# Remote Sensing in Watershed Scale Hydrology

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### Abstract

Remote sensing provides a means of observing hydrological state variables over large areas. The ones which we will consider is this paper are: land surface temperature from thermal infrared data, surface soil moisture from passive microwave data, snow cover and water equivalent using both visible and microwave data, water quality using visible and near infrared data, landscape cover using both visible and near infrared data and landscape surface roughness using lidar.

**Keywords:** remote sensing, watershed scale, soil moisture, snow, surface temperature, landscape features.

### Introduction

Remote sensing is the process of inferring surface parameters from measurements of the upwelling electromagnetic radiation from the land surface. This radiation is both reflected and emitted by the land. The former is usually the reflected solar while the latter is in both the thermal infrared and microwave portions of the spectrum. There is also reflected microwave radiation as in imaging radars. The reflected solar is used in hydrology for snow mapping vegetation/land cover and water quality studies. The thermal emission in the infrared is used for surface temperature and in the microwave for soil moisture and snow studies. Remotely sensed observations can contribute to our knowledge of these quantities and, especially, their spatial variation. With remote sensing we only observe the surface but can obtain the spatial variability and if observations are made repeatedly the temporal variability. A major focus of remote sensing research in hydrology has been to develop approaches for estimating hydrology/ hydrometeorological states. In this paper we will concentrate on those applications of remote sensing which we believe are the most promising in hydrology which are land surface temperature, near-surface soil moisture, snow cover/water equivalent, water quality, landscape features such as roughness and land cover. We will not discuss the use of radars for precipitation estimation.

### Land Surface Temperature

Land surface temperature is the result of the equilibrium thermodynamic state dictated by the energy balance between the atmosphere, surface and subsurface soil and the efficiency by which the surface transmits radiant energy into the atmosphere (surface emissivity). The latter depends on the composition, surface roughness, and physical parameters of the surface, e.g. moisture content. In addition, the emissivity generally will vary with wavelength for natural surfaces.

Land surface temperatures. derived using ASTER satellite imagery covering an area around the USDA-ARS Grazinglands Research Facility in El Reno, Oklahoma is displayed in Figure 1.

The spatial distribution of land surface temperature, $T_{SURF}$, reflects some significant differences in land cover conditions this time of year (September) with large areas of bare soil and wheat stubble from harvested winter wheat fields and grasslands used for cattle grazing, with a small areas of irrigated crop

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lands and water bodies. This type of spatially-distributed information is very useful for evaluating spatial patterns of evapotranspiration over large areas (Schmugge et al. 2002).

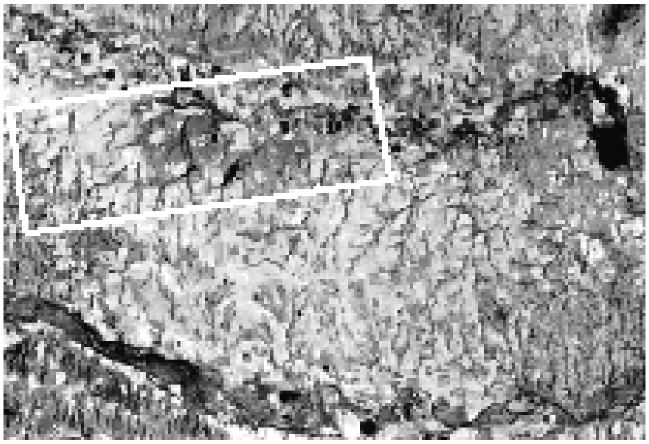

Figure 1. ASTER TIR imagery for a region in central Oklahoma on September 4, 2000 at 17:34 GMT for band13 of ASTER. The temperatures range from 36 degrees C ( black) to 57 degrees C (white). The spatial resolution is 90 m.

## Near Surface Soil Moisture

Passive microwave remote sensing techniques are used to measure near surface soil moisture because at microwave frequencies the most striking feature of the emission from the earth's surface is large contrast between water and land. Microwave remote sensing offers four unique advantages over other spectral remote sensing techniques:

1) The atmosphere is effectively transparent providing all-weather coverage in the decimeter range of wavelengths.
2) Vegetation is semi-tranparent allowing the observation of underlying surfaces in the decimeter range of wavelengths.
3) The microwave measurement is strongly dependent on the dielectric properties of the target which for soil is a function of the amount of water present.
4) Measurement is independent of solar
5) illumination which allows day or night observation.

