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Evaluating Depth to Shallow Groundwater Using Heat Capacity Mapping Mission (HCMM) Data

Daytime HCMM radiometric temperatures were correlated with water table depth when effects of vegetation on the surface thermal regime were considered.

ABSTRACT: *Four dates of Heat Capacity Mapping Mission (HCMM) data were analyzed to evaluate the utility of HCMM thermal data for evaluating depth to shallow groundwater. During the summer, shallow water tables can create lower soil temperatures throughout the diurnal temperature cycle. Because of large spatial and temporal ground cover variations, HCMM daytime radiometric temperatures alone did not correlate with water table depth. The radiometric temperatures consisted of radiance contributions from different crop canopies and their respective soil backgrounds. However, when surface soil temperatures were empirically estimated from HCMM temperatures and percent cover of each pixel, significant correlations were obtained between estimated soil temperatures and water table depth. Correlations increased as the season progressed and temperature gradients within the soil profile increased. However, estimated soil temperatures were also correlated with near-surface soil moisture since during the daytime, increasing soil moisture reduced surface soil temperature. Complementary effects of shallow water tables and soil moisture on daytime temperatures cannot be separated.*

INTRODUCTION

SOIL TEMPERATURES are controlled not only by meteorological factors and thermal properties within the depth of diurnal temperature variation, but also by thermal properties of the underlying material. For example, Cartwright (1968a, 1968b, 1970, 1974) found that water tables within the depth of annual soil temperature variation produced lower soil temperatures throughout the diurnal temperature cycle. Shallow water tables do not affect the amplitude of the diurnal temperature wave (Huntley, 1978). The magnitude of the temperature anomaly associated with shallow water tables is dependent upon aquifer thickness, rate of horizontal and vertical water movement, and water table depth.

Existence of temperature anomalies produced by shallow water tables has led investigators to evaluate the potential of thermal remote sensing for locating shallow groundwater. Chase (1969) found that apparent cool anomalies on thermal infrared imagery corresponded with shallow groundwater. Myers and Moore (1972) found a correlation between predawn radiometric temperatures and aquifer thickness. Huntley (1978) reported that surface temperature anomalies related to water table depth variations could be separated from reflectance and thermal inertia variations, but not from variations in evaporation rates.

We evaluated the utility of using Heat Capacity

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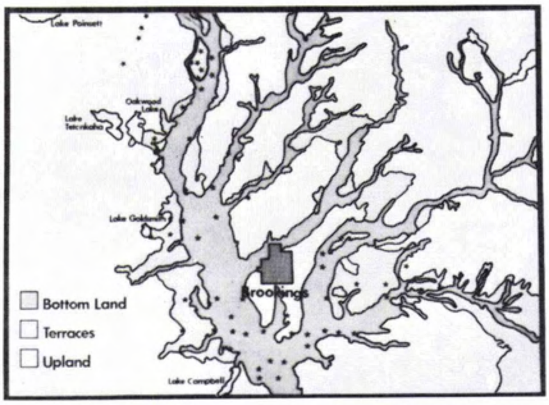

FIG. 1. Landform map of Brookings County, South Dakota showing the flood plain (bottomland) and terraces of the Big Sioux River Basin. The stars indicate locations of U.S. Geological Survey groundwater observation wells.

Mapping Mission (HCMM) radiometric temperatures to evaluate water table depth. The HCMM, launched in April 1978, carried a two-channel radiometer (0.55 to 1.1 and 10.5 to 12.5 μm) in a sun-synchronous orbit (orbital altitude was 620 km). Spatial resolutions were 0.5 by 0.5 km for the visible channel and 0.6 by 0.6 km at nadir for the thermal channel. The $ne\Delta T$ for the thermal channel was 0.4 K at 280°K. Swath width was 716 km. The HCMM collected data at approximately 0230 and 1330 local standard time (LST) with a repeat cycle of 5 or 16 days depending on latitude.

MATERIALS AND METHODS

The study was conducted in the Big Sioux River Basin in Brookings County in southeastern South Dakota (Figure 1). Surficial deposits in the drainage basin are predominantly of glacial origin, and consist of end moraine, ground moraine, and outwash deposits (Ellis *et al.*, 1969). Most groundwater in the basin is obtained from shallow outwash deposits (within 10 m of the surface) and from sand and gravel lenses in morainal deposits.

The Big Sioux River is in contact with the outwash deposits, and groundwater discharge forms the base flow of the river. Most of the aquifer recharge occurs from runoff from snowmelt and early spring rains. Groundwater levels in the basin usually rise from late March through May, and decrease from June through September.

