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MEMORANDUM

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(NASA-TM-X-62343) USE OF VISIBLE,
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SENSING TO STUDY SOIL MOISTURE (NASA)
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ABSTRACT

Measuring soil moisture remotely is an objective for many investigators. Applications of remotely determined soil moisture range from agriculture (where moisture relates to crop growth) to civil works (where moisture relates to slope failures in levees, dams, and along highways). Two methods are used to estimate soil moisture remotely using the 0.4- to 14.0-micron wavelength region: (1) measurement of spectral reflectance, and (2) measurement of soil temperature. The reflectance method is based on observations which show that directional reflectance decreases as soil moisture increases for a given material. The soil temperature method is based on observations which show that differences between daytime and nighttime soil temperatures decrease as moisture content increases for a given material. In some circumstances, separate reflectance or temperature measurements yield ambiguous data, in which case these two methods may be combined to obtain a valid soil moisture determination. In this combined approach, reflectance is used to estimate low moisture levels; and thermal inertia (or thermal diffusivity) is used to estimate higher levels. The reflectance method appears promising for surface estimates of soil moisture, whereas the temperature method appears promising for estimates of near-subsurface (0 to 10 cm). Both methods require additional laboratory and field investigations.

INTRODUCTION

Measuring soil moisture remotely has been an objective for many investigators. The applications of remotely determined soil moisture range from agriculture (in which moisture is related to crop growth) to civil works. A recent civil works application for remote sensing of soil moisture is the study of slope failures (e.g., landslides) (Greeley *et al.*, 1974). Moisture is a major factor in slope stability studies because it increases weight, reduces shearing resistance, and significantly reduces shear strengths of materials (especially certain clay minerals). Many slopes with marginal stability have become active landslides because of the addition of water. A recent study (Taylor and Brabb, 1972) showed that the costs of structurally damaging landslides in the San Francisco bay region during the winter of 1968-69 were over $25 million. Ames Research Center and the U.S. Army Corps of Engineers are attempting to combine remote moisture sensing with engineering geology to assess slope stability in the bay region. An illustration of the qualitative information provided in an infrared image of a selected landslide is shown in Fig. 1. Boundaries of the landslide head scarp, main body, and toe are clearly delineated by surface temperature differences. These differences, which coincide with shear zones, indicate subsurface moisture accumulations, ground water seepage localities, and regions of poorly consolidated materials. Clearly, remote measurements of soil moisture can be usefully applied to landslides on a qualitative basis. What remains to be determined is the extent to which remote measurements of soil moisture can be quantified.

Quantitative measurements of remotely determined soil moisture have been attempted using different regions of the spectrum: visible, near-infrared, and thermal infrared (Tanguay, 1969; Werner and Schmer, 1971; Allen, 1972; and Parks *et al.*, 1973); and microwave (Jean, 1971). Under controlled conditions, encouraging results have been obtained from laboratory experiments and from some field applications using methods in the visible to the thermal infrared region. Recently, positive correlations have also been observed using methods in the microwave region (Schmugge *et al.*, 1974); however, very sophisticated equipment is required and interference effects may pose serious problems for some geologic applications (Blinn *et al.*, 1972). We are initiating our remote sensing activities to study soil moisture in the 0.4- to 14.0-micron region because: the equipment is inherently simpler; the causes of anomalies are more easily determined; and the methods have already produced promising qualitative results.

Major factors affecting reflectance and temperature correlations with soil moisture include meteorology, albedo, thermal properties, and emissivity. The effects of these parameters are currently being assessed at Ames. This paper reviews the reflectance and temperature methods used for soil moisture correlations and identifies some of the features responsible for the behavior observed in the visible and infrared spectrum.

REFLECTANCE AND TEMPERATURE CORRELATIONS WITH SOIL MOISTURE

Two methods for estimating soil moisture remotely using the 0.4- to 14.0-micron wavelength region are: (1) measurement of spectral reflectance and (2) measurement of soil temperature. The reflectance method is based on observations showing that directional reflectance decreases as soil moisture increases for a given soil. The soil temperature method is based on observations showing that differences between daytime and nighttime soil temperatures decrease as moisture content increases for a given soil.

