Application of Remote Sensing for Monitoring the Soil Water Status

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A wide variety of recording methods, which may be helpful for the investigation of soil moisture are at the disposal of remote sensing. It should be stressed right at the beginning that the results obtained using remote sensing methods provide information about soil moisture at a given moment of time, that is, at the moment when this recording is made. The transition from this single piece of information to general information that reflects the behaviour of water in the soil requires logical reasoning based on many additional data.

The methods for determining soil moisture using remote sensing techniques and the method of transition from information about soil moisture to the estimation of soil water status will be the subject of this study.

Determination of soil moisture by remote sensing techniques

In the past twenty years or so about 200 articles and monographs have been published on the theoretical basis for the determination of soil moisture by means of remote sensing methods and on the results of laboratory, field, aerial and satellite experiments which determined soil moisture by different methods.

It should be recalled that registration techniques in the field of remote sensing are divided basically into photographic and electronic methods, or, according to spectral range, into techniques in the visible range, and in the near infrared /photographic/, medium infrared, thermal and microwave bands.

In order to estimate the usefulness of the photographic technique /mostly aerial photographs/ and to create patterns between soil moisture and photographic images, measurements on the reflectance of different wavelengths from surfaces with varying moisture contents have been widely used. Many examples of laboratory and field measurements on the spectral characteristics of soils with varying moisture contents have been published. Figures taken from the works of MINNUS /1967/ and the author /BIALOUSZ, 1978; 1977; 1986/ will illustrate this approach.

Laboratory measurements made by MINNUS /1967/ showed that the surface of a sample taken from level A of a lessivé soil /luvisol/ reflects less and less energy /it is darker and darker/ as moisture increases up till 12%. After a further growth in moisture to 20% the sample reflects more energy and gives a brighter image than at a moisture level of 12% /Fig. 1/.

A similar tendency was observed in measurements made by the author on level A of a lessivé soil /luvisol/ formed on loess /Fig. 2/. As the sample

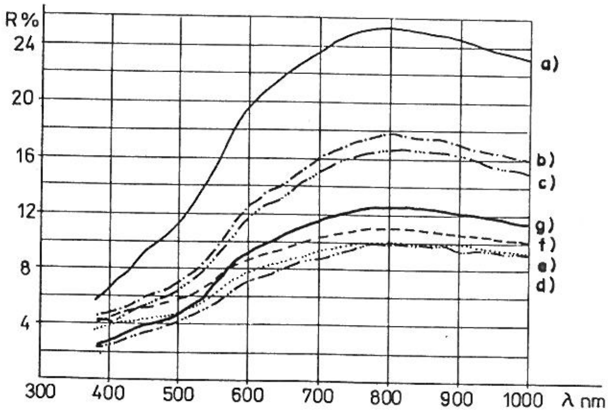


Fig. 1
Spectral characteristics of a luvisol formed on loam at moisture levels: a/ 1.3; b/ 6.1; c/ 9.2; d/ 11.8; e/ 13.2; f/ 13.7; g/ 20.3 % moisture

