SOIL MOISTURE ESTIMATION BASED ON THERMAL INERTIA FROM AIRBORNE MSS MEASUREMENTS

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ABSTRACT

The author examined several ambiguities in previous thermal inertia models and developed a model for determining soil moisture based on thermal inertia from experiments carried out at the experimental farm and Kujukuri coastal plain. The model should be applicable to a wide range of cases for accurate future determination of soil moisture using remote sensing data.

1. INTRODUCTION

The author has dealt with remote sensing of soil moisture and water quality estimation over the past 10 years using visible, near IR, thermal IR, and microwave(SAR) data. Since 1970, some algorithms for a thermal inertia model using remote sensing data have been developed. Soil moisture and evapotranspiration were estimated using thermal inertia of the soil layers (Rosema, 1975, Pohn et al., 1974, Idso et al., 1976, Gillespie and Kahle, 1977, Huntley, 1978, Pratt and Ellyett, 1979, Price, 1980, Carlson et al., 1981, Utsunomiya and Yamaguchi, 1986). Several ambiguities are present in previous thermal inertia models of other authors. Therefore, the author examined these problems and conducted soil moisture mapping. The results of thermal inertia modeling and mapping of soil moisture are presented.

2. DATA ACQUISITION AND PROCESSING

1) Study areas

Air monitoring facility (AMS)and experimental farm(FARM): Since April 1978, meteorological elements have been observed and following 1980 observations of soil surface temperature(Ts) and soil moisture(SM) of Kanto loamy soil have been made in addition to their measurements at AMS of NIES. The Experimental farm(FARM) is located 36°00'35"N, 140°4'50"E westward of NIES. From 1985 to 1987, heat balance measurements were made to estimate soil moisture(Photo. 1).

Kujukuri coastal plain: In the Kujukuri coastal plain(Fig. 1), elevated beach ridges, elevated bars, elevated sandspits and dunes several meters in height are distributed along the shoreline. The southern part of this coastal plain has been damaged by gas mining. The land of rice fields has submerged and contamination of well water by sea water and the inundation of the sea water of inner part of the plain have occurred.

2) Data sources

Measurements at experimental farm: Micrometeorological observation of the surface of Kanto loamy soil was carried out from December 1986 to July 1987. One tensio cup was set at a 5cm depth to measure soil moisture. Furthermore, electrodes were embedded at 1, 5, 10 and 20 cm depth for soil moisture measurements. A heat flux plate was set at a 0.5cm depth for heat flux measurement in the soil. Net radiation was measured using a net radiometer at 1.3m above the ground. Surface temperature was measured by IR radiometer set at a height of 1.5m. Global solar and reflected solar radiation were observed by solarimeters. Dry and wet bulb themocouple thermometers were set at heights of 0.1 and 1.1m above the ground. Soil temperature was measured at depths of 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, 40.0, 60.0, 80.0 and 100.0cm with couples of electric . Air pressure and wind speed data were obtained with a pressure gauge and wind vane/anemometer. These meteorological elements were measured every minute. Original(every 30 minutes) and averaged values were processed by a micro-computer (PC9801-Vm2 / EPSON HC-20) and fed to a floppy disk every 30 minutes.

Measurements in the Kujukuri plain:

Airborne measurements: With a Bendix M^2S of Pasco Co Ltd., airborne measurements were carried out along the Kujukuri coast about 25 km in length, at 6:18 (6:15 to 6:22), 9:15 (9:13 to 9:19) and 12:59 (12:58 to 13:00) on Nov. 15, 1985. Spectral reflectance over the 11 channels (wavelength bands) shown in Table 1 was recorded on a data recorder.

Ground truth: Measurements of soil surface temperature and weather elements, landuse survey and soil sampling were carried out in this plain. Soil surface temperature was measured with hand-carried IR radiometers. Because the ground resolution of MSS data was about 5 x $5cm^2$, soil surface temperature was measured three times at five points on each corner and center of the square target area; 15 sets of soil surface temperature were averaged for the each ground truth point. Net radiation(S) and other meteorological elements such as albedo, pressure, surface temperature, heat flow, global solar radiation and dry and wet bulb temperature, wind direction, wind velocity and humidity were measured at the ground truth center in the northern part of the area(Photo 2). The soils were sampled after measurement of soil surface temperature. At 20 sites, soil was sampled by the soil sampler having a volume of $100cm^3$ for soil layers between top and 5cm depths. The samples of land covers classified into 16 classes were collected for 4 days after the meteorological observation and soil sampling.