Reflectance Method – Directional reflectance measurements performed in the laboratory at Ames show that reflectance decreases as soil moisture increases for wavelengths from 0.4 to 1.3 microns (Fig. 2). While this observation is valid for any soil type, it can be applied only for a given soil at any one time because of effects produced in the soil by different grain sizes, textures, and mineralogy (Fig. 3). Recent studies (Parks *et al.*, 1973) show that this relationship may continue to a wavelength of 2.5 microns. However, in this region of the infrared, so little solar radiation reaches the ground that this wavelength may not be helpful for field studies. Total reflectance measurements performed in the laboratory using an integrating-sphere spectrophotometer (Bowers and Hanks, 1965) show that reflectance differences are greater in the near-infrared spectrum than in the visible and are greatest at 1.4 and 1.9 microns (Fig. 4), where water absorption bands occur. While these two wavelengths yield valid correlations for ground measurements, they cannot be used for remote sensing from an airplane or satellite because these bands are almost completely absorbed in the atmosphere by water vapor (Plass and Yates, 1965).

Recent field studies (Coulson and Reynolds, 1971) used hemispheric reflectance measurements to evaluate the influence of direct solar radiation, diffuse sky radiation, and polarization. These measurements are essential to an understanding of the nature of the reflected energy from natural surfaces and are more representative of the types of reflectance seen by multispectral scanners than those seen by typical directional reflectance instruments or total reflectance (integrating-sphere type) instruments.

Laboratory reflectance measurements from moist soils require special attention to prevent anomalous relationships from being observed. Anomalous relationships are results that may be observed in the laboratory but that would not be substantiated in the field. Two features that can produce anomalous reflectance values in the laboratory are related to: (1) type of instrument, and (2) geometry between the detector and light source. One integrating-sphere type of instrument commonly used for soil reflectance studies accepts only a small sample (a few centimeters square) and it must be mounted vertically. The soil must be pressed against a glass slide to prevent it from falling into the sphere and to form a flat reflecting plane. This procedure produces preferred orientation of mineral grains in the soil and could yield unrealistically high reflectance values for some soils (e.g., soils rich in micaceous minerals). Also, this method produces artificial reflection boundaries, or zones, that do not exist in naturally occurring moist soils. For example, capillary attraction of water to the glass slide occurs through intergranular pore spaces in the soil, forming a glass-water interface through which the radiation must pass before reaching the soil.

Geometry between the detector and light source strongly affects the intensity of the reflected radiation as the moisture content increases in the soil. Reflectance from natural soils is primarily diffuse (Coulson and Reynolds, 1971), whereas reflectance from water is strongly specular (Chen *et al.*, 1967). The specular component, which is strongest as the Brewster angle is approached, is responsible for orders-of-magnitude increases. Laboratory reflectance measurements from moist soils show two distinctly different reflectance curves (Fig. 5) for different geometric conditions. One condition occurs when the detector and light source are in the principal reflecting plane and represents the combined reflectance from both the diffuse component from the soil and the specular component from the water. This combination causes increased intensities at high moisture contents (curves A_1 and A_2, Fig. 5) and is observed for all angles between the detector and light source. The intensity is considerably stronger when the detector reaches 53° (Brewster angle) from the surface normal. The other condition occurs when the detector is not in the principal reflecting plane and represents only the reflectance of the diffuse component from the soil and water. In this case, the intensity gradually decreases (curve B, Fig. 5) as the moisture content of the soil increases until it reaches a minimum value and remains relatively constant even when a layer of water 1 mm deep covers the surface of the soil.

Laboratory reflectance measurements by others (Parks *et al.*, 1973; and Allen, 1972) have recently shown intensity increases (Fig. 6) for high values of soil moisture. This apparent anomalous behavior may be the consequence of confusing the diffuse reflectance from the soil with the specular reflectance from the water.