Remote sensing cannot replace ground based methods for providing high quality profile data at a point. Its advantage is in mapping conditions at regional, continental and even global scales and possibly on a repetitive basis (Schmugge et al. 2002). Recently it has been shown that repetitive measurements of microwave brightness temperatures can yield subsurface soil hydraulic properties (Burke et al. 1998).

Passive microwave observations were made on eight days. The ESTAR data were processed to produce brightness temperature maps of a 740 km$^2$ area on each of the eight days. Using the algorithm developed by Jackson et al. (1995), these data were converted to soil water content images. Gray scale images for each day are shown in Figure 2.

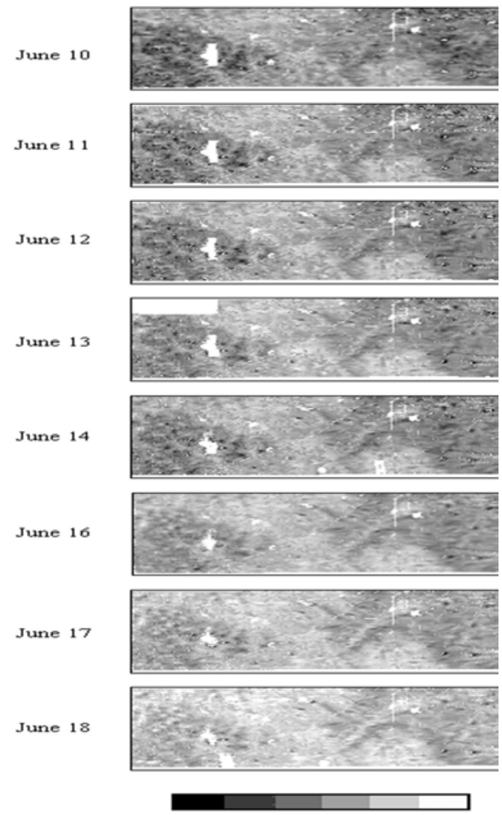


Figure 2. Near Surface (~ 0-5 cm) soil water content maps for the USDA-ARS Little Washita Experimental Watershed derived from passive microwave data collected onna series of days in June 1992. The spatial resolution is 200 m.

For most satellite systems the revisit time can be a critical problem in studies involving rapidly changing conditions such as surface soil water content. With very wide swaths it is possible to obtain twice daily coverage with a polar orbiting satellite. For most satellites, especially if constant viewing angle is important, the revisit time can be much longer. Optimizing the time and frequency of coverage is a critical problem for soil water content studies. Currently, all passive microwave sensors on satellite platforms operate at high frequencies (> 7 GHz). A more recent option is the multiple frequency Advanced Microwave Scanning Radiometer (AMSR) satellite systems that will include a 6.9 GHz channel. AMSR holds great promise for estimating soil water content in regions of low levels of vegetation. AMSR is not the optimal solution to mapping soil water content but it is the best possibility in the near term. Based on the published results and supporting theory (Wang 1985, Choudhury and Golus 1988, Owe et al. 1992, Ahmed 1995, Njoku and Li 1999), this instrument should be able to provide surface moisture information in regions of low vegetation cover, less than 1 kg $m^{-2}$ vegetation water content. To pursue the use of space observations further research programs are underway to develop a space based system with a 1.4 GHz channel which would provide improved global soil moisture information (Kerr et al. 2001). The Soil Moisture and Ocean Salinity (SMOS) mission is currently being implemented by the European Space Agency. This instrument will extend the aperture synthesis approach pioneered by ESTAR to two dimension and will make dual polarized measurements at a range of angles. With these data it is expected to be able obtain not only soil moisture but also vegetation water content at a 50 km resolution (Wigneron et al. 2000).