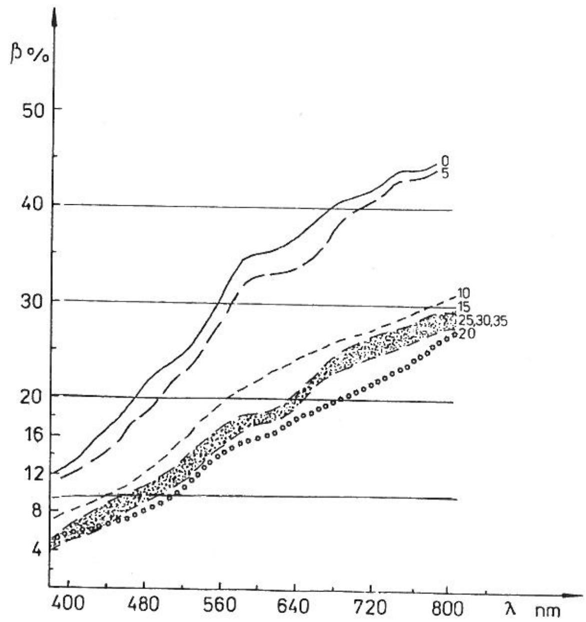
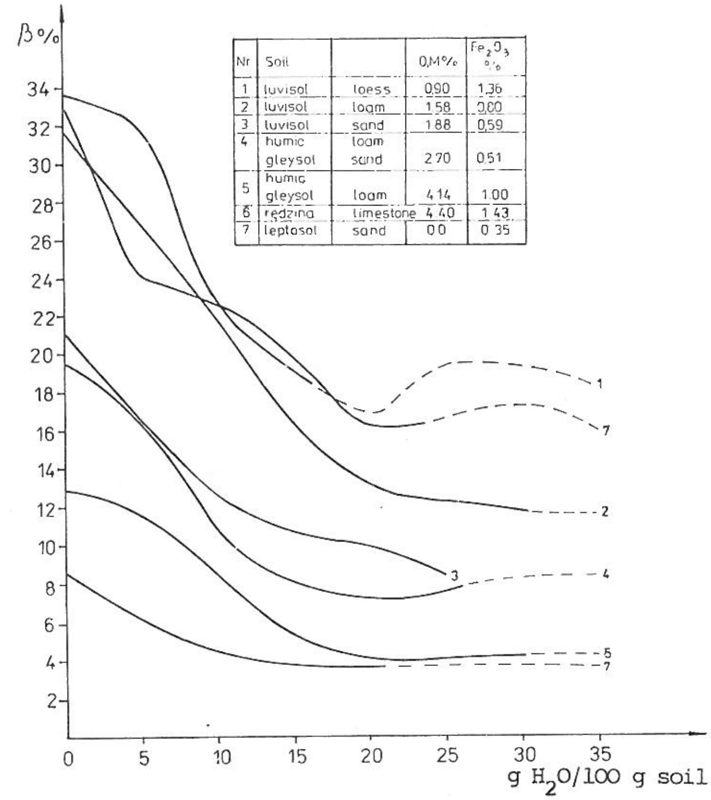


Fig. 2
Spectral characteristics of level A of an eroded luvisol formed on loess, saturated with 0-20 g H_2O/100 g soil

was saturated up to 20 g of water to 100 g of soil it reflected less and less energy and became darker. But further increase in the moisture caused the sample to become brighter. Measurements carried out on different genetic types of soil showed that this tendency is similar in all cases, but the boundary moisture value, above which the surface of the sample ceases to become darker and may even become brighter, varies from one soil type to the other.



Nr	Soil		O,M %	Fe_2O_3 %
1	luvisol	loess	0,90	1,36
2	luvisol	loam	1 58	0,80
3	luvisol	sand	1 88	0,59
4	humic gleysol	loam sand	2 70	0 51
5	humic gleysol	loam	4 14	1 00
6	redzina	limestone	4 40	1 43
7	leptosol	sand	0 0	0 35

Fig. 3

Mean values /in the range 530-700 nm/ of the brightness coefficient /β %/ of different soil types at various moisture levels

This tendency is shown in Fig. 3, from which it follows that:

- in the spectral range corresponding to photographic registration, the decrease in brightness of the soil surface, i.e. the increase in the optical density of the contours on the photograph, appears only up to a certain boundary moisture value. A further increase in moisture does not affect the optical density of the photograph to increase;
- the boundary values mentioned above are different for each soil;
- at the same moisture level, e.g. 15 g H_2O/100 g soil the reflectance is different for each soil, which means that at the same moisture level each of them will have a different optical density on the photograph. It follows that the optical density of the image does not give unequivocal information on soil moisture if it is not related to the size distribution data for the soil.

Some authors /BIALOUSZ, 1978; CIERNIEWSKI, 1985; TOLCHEINIKOV, 1974; VINOGRADOV, 1973/ have pointed out that a better correlation between the spectral characteristics of the soil and its moisture content are acquired if one operates not only with the water content in the soil expressed as a % of soil weight or soil volume, but also with the forms of water appearance. TOLCHENIKOV /1974/ and others have pointed out that film water has a different influence on reflectance than hydroscopic water, while capillary water is different again. CIERNIEWSKI /1985/ and other investigators describe this dependency in the categories of water potential. The relation between the reflectance and moisture expressed in terms of pF is shown in Fig. 4.

