. (1986) and van de Griend and O'Neill (1986) employed ground-based passive microwave remote sensing and physical models for the estimation of the saturated hydraulic conductivity. In these studies, the soil properties at the plot scale were derived

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through an iterative process of matching remotely sensed T_B with values generated by a microwave simulation model. This approach requires detailed inputs describing the profile of soil water content and temperature, which are not available over large areas.

Ahuja et al. (1993) hypothesized that the change in soil surface moisture following a wetting event and 2 days later could be used to determine the average hydraulic conductivity of the soil profile. Using simulations for soils of different textures, they observed that a relationship exists that is strongest for sandy soils and weakens as clay content increases. In addition, they observed that a measurement of the 0–5 cm layer provides as much information as a 0–30 cm observation on the deep soil moisture profile. These relationships were affected by evaporation; however, the effect was more significant for soils with lower hydraulic conductivity and with a shallow depth of observation. Tests using observations of soil moisture showed R^2 values that were generally greater than 0.6. Chen et al. (1993) followed up on this approach and utilized a time series of soil moisture to estimate hydraulic properties of macropore soils, which are difficult to characterize based upon readily available soils data.

Hollenbeck et al. (1996) explored the use of passive microwave observations at 1.4 GHz for identifying areas of relatively slow or fast drainage in a region. Differences in drainage rates were interpreted as being caused by heterogeneity of the soil hydraulic properties in the region. In this study, the responses were correlated with soil type and geomorphic features. The authors note that antecedent conditions and the timing of the observations impact the value of the observations for assessing soil properties.

Mattikalli et al. (1998a, 1998b) took the approach presented by Ahuja et al. (1993) a step further by utilizing remotely sensed data to derive spatially distributed information. They hypothesized that surface soil moisture changes could be used to identify soil texture classes. A conclusion was that even if this method were not highly accurate for each and every sensor resolution element (pixel), the results would significantly improve the definition of the spatial domain of the soil hydraulic properties. In their opinion, this result was more valuable than the accuracy of individual point estimates.

Mattikalli et al. (1998b) used microwave remote sensing data from the Washita'92 experiment, described earlier to obtain spatial and multitemporal data on soil water content over the Little Washita watershed in Oklahoma. Analysis of the multitemporal water content maps with the soil maps suggested that the remotely sensed soil moisture and its temporal changes could be used to identify soil texture and to estimate soil hydraulic properties as hypothesized. Validations of the technique indicate that this result could be accomplished with acceptable accuracy.

Thermal Remote Sensing of Subsurface Water

Nearly all of the examples presented above utilize the microwave portion of the electromagnetic spectrum. However, subsurface water-related features of the landscape can also be detected by using thermal infrared methods. Surface temperature observations are widely available at a variety of spatial and temporal scales.

Van de Griend et al. (1985) examined the use of daily maximum and minimum surface temperatures for detecting the presence of shallow water tables. Using a simulation model, the authors generated sequences of daily minimums and maximums for various soil moisture conditions with and without a shallow water table. For the water-table tests, the depth ranged from 10–250 cm.

What van de Griend et al. (1985) observed was that when the water table was within a certain distance of the surface (90 cm for their test, but this is soil-texture dependent), the capillary rise provided enough moisture to allow ET to keep the surface cool, and the resulting difference between the minimum and maximum surface temperature was low. Greater water-table depths resulted in warmer and dryer surfaces. The authors suggest that if measurements were made using thermal infrared sensors after a long period without rain, it should be possible to map regions of shallow water table and infer recharge and discharge.

Integrating Satellite Estimates of Soil Moisture with a Water-Balance Model for Regional Recharge Assessment

Gouweleeuw (2000) conducted an investigation that utilized satellite-based passive microwave remote sensing of surface soil moisture and a water-balance model to determine the annual groundwater recharge for the West La Mancha catchment in semiarid Spain. As described in previous sections, the surface soil moisture can be measured and monitored using passive microwave sensors. In this study, the author utilized a data set collected by the SMMR between 1978 and 1987. SMMR is not an ideal sensor of surface soil moisture because it operates at higher frequencies (>6.6 GHz) than desired and it has a very coarse spatial resolution of 150 km. However, regions with low levels of vegetation, such as those used in the study, are compatible with using a higher frequency sensor.

Soil moisture values derived from remote sensing were used to calibrate and refine the spatially distributed results of the water-balance model. Remotely sensed estimates and model-predicted values were compared, and alternative models were considered. Long-term annual recharge for the catchment was estimated using streamflow observations. The annual a priori estimate of recharge from the model was several times greater than the long-term results. Two modifications were considered, adjusting the soil hydraulic properties and increasing the ET. A better match of the observed and model-predicted soil moisture was obtained when ET was increased.

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Using a water-balance model to derive regional soil moisture is difficult, generally inaccurate, and data insensitive. The use of satellite observations of the surface soil moisture is straightforward. The success of this study shows that satellite-based remote sensing of surface soil moisture can provide valuable information for estimates of regional recharge. More reliable estimates of recharge could help guide development of the region.