Temperature Method – Initial attempts to correlate soil moisture with temperature were qualitative. These studies (Myers and Heilman, 1969) revealed that temperature differences occurred between wet and dry areas of a given soil. In general, in the daytime, the wet soil was cooler than the dry soil, and in the nighttime the wet soil was warmer than the dry soil. For example, daytime airborne thermal infrared images (Fig. 7) taken over a fallow soil plot at the Renner Ranch agricultural research site (Texas) showed the dry soil (27% moisture) was 9° C warmer than the wet soil (33% moisture) for the same soil type. However, at the Van Norman Dam site, a nighttime image (Fig. 8) showed the wet soils were cooler than the dry soils. In this case, the ground temperature was inversely related to moisture content (Fig. 9) for near vertically dipping sedimentary strata of interbedded sandy silts and silty sands. Some of the silty sands were seeping free-flowing cold ground water, which accounts for why they were nearly the same temperature. The anomalous results described above clearly establish the need to conduct more quantitative studies, which include heat transfer characteristics of the material being observed.

Recent experiments performed at Ames have shown that small temperature differences occurring in sandy soils are related to subsurface moisture differences at depths greater than 10 cm. In these experiments, two soil bins were filled with sand and instrumented with thermistors for *in situ* temperature measurements. The thermistors were coated with sand and placed level with the surface. One bin was saturated with water; the other was not. The mean temperature, calculated from five separate thermistors, of both bins was plotted *vs.* time (Fig. 10) for 2 weeks under ideal weather conditions. After the first week, the moisture content at 0 to 10 cm deep was the same in both bins (about 1% at 0 to 5 cm, and 2% at 5 to 10 cm) yet small temperature differences were commonly observed (2 to 3° C in the daytime and 1° C in the nighttime). The data show that surface temperature differences of 2 to 3° C can be produced by subsurface moisture differences occurring in the same soil at depths greater than 10 cm.

Data from unpublished field investigations performed by R. Jackson, USDA Water Conservation Laboratory in Phoenix, Arizona, and T. Schmugge, NASA-Goddard Space Flight Center in Greenbelt, Maryland (personal communication) indicate the difference between maximum and minimum soil temperatures taken over a diurnal cycle decreases with increasing soil moisture. This correlation (Fig. 11) is valid for surfaces to 1 cm and soil layers to a depth of 5 to 9 cm. This correlation is likely valid for soil depths equaling the solar heating influence (approximately 75 cm) during the diurnal cycle. The correlation is possible because water changes the heat-transfer characteristics of soil. As the moisture content increases in the soil (by displacing air in the intergranular pore spaces), it increases the bulk density (ρ) specific heat (c), and thermal conductivity (k). Because water affects each of these, it is necessary to relate them to some other parameter that is a measure of ρ, c, and k. Thermal inertia ($\sqrt{k \cdot \rho \cdot c}$) or thermal diffusivity ($k/\rho \cdot c$) are two possible parameters. Thermal inertia is a measure of the rate of heat transfer at the interface between two dissimilar media (e.g., soil and air), whereas thermal diffusivity is a measure of the change in temperature produced in a substance as heat flows through it (e.g., soil at different depths). For all soils, thermal diffusivity increases more rapidly than thermal inertia as moisture content increases. For example, in a saturated sand, thermal diffusivity is about 10 times greater (Fig. 12) than when the sand is dry (Nakshabandi and Kohnke, 1965). At saturation, the thermal diffusivity no longer increases with increasing water content. In contrast, for a water-saturated soil (intergranular pore spaces filled with water) with 30% porosity, the thermal inertia is two times greater (Fig. 13) than when the soil is dry (Watson *et al.*, 1971).