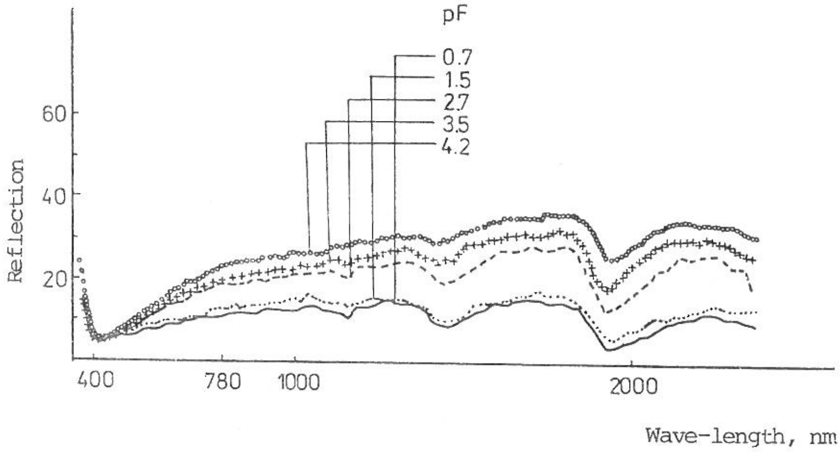


Fig. 4
Relationship between reflectance and soil moisture suction

Laboratory measurements are made on artificially smooth surfaces. These measurements do not take into account the influence of soil surface roughness, which is a natural feature of soil in the field and causes a decrease in reflectance in the visible range and the near to infrared. The influence of soil roughness on the spectral characteristics of two soils is shown in Fig. 5.

This influence is greater in soils with a low humus content than in soils with a considerable humus content. The influence of soil roughness is not always as great as that shown in Fig. 5, on which curve a/ represents an artificially smooth surface rarely found in the field. In some cases the influence of moisture on the change in spectral characteristics is greater than the influence of soil roughness, as shown in Fig. 6.

Nevertheless, at the same moisture level, the brightness of the surface and the optical density are modified by soil roughness.

Another factor modifying the spectral characteristics is the humus content. The influence of humus is similar to the influence of moisture, and these two factors are related. The interrelated effects of these factors, on which the amount of energy reflected from the soil surface depends, mean that the optical density, which is the direct feature of recognition and which can be measured, cannot be used to draw quantitative conclusions about soil moisture. It is shown that darker contours, i.e.

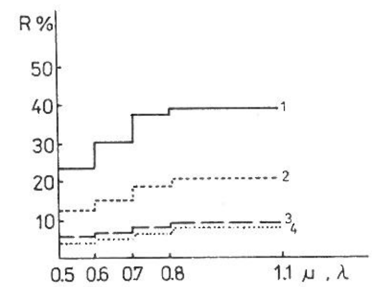


Fig. 5

Influence of soil roughness on the coefficients of reflectance

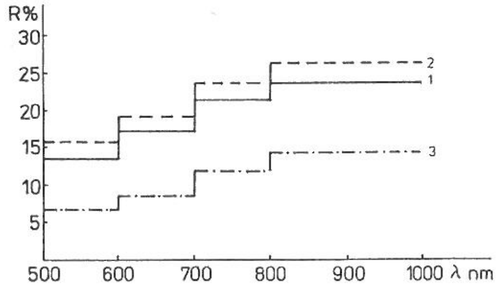


Fig. 6

Spectral curves of an arenosol

greater optical density, are connected with drier soils, but additional data are required to make this information more precise.

It is sometimes possible to obtain numerical correlations between the optical density of the photographs taken in the red and infrared bands and the moisture during experiments carried out on small plots. But these correlations come from single experiments and there are no results of their extrapolation to bigger areas.

Great hopes are attached to the use of registration in the thermal and microwave bands. Many researchers have shown a smaller correlation between the soil temperature and the moisture content but a greater and sometimes more important correlation between the amplitude of the day-night temperatures and the soil moisture. The beam of radiated energy /i.e. the temperature registered/ from bare soil and from soil covered with plants was related to the soil moisture at different levels. Figures 7 and 8 illustrate