Shallow Water Tables

Reutov and Shutko (1992) developed and demonstrated a method for estimating the depth to a shallow water table using passive microwave remote sensing. This is one of the best examples of the use of remote sensing to obtain quantitative information related to recharge.

The basis of the technique is the assumption that when the water table is shallow, capillary rise results in a soil moisture profile that is indicative of the water-table depth. The authors note that this only applies under some climate and geographical conditions.

For the best results, two low-frequency microwave observations (1.0 and 1.6 GHz) should be utilized. These measurements provide information on the shape and level of the near-surface soil moisture profile. The authors suggest that a priori estimates of the typical shape of this profile can be used to constrain the technique. These can be developed using ground observations or models. Figure 2 illustrates the components of the problem.

The technique has been applied to large regions of Uzbekistan, Turkemenia, Estonia, and Moldavia, which provided a variety of climate conditions. In these experiments and applications, ground observations were made every 200–600 m on flight lines of 2–10 km in length. Figure 3 shows the continuous microwave observations and the ground samples of the water-table depth for one site. The frequencies shown are 13 and 1 GHz. For this flight, a correlation exists between the 1-GHz response and the water-table depth. A conclusion is that areas with shallow water table result in lower observed emissivities.

Tests in Estonia and Turkemenia, which included over 90 samples, showed that the method could retrieve the water-table depth with near zero bias and a standard error of estimate of 0.4 m. The authors note that the error tends to increase with depth.

Other considerations are the vegetation type and density and the soil type. However, by choosing the right set of antecedent conditions and utilizing some limited data collection for calibration, the method probably is useful in mapping larger regions.

Unsaturated-zone soil moisture is influenced by soil characteristics, depth of the water table, and the antecedent meteorological conditions. To some degree, the effects of soil and climate can be normalized for an area. Shutko (1986) suggests that one should wait 3–7 days following a rainfall before attempting to use this method. A shallower water table and a lower microwave frequency improve the chances of obtaining useful data.

Uri et al. (1991) utilized passive microwave radiometry (1.46 GHz) in the evaluation of drainage over 73,000 ha. Using data collected 5 days apart (with no rainfall), the authors were able to detect areas that drained, stayed the same, or increased in soil moisture. These results led to the detection of areas with shallow water tables.

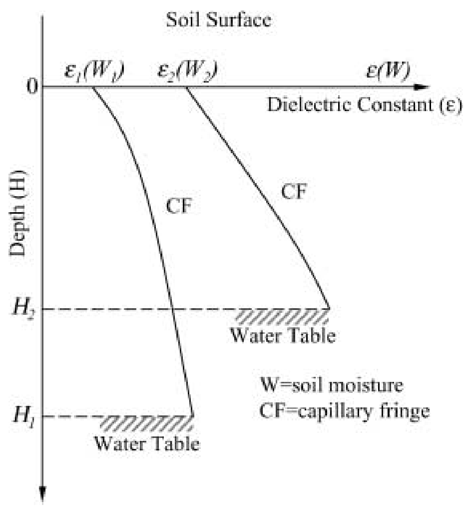

Fig. 2 Variation in dielectric constant within the capillary fringe as a function of water-table depth (Reutov and Shutko 1992)

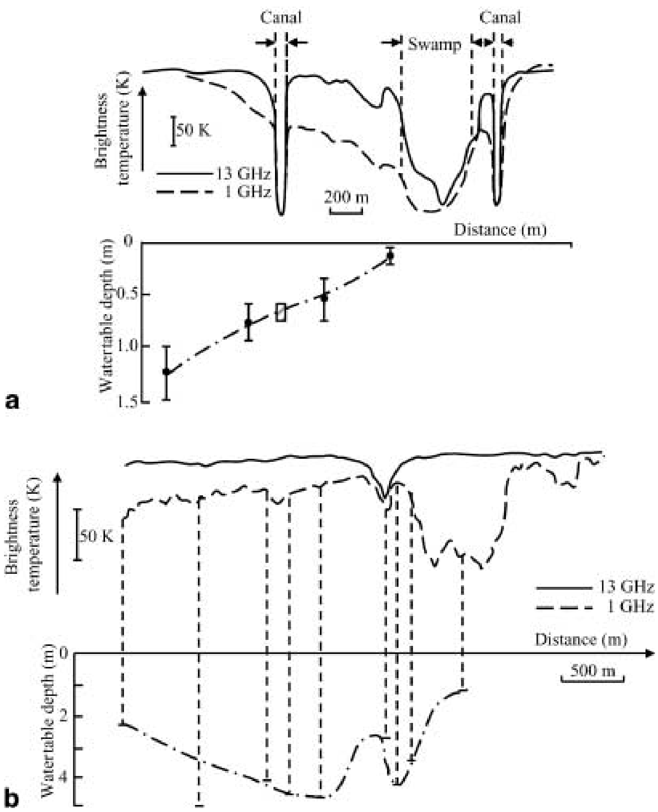

Fig. 3 Observed variation in microwave brightness temperature at frequencies of 13 and 1 GHz, and measured water-table depth for an area in **a** the Ukraine and **b** central Asia (Shutko 1986)