Soils in the basin are generally poorly drained in the flood plain and well drained in the slightly elevated terraces. Major agricultural land-use categories in the basin are small grains (oats, spring wheat, barley), row crops (corn, soybeans), hayland, and pasture.

Water table elevations in the basin were measured in U.S. Geological Survey observation wells (Figure 1). Soil water contents (0 to 4 cm layer) at selected locations were determined gravimetrically on soil samples collected on days of HCMM overpass.

Percent cover at several locations representative of the major land-use categories was determined using 35-mm slides of the canopies (photographed from a vertical position approximately 1 m above the canopies) projected on a random dot grid. When canopies were too tall for the photographic procedure, percent cover was estimated from visual inspection. These data were used to prepare average growing season percent cover curves for each land-use category. Many of the HCMM pixels ultimately contained more than one land use.

Radiometric temperatures from five HCMM scenes (Table 1) were extracted for each pixel encompassing an observation well by overlaying computer gray maps of HCMM data with a Brookings County map containing the well locations. Radiometric temperatures were corrected for atmospheric effects by comparing HCMM and ground measurements of Missouri River reservoir temperatures in central and southeastern South Dakota. Radiometric temperatures were not corrected for emissivity variations.

Percentage of each land-use category in each pixel containing an observation well was determined using photointerpretation of a 13 May, 1978 Landsat color composite (scene I.D. E-21207-16803) superimposed on HCMM computer gray maps by means of a Bausch & Lomb Zoom Transfer Scope. Percentage of each land use within a pixel, and the average percent cover curves for each land-use category, were used to calculate a percent cover for each pixel for every date of HCMM data analyzed.

RESULTS AND DISCUSSION

In an earlier paper we reported a significant relationship ($r = 0.68^{**}$) between 50-cm soil temperatures and water table depths of 3 m or less in the flood plain of the Big Sioux River Basin (Heilman and Moore, 1979). Subsequent analysis of additional temperature data indicated that the relationship could be extended to water tables as deep as 5 m. Water table depths in terraces and uplands were greater than 9 m and did not correlate with 50-cm soil temperatures. Thus, depths

TABLE 1. HCMM SCENES ANALYZED IN WATER TABLE STUDY

Date	Time	Scene I.D.
5 June 1978	1330 LST	AA0040-19500
13 July 1978	1330 LST	AA0070-19570
13 July 1978	0230 LST	AA0078-09020
8 August 1978	1330 LST	AA0104-19400
4 September 1978	1330 LST	AA0131-19420

TABLE 2. COEFFICIENTS OF DETERMINATION (r^2) BETWEEN HCMM RADIOMETRIC TEMPERATURES AND WATER TABLE DEPTH

Date	Time	r^2
5 June	1330 LST	0.02
13 July	1330 LST	0.02
13 July	0230 LST	0.03
8 August	1330 LST	0.06
4 September	1330 LST	0.02

greater than 5 m were excluded in the analyses of HCMM data.

Myers and Moore (1972) found that, on daytime thermal imagery, thermal anomalies related to shallow water tables were overshadowed by vegetation differences (primarily differential evapotranspiration rates and shading). Similar results were found with the HCMM data (Table 2). HCMM temperatures at 1330 LST did not correlate with water table depth, primarily because the temperatures measured were mainly those of vegetation, or a composite of vegetation and soil. Estimated percent cover for the pixels ranged from 10 to 95 percent during the study.

Myers and Moore (1972) also reported that effects of vegetation were minimized at night and thus were able to obtain significant relationships between radiometric temperature and aquifer thickness using predawn thermography. We did not find any significant correlation between HCMM temperature and water table depth for 13 July, 0230 LST data (Table 2), possibly because of the small variation in radiometric temperatures (less than 2°C) within the Sioux River Basin.

Heilman and Moore (1980) found that surface soil temperatures beneath a crop canopy could be estimated from remote measurements of composite temperature using the equation

$$T_s = 0.79\, T_c e^{(-0.80\ \mathrm{PC})} + 20.35 \qquad (1)$$

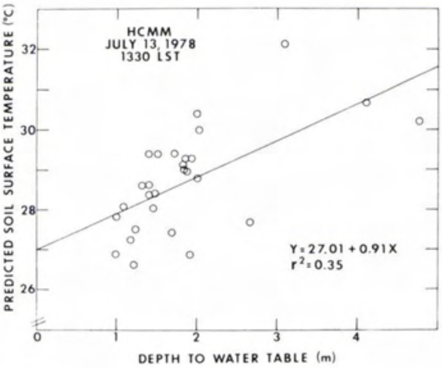

FIG. 3. Relationship between predicted soil surface temperature and water table depth on 13 July 1978.

where $T_s(C)$ is surface soil temperature, $T_c(C)$ is a composite radiometric temperature consisting of radiance contributions from the soil and crop, and PC is percent cover expressed as a fraction. Equation 1 was developed for measurements at 1330 LST.