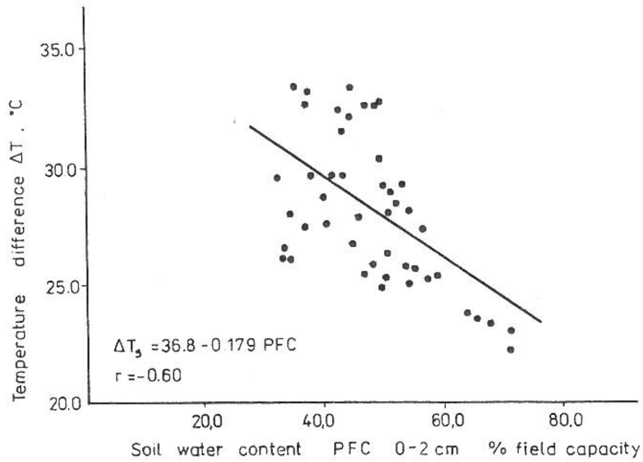


Fig. 7

Diurnal soil surface temperature differential ΔT, as a function of water content in the top 2 cm of fallow fields /according to CIHLAR, 1980/

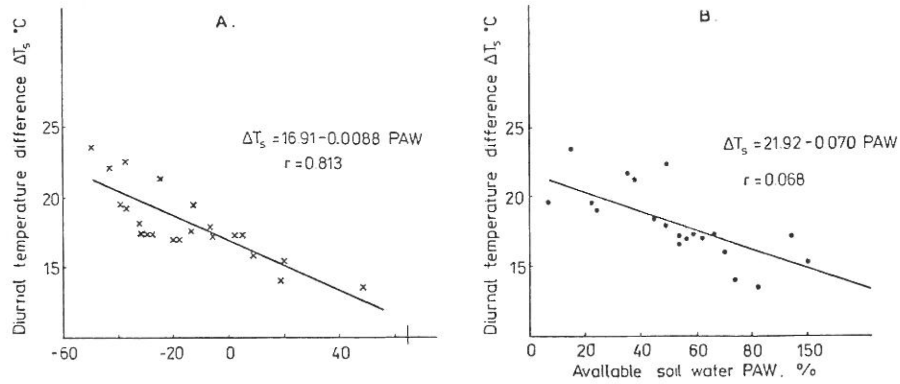


Fig. 8
Relationship between available soil water and the diurnal surface temperature difference for a barley field. A. 0-4 cm. B. 0-20 cm. /according to CIHLAR, 1980/

relations acquired for bare soils and for soils covered with plants by CIHLAR /1980/ and CIHLAR et al. /1979/.

The correlation of the soil moisture, not only with the amplitude of the day-night temperatures but also with other indexes either measured or

Table 1
Correlation with volumetric soil moisture content /0-5 cm/ from samples with a humus content ≥ 0.1 /according to AXELSSON and LUNDEN, 1986/

Parameters	Soil moisture correlation	Explanation of parameters
T_D	-0.76	Day IR temperature
T_N	0.84	Night IR temperature
A	-0.50	Reflectance at 400-1100 nm
ΔT	-0.78	$T_D - T_N$
$\bar{T}$	-0.67	$\frac{T_D + T_N}{2}$
NE_D	0.66	Instantaneous daytime values of net radiation
E_D	0.74	Net radiation minus the sensible heat losses
M	0.70	Evaporation index /actual: potential evaporation/
P	0.83	Thermal inertia

calulated, is given by AXELSSON and LUNDEN /1986/. A summary of their results is shown in Table 1, from which it can be seen that the closest correlations were acquired for the coefficient of the thermal inertia, for the temperatures measured at night and for the day-night temperature differences.

Similarly interesting results are given by authors who measured the moisture level by means of registration in the microwave band. Three examples will be cited.

MUSY et al. /1978/ discovered an important dependency /$0.70 \leq r \leq 0.88$/ in the 4.9 GHz and 10.5 GHz bands /Fig. 9/.