3) Data processing

The diurnal range in Ts and meteorological elements was obtained by subtracting minimum from maximum data. Soil moisture data were averaged. The moisture of soil samples was determined by weighing each sample before and after oven drying at a constant temperature (110°C) for 48 hours at our laboratory.

These ground truth and conspicuous control points were plotted on digital maps processed on the airborne MSS data and used as the basis for geometric rectification and registration of MSS images. Two imageries obtained at the first and third flights were geometrically corrected by computer programming based on projective transformation methods. Subsequently, the data were processed by discriminant and regression analyses, and computer mapping.

Volumetric soil moisture was also determined by the sample weighing method. Volumetric soil moisture(total water storage (mm/5cm depth of soil layer)) was determined by multiplying moisture content by dry bulk density.

3. THERMAL MODEL AND SOIL PHYSICS

As already described by several researchers(e.g. Budyko, 1956; Sellers, 1965), the energy balance of the earth's surface is essentially given as follows:

$$S = lE + H + B \qquad (1)$$

where S is net radiation flux, lE, latent heat flux, H, sensible heat flux, and B, soil heat flux.

According to the one-dimensional equation of heat transfer, lE, H and B are given by equations 2, 3 and 4, respectively(Oga, 1931, Uchijima, 1964, Monteith, 1973).

$$lE = -K_1 \left. \frac{dQ}{dh} \right|_{h=0} \quad \text{.........} (2)$$

$$H = -K_2 \left. \frac{dTs}{dh} \right|_{h=0} \quad \text{.......} (3)$$

$$B = -\lambda \left. \frac{dTs}{dz} \right|_{z=0} \quad \text{.......} (4)$$

where K_1 is the molecular diffusion coefficient for water vapor, K_2, thermal conductivity of air, Q, specific humidity, Ts, surface temperature, h, height, and z, depth. Boundary conditions of height(h) and depth(z) are zero.
On substituting Eq. 2, 3, 4 into Eq. 1

$$-K_1 \frac{dQ}{dh} - K_2 \frac{dTs}{dh} - \lambda \frac{dTs}{dz} = S \quad \text{..........} (5)$$

The specific humidity(Q) at the earth's surface can be expressed as follows(Laiktmah,1961; Uchijima 1964):

$$Q = \mu fq(Ts) \quad \text{...........................} (6)$$

where Ts is the surface temperature, and μ, relative humidity of the earth's surface. Function fq(x) was obtained from regression results.

Since evaporation from soil decreases with drying, the evaporation rate was estimated excessively. Therefore, the relative humidity at the soil surface must be known and evaporation from dry soil can be estimated more precisely by introducing a parameter described by Laiktmah(1961) as "g" and lately defined by Uchijima(1964) as "μ(qs/q(Ts))".
μ defined as follows:

$$\mu = \{ lE/\rho lD + q(T) \} / q(Ts) \quad \text{..........} (7)$$

To simplify the analysis, the value of the coefficient of kinematic viscosity(kw) was assumed equal to that of thermal diffusivity of air(ka) and both can be expressed as "k". According to Laiktmah(1961), rearranging Eq 5 by substituting Eq. 6 into Eq. 5 gives

$$-K\rho Cp\left(1 + \frac{l\mu fq}{Cp}\right) \frac{dTs}{dh} - acr \frac{dTs}{dz} = S \quad \text{.........} (8)$$

where k is thermal diffusivity and kinematic viscosity of air, ρ, air density, Cp, specific heat of air, λ, thermal conductivity of soil, a, thermal diffusivity of soil($a=\lambda/cr$), c, specific heat of soil, r, specific gravity of soil, and l, latent heat of vaporization.
Soil heat flux in a hemicycle($\tau/2$) was obtained as follows: Each term on the left hand side of Eq. 8 was differentiated and the results were substituted into Eq. 8 to give

$$\left(-\sqrt{K\rho}\,Cp\left(1+\frac{l\mu fq}{Cp}\right)-\sqrt{\lambda cr}\right)\Theta m\sqrt{\frac{2}{\pi}}\sqrt{\tau}=dS \quad ......(9)$$

where Θm is daily range of surface temperature and τ, a periodic time.