The temperature versus soil moisture correlation has been determined from ground measurements using thermistors and thermocouples as sensors. The temperature can also be determined remotely from an airplane by using a radiometer sensing emitted radiation in the 8 to 14 microns region. Unfortunately, infrared radiometric temperature measurements of soils do not equal actual soil temperatures (Marlatt, 1967) because the soils have emissivities less than a blackbody. The temperature value determined by radiometric methods is lower than the actual temperature after corrections for sky radiance have been applied (Ludlum, 1965). Most soil emissivities vary from 0.7 to 0.9, depending on texture, grain size, and mineralogy. The emissivity value of the soil increases also with water content (Fuchs and Tanner, 1968). However, for the same soil type and given conditions, the change in temperature observed using a radiometer is the same as the actual change.

For the soil moisture-temperature correlation to be valid, both maximum and minimum soil temperatures must be known; this is not possible without real-time monitoring. However, maximum and minimum soil temperatures can be derived. To derive these values, soil temperatures must be measured near the diurnal extremes of heating and cooling with a calibrated infrared radiometer. The thermal inertia or thermal diffusivity of that same soil must also be measured. The temperature and thermal data can then be used in a radiative heat-transfer model (Watson, 1971) (Fig. 14) to calculate ground temperature versus time over a diurnal cycle for materials of different thermal properties. In addition to calculating temperature versus time for materials having different thermal inertias, this model provides corrections for site latitude, slope directions, slope angle, solar declination, and albedo. Therefore, with only a one-time measurement of thermal properties, a radiative heat-transfer model, and periodic day and nighttime remotely sensed temperature values, seasonal changes in soil moisture can be assessed to a depth of approximately 10 cm.

Combination of Reflectance and Temperature Methods – Under some circumstances, separate reflectance or temperature measurements yield ambiguous data. In these cases, the two methods may sometimes be combined (Fig. 15) to obtain a valid reading. Suggestions have been made (Allen, 1972) that reflectance methods should be employed to estimate low levels of soil moisture and thermal diffusivity to estimate higher levels. Each method is reliable if used in its region of greatest sensitivity. For example, reflectance should be used in region I on Fig. 15 and thermal diffusivity in regions II and III.

DISCUSSION

Reflectance methods for estimating soil moisture are further developed than temperature methods. The reflectance method appears promising for estimating soil moisture at the surface, and the temperature method appears promising for estimating soil moisture near the surface (0 to 10 cm) and perhaps slightly deeper. However, both methods require additional laboratory and field investigations. The laboratory studies are required to determine the conditions under which positive soil moisture correlations are possible. These results are needed to interpret apparent anomalies occurring in the field data. In addition to laboratory studies, rigorous field tests are essential. The field program must include actual ground measurements of all significant parameters for comparison with data acquired remotely by aircraft.

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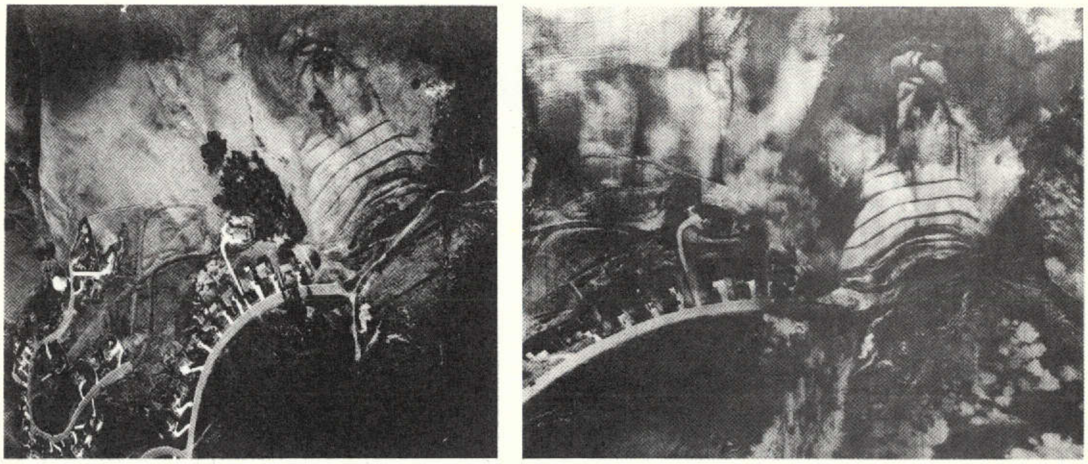