## Snow Cover and Water Equivalent

Snow cover can be detected and monitored with a variety of remote sensing devices. The greatest number of applications have been found in the visible and near infrared region of the electromagnetic spectrum. Because of Landsat and SPOT frequency of observation problems, many users have turned to the NOAA polar orbiting satellite with the AVHRR, which has a resolution of about 1 km in the 0.58-0.68Fm red band. The frequency of coverage is twice every 24 hours (one daytime pass and one nighttime pass). The major problem with the NOAA-AVHRR data is that the resolution of 1 km may be insufficient for snow mapping on small basins. Data from the MODIS instrument on NASA’s EOS satellites with 250 m resolution in two visible bands will partially alleviate this problem. Despite the various problems mentioned, visible aircraft and satellite imagery have been found to be very useful for monitoring both the buildup of snow cover in a drainage basin and, even more importantly, the disappearance of the snow covered area in the spring. This disappearance or depletion of the snow cover is important to monitor for snowmelt runoff forecasting purposes. It has been recommended that the optimum frequency of observation of the snow cover during depletion would be once a week (Rango 1985). Depending on the remote sensing data used, it could be very difficult to obtain this frequency. Certain snowmelt-runoff applications have been possible with as few as two to three observations during the entire snowmelt season (Rango 1985).

Passive microwave data provides several advantages not offered by other satellite sensors. Studies have shown that passive microwave data offer the potential to extract meaningful snowcover information, such as *SWE*, depth, extent and snow state. SSM/I is a part of an operational satellite system, providing daily coverage of most snow areas, with multiple passes at high latitudes, hence allowing the study of diurnal variability. The technique has generally all-weather capability (although affected by precipitation at 85GHz), and can provide data during darkness. The data are available in near-real time, and hence can be used for hydrological forecasting. There are limitations and challenges in using microwave data for deriving snow cover information for hydrology. The coarse resolution of passive microwave satellite sensors such as SMMR and SSM/I (~25km) is more suited to regional and large basin studies, although Rango et al. (1989) did find that reasonable *SWE* estimates could be made for basins of less than 10,000 $km^2$. The AMSR to be launched on NASA’s EOS satellite, AQUA, in 2002 will provide a wider range of wavelengths and with better spatial resolution than what is currently available (Schmugge et al. 2002).

## Water Quality

Remote sensing techniques for monitoring water quality depend on the ability to measure these changes in the spectral signature backscattered from water and relate these measured changes by empirical or analytical models to water quality parameters. The optimal wavelength used to measure a water quality parameter is dependent on the substance being measured, its concentration, and the sensor characteristics.

Major factors affecting water quality in water bodies across the landscape are suspended sediments (turbidity), algae (i.e., chlorophylls, carotenoids), chemicals (i.e., nutrients, pesticides, metals), dissolved organic matter (DOM), thermal releases, aquatic vascular plants, pathogens, and oils. Suspended sediments, algae, DOM, oils, aquatic vascular plants, and thermal releases change the energy spectra of reflected solar and/or emitting thermal radiation from surface waters which can measured by remote sensing techniques. Most chemicals and pathogens do not directly affect or change the spectral or thermal properties of surface waters so they can only be inferred indirectly from measurements of other water quality parameters affected by these chemicals.

Remote sensing has been used to measure chlorophyll concentrations spatially and temporally. As with suspended sediment measurements, most remote sensing studies of chlorophyll in water are based on empirical relationships between radiance/reflectance in narrow bands or band ratios and chlorophyll. A variety of algorithms and wavelengths have been used successfully to map chlorophyll concentrations of the oceans, estuaries and fresh waters. While estimating chlorophyll by remote sensing technique is possible, studies have also shown that the broad wavelength spectral data available on current satellites (i.e., Landsat, SPOT) do not permit discrimination of chlorophyll in waters with high suspended sediments (Dekker and Peters 1993, Ritchie et al. 1994) due to the dominance of the spectral signal from the suspended sediments. Research on the relationship between chlorophyll and the narrow band spectral details at the "red edge" of the visible spectrum (Gitelson et al. 1994) has shown a linear relationship between chlorophyll and the difference between the emergent energy in the primarily chlorophyll scattering range (700-705 nm) and the primarily chlorophyll absorption range (675-680 nm).