The following was obtained:

$$\sqrt{\lambda cr}=\frac{dS}{\Theta m\sqrt{\frac{2}{\pi}}\sqrt{\tau}}-\sqrt{K\rho}\,Cp\left(1+\frac{l\mu fq}{Cp}\right) \quad ....(10)$$

The parameter $\sqrt{\lambda cr}$ is thermal conductance (Oga 1931) and recently, named thermal inertia(Rosema, 1975, Pratt and Ellyette, 1979, Price, 1980, Idso et al 1976 etc.). The thermal inertia($\sqrt{\lambda cr}$) controls the heat diffusion of the soil. Though it is principally given by the right hand first term, the right hand second term cannot be omitted for precise determination.

In soil, the thermal conductivity(λ) is a function of the rate of soil moisture(SW) and expressed as λ = f(SW). C times r equals cv; Cv(volumetric heat capacity) is also well known to be a function of soil moisture and is expressed as Eq. 11 and 11'.

cv = 0.46 fm + 0.60 fo + fw (de Vries, 1963) ....(11)

cv = 0.2 ρv+SWv/100 (Chudonovsky 1959, after Uchijima, 1964) ....(11')

where fm is mineral matter, fo, organic matter, fw, water, v, bulk density of the soil(g/cm3) and SW, volumetric soil moisture. Therefore, the thermal inertia($\sqrt{\lambda cr}$) is expressed as a function of soil moisture, λcr = f(w) and ultimately soil moisture can be estimated from Eq. 12.

$$W = f^{-1}(\sqrt{\lambda cr}) \quad ....(12)$$

The soil moisture is physically and closely correlated to thermal inertia(λcr). The diffusion coefficient(k) was replaced by the diffusion speed(D) between 10 and 110cm above the ground. Parameters D and μ were derived from the data(dry and wet bulb temperatures, net radiation and soil heat flux) obtained at FARM. Parameters such as dS, Θm and q of second term of right hand in the model(Eq. 10) were derived from the micrometeorological data. Thermal inertia was determined by the Eq. 10. The diffusion speed (D) was calculated by the famous heat balance method:

$$D_{10-110cm} = lE / \{ 0.622\, l\rho (e_{10} - e_{110}) / p \} \quad ....(13)$$

where e is water vapor pressure. Subscripted 10 or 110 means heights above the ground surface in centimeter.

As shown above, soil moisture(SW) and thermal inertia($\sqrt{\lambda cr}$) can be adequately correlated. Therefore, the soil moisture(SW) and thermal inertia were processed by regression analysis. The values of thermal inertia from 11:30 to 13:00 ranged from 0.001 to 0.05. The model for estimating soil moisture, thus obtained, at FARM is as follows.

Soil moisture(mm) = -1.46 + 663.08 $\sqrt{\lambda cr}$ ....(14)
(cal/cm^2.sec)

(r=0.72 , standard deviation : 4.38 mm)

The energy balance of the earth's surface(Eq. 1) is also expressed by components of short and long wavelength;

$$(1-\alpha)\ Sr + Dr = U + lE + H + B \quad ......(15)$$

Substituting Eq. 1 into Eq. 15 yields

$$Dr = U + S - (1-\alpha)\ Sr \quad ....(16)$$

where S is net radiation, Sr, solar radiation, Dr, downward longwave radiation from the sky and U, upward longwave radiation from the soil surface. Sr, α, Ts, B and S(lE + H + B) were directly observed at the ground truth center.

Meteorological elements such as surface temperature(Ts) and albedo(α) were observed in and around the ground truth center. The longwave radiation from the surface(U) was calculated from Eq. 17.

$$U = \delta\sigma\ (Ts+273.15)^4 + (1-\delta)\ Dr \quad ...(17)$$

where Ts is obtained by IR radiometer and MSS; σ is Stefan-Boltzmann constant and emmisivity(δ) is assumed as 0.961 in this study.

The second term on the right hand side of Eq.17 can be eliminated because it is negligible small when the emmisivity(δ) is greater than 0.95 (Uchijima, 1974). The value of Dr at the ground truth center is obtained by substituting these radiation balance terms into Eq. 16. Therefore, the parameter U and Dr are easily calculated at the ground truth center.
Effective radiation(F) in daytime is estimated by Eq. 18.