AERIAL PHOTOGRAPH

INFRARED LINE SCANNER
WHITE = WARM
DARK = COOL

FIGURE 1. IMAGES OF LANDSLIDE AT SAN JOSE HIGHLANDS, CALIFORNIA: (a) Aerial photograph, and (b) Infrared scanner.

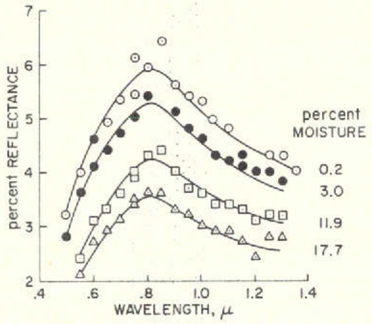


FIGURE 2. PERCENT REFLECTANCE VS WAVELENGTH FOR A CLAY SOIL WITH VARIOUS MOISTURE LEVELS (PERCENT DRY WEIGHT).

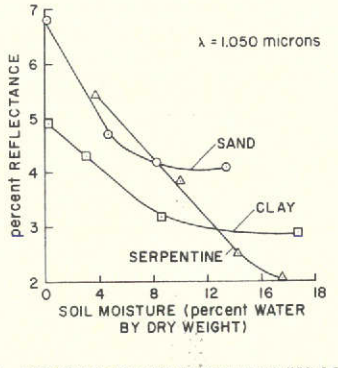


FIGURE 3. PERCENT REFLECTANCE VS MOISTURE FOR VARIOUS SOILS AT A WAVELENGTH OF 1.050 MICRONS.

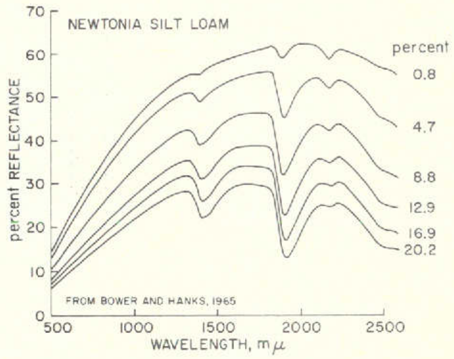


FIGURE 4. PERCENT TOTAL REFLECTANCE VS WAVELENGTH FOR VARIOUS MOISTURE CONTENTS SHOWING WATER ABSORPTION BANDS AT 1.4 AND 1.9 MICRONS (BOWERS AND HANKS, 1965).

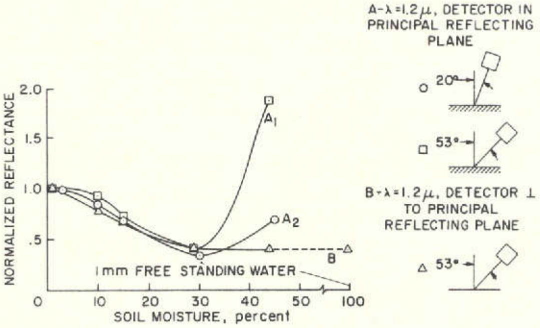


FIGURE 5. NORMALIZED REFLECTANCE VS SOIL MOISTURE. Curves A_1 and A_2 illustrate reflectance of the diffuse component from soil and the specular components from water for detector view angles of 53° and 20° from the surface normal. Curve B illustrates reflectance of the diffuse component from soil and water for detector view angle of 53° from the surface normal.