We used Equation 1 to estimate soil surface temperatures from HCMM temperatures (corrected for atmospheric effects) and pixel percent cover, and found linear relationships between the predicted soil temperatures and water table depth (Figures 2 to 5). The correlations between T_s and depth increased as the season progressed which parallels theoretical predictions that the maximum temperature anomalies should occur during the period of maximum downward temperature gradient (August and early September in South Dakota (Myers and Moore, 1972).

Predicted soil temperatures were correlated not only with water table depth, but also with soil moisture (Figure 6). Multiple regression analysis of the 4 September data yielded the equation

$$T_s = 26.60 - 0.05\, SWC + 2.50\, D \qquad (2)$$

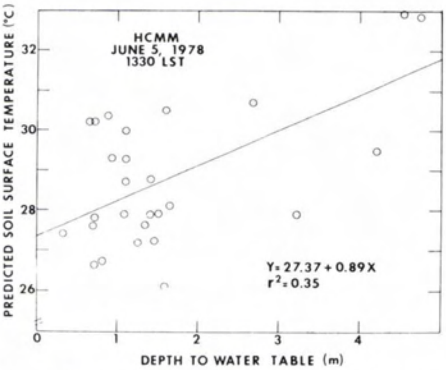

FIG. 2. Relationship between predicted soil surface temperature and water table depth on 5 June 1978.

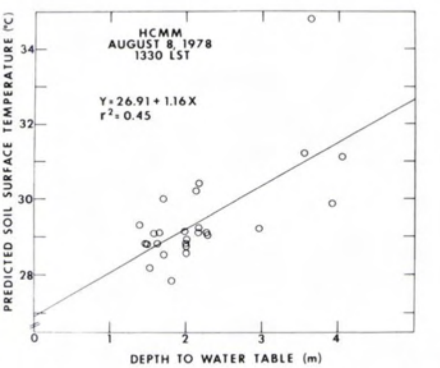

FIG. 4. Relationship between predicted soil surface temperature and water table depth on 8 August 1978.

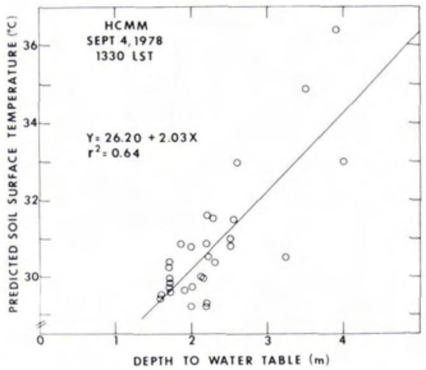

FIG. 5. Relationship between predicted soil surface temperature and water table depth on 4 September 1978.

with an r^2 of 0.87 where SWC (%) is the volumetric soil water content in the 0 to 4 cm layer and D (m) is water table depth. Increasing soil water content reduces the amplitude of the diurnal surface temperature variation through thermal inertia and evaporation effects which cannot be separated from effects of shallow groundwater using a single daytime measurement (Huntley, 1978).

Results of this investigation demonstrate that radiometric temperature measurements from satellites can be correlated with depth to shallow groundwater if appropriate considerations are given to the effect of vegetation on the surface thermal regime. However, techniques for separating water table influences from those of soil moisture must be developed before satellite thermography can be a useful tool for groundwater studies.

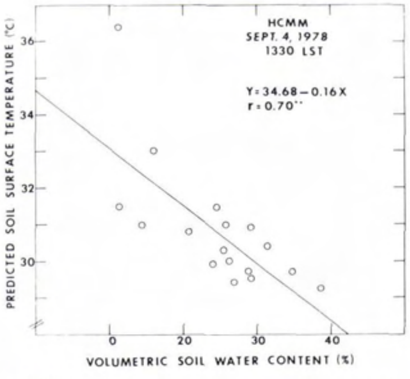

FIG. 6. Relationship between predicted soil surface temperature and volumetric soil water content in the 0 to 4 cm layer on 4 September 1978.

ACKNOWLEDGMENT

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