$$F = Dr - U \quad .... (18)$$

Airborne sensor(MSS) measures the only reflected spectral energy within narrow wavelength and longwave radiation(Ts) in each pixel. Thus, net radiation in each pixel can be calculated using these visible and IR radiation data. As above, albedo and global solar radiations (α and Sr) were obtained in and around the ground truth center. Albedo (α') in each pixel is calculated from

$$\alpha' = f(\sum_{i=1}^{10} \lambda i) \quad ....(19)$$

where λi is reflectance of the i-th visible wavelength band; α' is the estimated albedo. Function f(x) is obtained from relationships between albedo and CCT count of airborne MSS data. The net radiation of each pixel of MSS data is thus calculated from Eq.20.

$$S = (1-\alpha')\ Sr - F \quad ....(20)$$

dS and dTs are estimated from Eq. 21 and 22, respectively.

$$dS = S_{max} - S_{min} \quad ....(21)$$

$$dTs = Ts_{max} - Ts_{min} \quad ....(22)$$

where ds is the daily range of net radiation, S_{min}, minimum net radiation obtained in the first flight(6:15-6:22), S_{max}, maximum net radiation obtained at the third flight(12:58-13:00), dTs is daily range of surface temperature, Ts_{min} minimum surface temperature obtained in the first flight, and Ts_{max}, maximum surface temperature at the third flight.

The diffusion speed(D) obtained at the ground truth center was used as the diffusion coefficient(K) of each pixel in the study area.

Relative humidity was estimated from the albedo. Albedo of the wettest soil(21mm at field capacity) was about 6%, while the albedo of dry soil(1.2mm) approximated about 24% and the albedo was well correlated with soil moisture. Therefore, albedo was automatically normalized by regression results based on relationships between albedo and soil moisture(Fig. 2). Normalized albedo(μ) thus obtained, was used for the relative humidity of soil surface.

Thermal inertia was calculated using the micro-meteorological data at ground truth and airborne MSS thermal and visible data. The estimation model for soil moisture obtained by airborne MSS measurements in the Kujukuri coastal plain is follows:

$$\text{Soil moisture(mm)} = -3.59 + 574.66\sqrt{\lambda c r} \quad (\text{cal/cm}^2.\text{sec}) \qquad (23)$$

(r: 0.92 ; standard deviation: 1.84)

4. SOIL MOISTURE MAPPING

Discriminant analysis for land cover classification, computer mapping and overlay/compilation of maps are systematically utilized for soil moisture mapping.

Sixteen categories of land covers were used for the discriminant analysis. One pixel of CCT data is classified into groups having the shortest distance of the Mahalanobis's generalized distance(Okuno et al, 1976; Clark and Hosking, 1986). A land cover map is automatically depicted using the electric computer through these statistical processing. The above model (Eq. 23) was applied to MSS data which were clustered into bare soil and rice field. Photograph 3 shows moisture distribution based on the thermal inertia model in and around Iyobo village in this plain.

Thermal inertia can be used to determine soil moisture. Though input parameters covering the solar radiation and other weather element were introduced in previous thermal inertia models, surface relative wetness was ignored or assumed constant(1.0) and application of the relative humidity based on heat balance was not recognized in previous thermal inertia models. Thus, this correction parameter(μ) should be used for evaporation in remote sensing; substituting this normalized albedo(μ') for the parameter(μ) is proper in thermal inertia models developed by the author, while albedo of surfaces depends color, moisture and kinds of soil minerals.

Another problem arose from the MSS hardware. The energy for the denominator of the albedo calculation cannot be obtained because incident energy from the sky cannot be observed by the MSS measurement system. Thus, for the albedo calculation, the author used regression analysis because of the strong correlation between albedo and MSS data. In strictly speaking, the estimated albedo may not be sufficiently accurate due to the narrow wavelength band(0.4-1.06μm).

Diffusion coefficient(K) of the study area was substituted by the diffusion speed(D) obtained by micro-climate observation at the ground truth center.

The diffusion coefficient in each pixel differs from the others according to regional differences in zero plane displacement and roughness length of the surface. One problem for the input parameter is the diffusion coefficient(k). Diffusion coefficient may be observed at each pixel of MSS data. The direct measurement of this parameter is quite difficult because such information as roughness of surface and wind speed of the boundary layer in contact with the soil surface in each pixel is required.

In soil physics, porosity and mineral component in the whole area of the Kujukuri coastal plain was also assumed as constant in this study. Strictly speaking, porosity and mineral components vary with the location. The former (porosity) varies also with time.

Some of these problems above should be solved by physical and in vitro experimental methods in the laboratory under the same conditions and not by remote sensing. The author tried to exclude other ambiguities in the thermal inertia model and theoretically and empirically established an equation that can be used to estimate moisture in a soil layer 0 to 5cm depths.