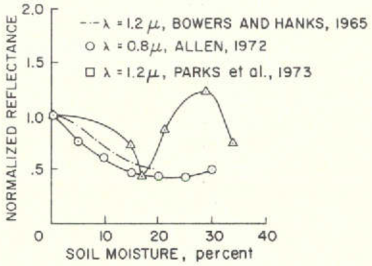


FIGURE 6. NORMALIZED REFLECTANCE VS SOIL MOISTURE. Curve A illustrates reflectance decreases with rising moisture content. Curves B and C illustrate intensity increases for soils having high moisture contents. This anomalous behavior may result from observing diffuse reflectance from the soil and specular reflectance from the water.

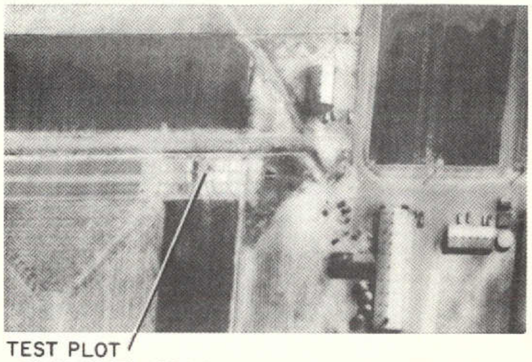


FIGURE 7. DAYTIME INFRARED LINE SCANNER IMAGE OF AGRICULTURAL RESEARCH TEST SITE AT RENNER RANCH, TEXAS (courtesy of D. Mohr, Texas Instruments).

FIGURE 8. NIGHTTIME INFRARED LINE SCANNER IMAGE AT NEAR VERTICALLY DIPPING SEDIMENTARY BEDS OF SAND AND SILT AT VAN NORMAN DAM SITE. The sands have freeflowing cold ground water. This explains why these beds, with the highest moisture content, are colder than the drier silts.

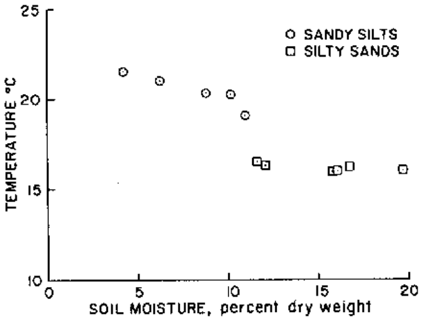
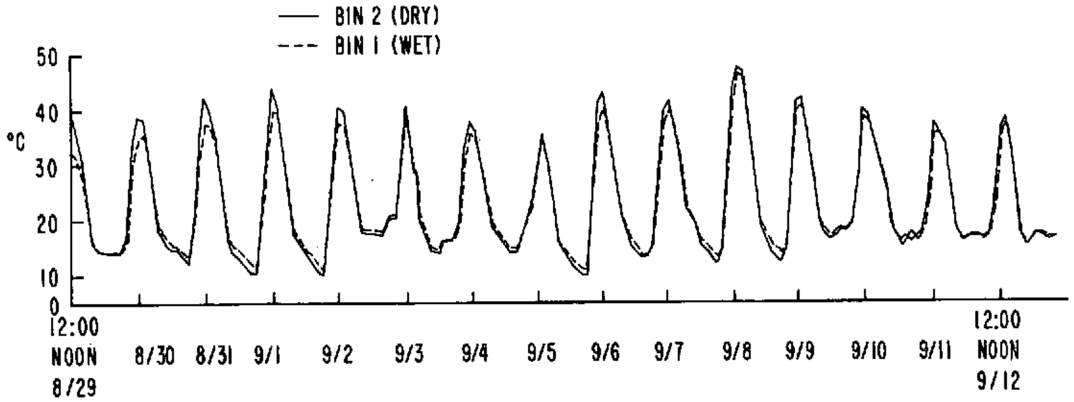
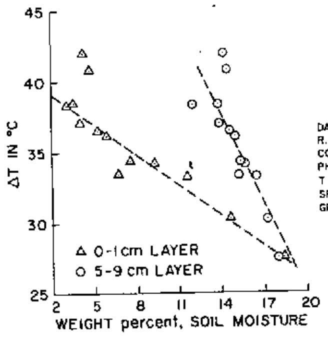


FIGURE 9. TEMPERATURE VS SOIL MOISTURE FOR NEAR VERTICALLY DIPPING INTERBEDDED SILTY SANDS (WET) AND SANDY SILTS (DRY) AT VAN NORMAN DAM SITE, CALIFORNIA.