While current remote sensing technologies have many actual and potential applications for assessing water resources and for monitoring water quality, limitations in spectral and spatial resolution of many current sensors on satellites currently restrict the wide application of satellite data for monitoring water quality. New satellites (i.e., SEAWIFS, EOS, MOS, IKONOS, etc.) and sensors (hyperspectral, high spatial resolution) already launched or planned to be launched over the next decade will provide the improved spectral and spatial resolutions needed to monitor water quality parameters in surface waters from space platforms (Schmugge et al. 2002).

## Landscape Features

The landscape features most important to hydrology are landscape roughness, land cover and leaf area.

## Landscape roughness

Roughness refers to the unevenness of the earth's surface due to natural processes (i.e., topography, vegetation, erosion) or human activities (i.e., buildings, power lines, forest clearings). Roughness affects transport of hydrometeorological fluxes between the land surface and atmosphere as well as below the surface, i.e., infiltration and water movement. Roughness is often separated in different complexities related to its effects on land surface-atmosphere dynamics. The complexities are 1) vegetation and urban roughness where the horizontal scale is relatively small, 2) transition roughness between landscape patches (i.e., plowed field next to a forest), and 3) topographic roughness due to changing landscape elevations. These complexities and scales have different effects on wind, heat, and water movement and are difficult to measure in the field at large scales. Lidar, Synthetic Aperture Radar (SAR), Digital Elevation Models (DEM), and photogrammetry are among the remote sensing techniques that have been used to measure landscape surface roughness properties over large areas.

The need for accurate and rapid measurements and assessments of land surface terrain features to estimate the effects of land surface roughness on hydrometeorological processes led to the application of lidar distancing technology from an aircraft-based platform (Ritchie and Jackson 1989, Ritchie 1996). Satellite platforms have also been employed (Harding et al. 1994).

The first applications of the airborne lidar altimeter were to measure topography (Link 1969) and sea ice roughness (Robin 1966). Lidar altimeters can measure long topographic profiles quickly and efficiently

Vegetation canopies are an important part landscape roughness that are difficult to measure by conventional techniques. Airborne lidar measurements provided accurate measurements of canopy top roughness (Figure 8a), heights (Figure 8b) and cover (Ritchie et al. 1992, Ritchie et al.

1993, Weltz et al. 1994). Scanning lasers (Rango et al. 2000) can provide a three-dimensional view of canopy structure needed understand canopy roughness.

## Land cover

Landsat data is the used in developing the landuse and land cover for the agricultural scene. Multi-temporal coverage acquired during the crop season is used for developing the classification. A minimum of four images acquired during the entire season is desirable for creating signature files for the classification. A set of ground data is collected to do the validation of the classification, choosing predominant crops as well as the vegetation cover that may cause confusion in the classification. The base classification is created using four visible and Near- IR bands (Landsat 3, 4, 5 & 7) for the various classes in the scene. The signatures for each land cover class are developed using non-supervised classification for each set of AOI (Area of Interest). Signatures based on all AOI's are combined into one signature file for each area and used within supervised classification. The supervised classification is performed and an accuracy table is generated based on classification performance where ground data was acquired (Doraiswamy et al. 2001).

## Leaf area index

The first step toward the development of the canopy level leaf areas index (LAI) is the development of an accurate land cover map. MODIS imagery (250 m resolution) is used in developing an LAI image for every clear acquisition available during the growing season. The one dimensional canopy reflectance model, SAIL (Scattering by Arbitrarily Inclined Leaves) (Verhoef 1984), provides simulated canopy reflectance in the direction of the sensor. The SAIL model calculates reflectance in the sensor direction as a function of canopy parameters and acquisition and sun angles and requires canopy parameters as leaf angle distribution, single leaf reflectance and transmittance and soil reflectance. The model run in the inversion mode using canopy reflectance as input simulates the canopy LAI. The model simulated LAI is calculated by minimizing the mean square differences of measured and simulated canopy reflectance for the visible and near infrared bands (Doraiswamy, et al. 2002). The model is run separately for each of the crop types in the scene and integrated to get the scene LAI.

## Summary/Conclusions

Remote sensing provides a means of observing hydrological state variables temporally and over large areas. This paper summaries the state of the art of estimating from remote sensing land surface temperature, near-surface soil moisture, snow cover/water equivalent, water quality, landscape roughness and land cover.

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