Since the porosity and mineral component of two soil(sandy soil and Kanto loamy soil) differ from each other, the values of regression coefficient and constant of equations obtained by experiments carried out using airborne MSS and experimental system at FARM of NIES are not equal but are similar.

5. CONCLUSIONS

The author examined thermal inertia model. The model for estimating soil moisture was developed by introducing relative humidity(μ) at the soil surface and heat balance terms obtained from ground truth measurements. The thermal inertia model was also applied to airborne MSS data in the Kujukuri coastal plain. In the latter case, relative humidity was substituted by normalized albedo during the daytime. The model obtained by airborne MSS experiments was close to that of FARM. From the above results, it is concluded that the thermal inertia model is most appropriate for soil moisture estimation and should be applicable to a wide range of cases for accurate determinations of soil moisture using remote sensing data.

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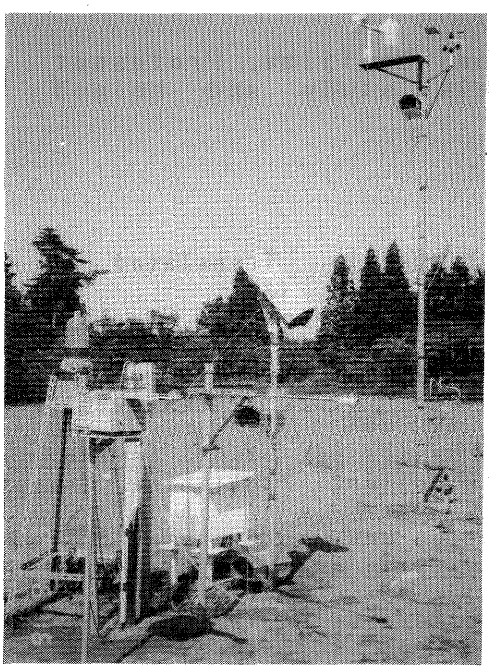
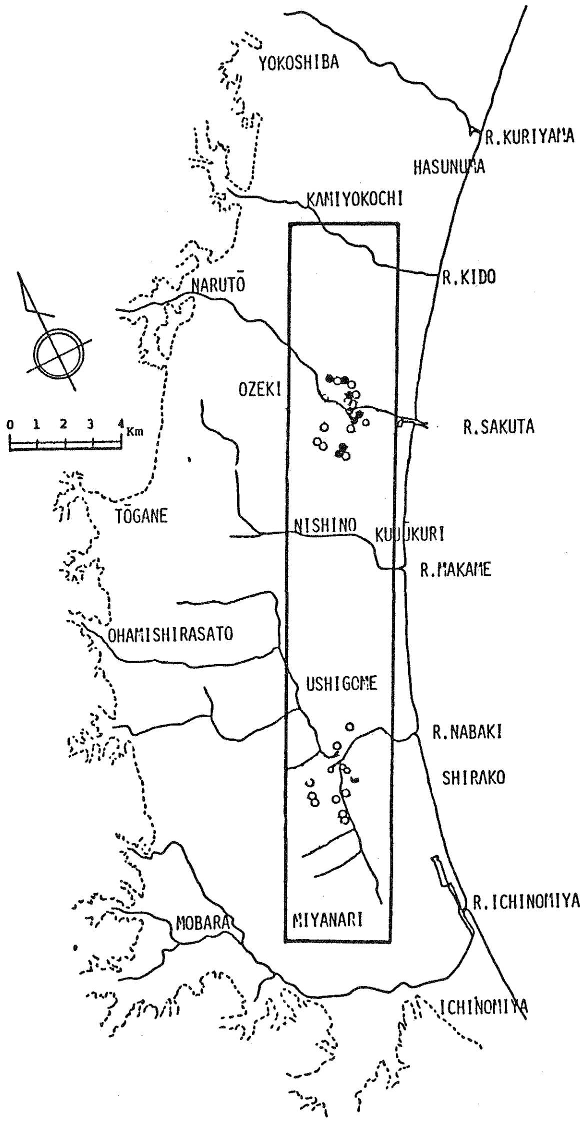