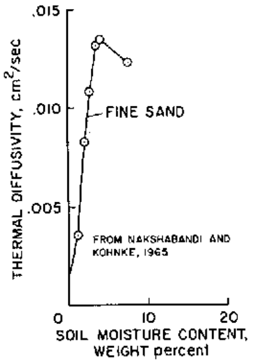
KEY: (1) EACH DATA POINT REPRESENTS MEAN OF 5 MEASUREMENTS
(2) BIN No. 1 WAS SATURATED WITH WATER ON 8-29-73
(3) TOP 10cm OF SAND HAD SAME MOISTURE CONTENT ON 9-7-73

FIGURE 10. MEAN SURFACE TEMPERATURE VS TIME FOR TWO SOIL BINS FILLED WITH SAND. Bin 2 was saturated with water on August 29, 1973. By September 7, 1973, the moisture content in the top 10 cm of each bin was the same, yet measurable temperature differences were observed.



DATA FROM:
R. JACKSON, USDA WATER CONSERVATION LAB PHOENIX, ARIZONA AND
T SCHMUGGE, NASA-GODDARD SPACE FLIGHT CENTER, GREENBELT, MARYLAND

FIGURE 11. DIURNAL TEMPERATURE VARIATION VS SOIL MOISTURE (Schmugge and Jackson, 1974, personal communication).



FROM NAKSHABANDI AND KOHNKE, 1965

FIGURE 12. VARIATION OF THERMAL DIFFUSIVITY VS SOIL MOISTURE CONTENT FOR A FINE SAND (Nakshabandi and Kohnke, 1965).

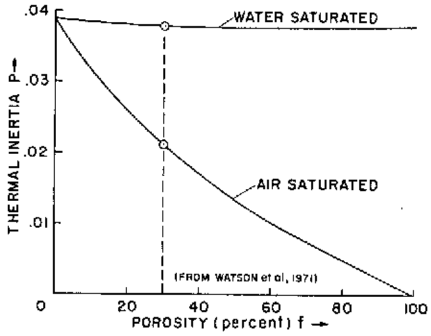


FIGURE 13. THERMAL INERTIA VS SEDIMENT POROSITY FOR AIR- AND WATER-SATURATED SEDIMENT (Watson *et al.*, 1971).

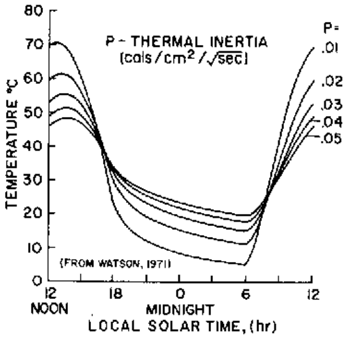


FIGURE 14. SURFACE TEMPERATURE VS TIME OF DAY COMPUTED FROM WATSON'S MODEL FOR MATERIALS WITH DIFFERENT THERMAL INERTIAS (Watson *et al.*, 1971).

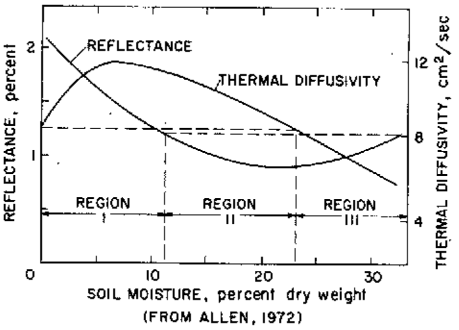


FIGURE 15. POSSIBLE USE OF COMBINED EFFECTS FROM REFLECTANCE AND THERMAL DIFFUSIVITY FOR CORRELATION WITH SOIL MOISTURE (Allen, 1972).