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Radar Detection of Subsurface Features

Images obtained over desert regions using synthetic aperture radar (SAR) during the Space Shuttle Missions (SIR-A and SIR-B) show that subsurface features related to current and past hydrology can be detected (McCauley et al. 1982, 1986; Elachi et al. 1984; Farr et al. 1986; Schaber et al. 1986). Typically, a sand layer masks the features from visible and near-infrared sensors. Features detected by radar are typically related to drainage characteristics, which may be of value in groundwater hydrology. As noted in Meijerink (2000), in addition to information on ancient drainage and climate, these paleohydrology areas sometimes act as active storage sites for near-surface groundwater.

The basis of the results described above lies in the low value of the dielectric constant of the overlying material, typically sand, and the existence of a subsurface dielectric boundary. Lower-frequency sensors, such as the 1.2-GHz radar used in these studies, have a greater penetration depth than high frequencies, which increases the chances that subsurface features can be detected.

Elachi et al. (1984) developed a model that describes the attenuation by the surface layer and the refraction at the subsurface interface as a function of target and sensor parameters. They note that HH polarization data obtained at high incidence angles (>50°) provide more information than alternative configurations.

Farr et al. (1986) conducted an experiment during the SIR-B mission to quantify the attenuation of a soil layer and to validate a dielectric-based model. They buried receivers under desert soils in Nevada during the mission and measured the attenuation. Unlike studies in Egypt described above, these soils did have some, although low, soil moisture. For the tested conditions, they verified that for depths of 0.7–1.7 m it is likely that subsurface features related to subsurface moisture and drainage could be detected.

Follow-on studies by McCauley et al. (1986) and Schaber et al. (1986) have improved the understanding of what particular physical characteristics of the Egyptian site influence the images, and what these features mean in terms of current and historic hydrology. These investigators verified that the maximum depth at which subsurface features could be detected was less than 2 m. Schaber et al. (1986) associated some image features with locations of shallow water tables. McCauley et al. (1986) focused on the paleodrainage information that was obtained. These results raise interesting questions on where the drainages originated and to where they drained. Schaber et al. (1986) suggest that evidence of groundwater depletion from well use could be inferred.

In summary, as noted in Schaber et al. (1986), specific conditions make the detection of subsurface features possible using radar remote sensing. These include very low moisture contents (low dielectric constants) in the surface layer, the physical characteristics of the soil, and reduced geometric scattering. Anomalies can be detected more easily if the overall regional conditions are homogeneous. Finally, the features have to be within the penetration depth of the radar. Results suggest that for L-band (1.2 GHz), this depth is 1.5 m in the absence of soil moisture.

Continental-Scale Assessment of Groundwater Using Satellite-Based Gravity Measurements

One of the factors that contributes to variations in the Earth's gravity field is the mass of water at and below the surface. Assuming that other large-scale mass variations that affect the gravity signal, atmospheric circulation in particular, can be quantified by models or additional observations, variations in terrestrial water storage can be related to changes in the gravity field. NASA plans to launch the Gravity Recovery and Climate Experiment (GRACE) in 2002 to monitor the Earth's gravity field over a 5-year period.

Only changes in water storage and not an absolute mass of water storage can be derived from gravity measurements. Due to the nature of the GRACE technique, the accuracy and reliability of the derived information on water-storage change increase with the size of the region, the averaging time period, and the amplitude of the changes themselves (especially as related to the quality of the models used to remove the atmosphere's contribution to the gravity signal). Simulation studies using models and surrogate observations (Rodell and Famiglietti 1999, 2001) indicate that regions of about 200,000 km^2 or larger are most likely to yield useful information.

Gravity measurements provide data on the change in total mass over the entire atmosphere–soil column, including groundwater, air, and vegetation. As noted by Rodell and Famiglietti (2001), soil moisture is often a major contributor to the variability; therefore, it must be accounted for in order to extract groundwater changes from the gravity data. This provides a direct link to the microwave remote sensing of soil moisture described in the previous sections. Through the synergistic use of GRACE and satellite microwave remote sensing, it may be possible to monitor seasonal groundwater recharge over large regions in the near future.

Conclusions

Remote sensing has been a valuable tool in groundwater studies for many years, primarily as an exploration technique. Recent developments in microwave remote sensing, theory, and sensor availability have resulted in new capabilities and potential. Research results show that it is possible to estimate surface soil moisture. Limited studies demonstrate the potential to infer subsurface parameters and features using these techniques. This quantitative information can be used to assess and estimate groundwater recharge. More research is needed to refine and implement these approaches. Microwave remote

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sensing data are available on a multitemporal and spatial basis, which can complement monitoring and modeling of groundwater recharge.

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