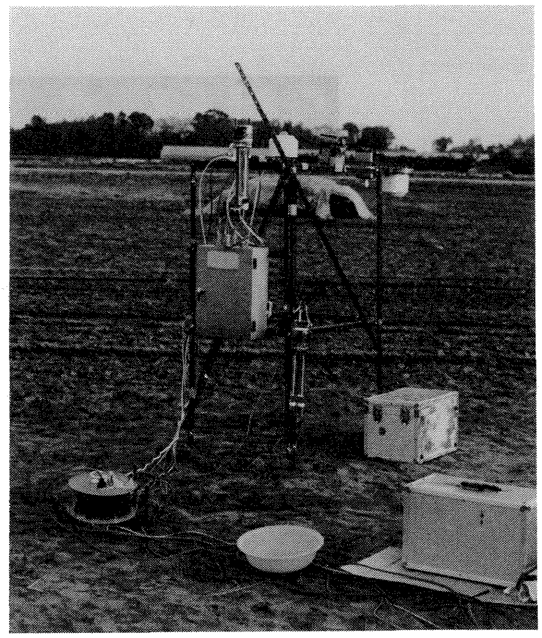
Photograph 1
Meteorological measurement at experimental farm of NIES

Table 1 Spectral wavelengths in each band of airborne MSS CCT data(Bendix M^2S)

Nov. 15 1985

channel No.	wavelength μm
1	0.38-0.44
2	0.44-0.49
3	0.49-0.54
4	0.54-0.58
5	0.58-0.62
6	0.62-0.66
7	0.66-0.77
8	0.70-0.74
9	0.77-0.86
10	0.97-1.06
11	8.0-13.0





Photograph 2
Meteorological measurement at ground truth center in Kujukuri coastal plain

Figure 1
Study area in Kujukuri plain

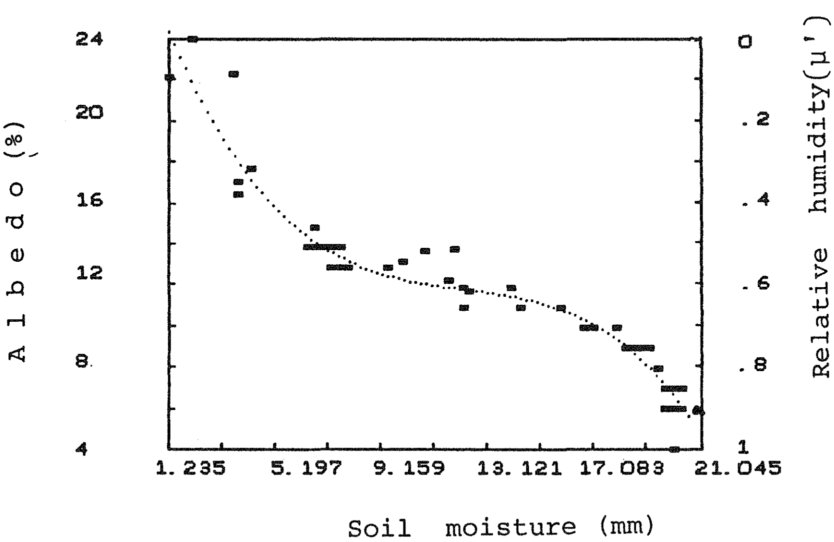
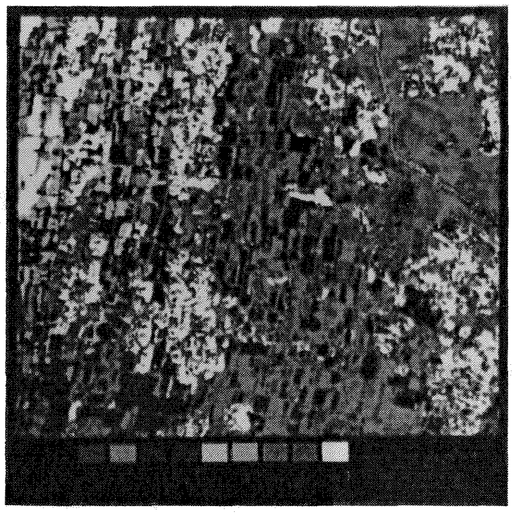


Figure 2
Relationship between albedo and relative humidity(μ')



Legend

1: 0 - 2
2: 3 - 5
3: 6 - 8
4: 9 - 11
5: 12 - 14
6: 15 - 17
7: 18 - 20
8: 21 - 23
9: 24 - 26
10: 27 -
11: unknown

(unit: mm)

Photograph 3

Distribution of soil moisture (total water storage (mm/5 cm depth of soil layer)) in Kujukuri coastal plain (Nov. 15, 1985)