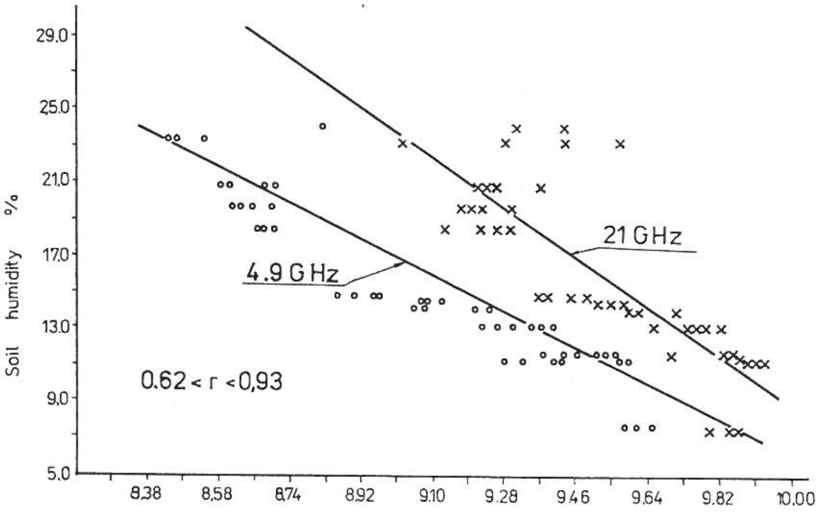


Fig. 9

Relationship between soil humidity and the emissivity of the soil for frequencies 4.9 GHz and 21 GHz /according to MUSY et al., 1978/

KING /1979/ used a scatterometer in the 1.5, 3.0, 4.0 and 9.6 GHz bands with frequency modulation. The coefficient of retrodiffusion depended on the parameters of the system and the soil.

$$\sigma_o = f\ (F, p, i, H, rg, t^o)$$

where: F = frequency, p = power, i = the angle of incidence, H = soil moisture, rg = soil roughness, t = soil temperature.

In the 1.5 and 4.5 GHz bands where soil roughness had no influence, the coefficient of the correlation between H and σ_o was found to be 0.90, at a level of significance of 0.01. At all frequencies used, an increase in moisture was accompanied by an increase in energy diffusion from the surface layer of the soil.

However, EVANS and CARROL /1986/ state that on interpreting X and C-band synthetic aperture radar images it can be seen that there is not always a dependency between soil moisture in the layer down to 50 mm and the diffused energy registered. They claim that the technique of radar calibration should be reconsidered and the influence of soil roughness estimated.

The estimation of soil moisture based on photographic registration, or in the thermal or microwave bands requires the calibration of this registration based on field or laboratory moisture measurements. All the authors accept direct moisture measurements as true values which are indisputable. But this is not so, because there is considerable differentiation in soil moisture both in the vertical and horizontal directions. Especially in the root zone during the period of plant growth considerable differences in moisture appear at a depth of a few centimetres. This is clearly visible in the case of irregular root disposal in the soil. Thus, a sample which is not representative or is of small quantity does not give representative information on the real soil moisture of the surface or the soil zone and this leads to an incorrect calibration of the remotely sensed data. The correct estimation of moisture in representative places is necessary for the calibration of remotely sensed data and is just as important as the data registration methods for the estimation of soil moisture by means of remote sensing methods.

Estimation of the soil water status

Reverting to what was said at the beginning, it can be seen that registration by means of remote sensing methods, whatever they are, provides single pieces of information about soil moisture /quantitative and qualitative/, with better or worse calibration, which corresponds to the moment the recording, i.e. the aerial photograph or thermal image, was made. How, then, can a transition be made from this single piece of information, important for a single moment, to the estimation of soil water status?

For the estimation of soil water status, information is acquired on soil moisture at different periods of the year and at different depths in the soil profile. Not only does the registration of remotely sensed data give single pieces of information, but this information refers only to the surface of the soil or to the surface layer to the depth of a few centimetres. These data must be extrapolated both in time and into the soil profile. Instead of extrapolating in time it is possible to make several registrations of remotely sensed data in characteristic periods, so that changes in the moisture content can be traced. But this involves high costs. The use of multitemporal satellite images may be considered for larger territories, but the reiterated use of airborne acquisition data questions the value of this technique. Another way must be found to extrapolate in time. In order to pass from results obtained from a single registration to the estimation of water status it is necessary to know how representative they are for the average soil moisture during the vegetation period and how they are related to the extreme values. In order to do this, both detailed technical data on remote sensing registration and the results of registration should be analysed in comparison with annual changes in soil moisture on the area under investigation and with climatic data /rainfall, temperature/ during a period of at least two weeks before registration.

Results analysed in this way are expressed by the distribution of the optical density /tones/ on aerial photographs, or by the moisture measured from data recorded in the thermal or microwave bands. All this should be compared to other factors which are easily defined and on which water status depends. These factors include the structure of the soil profile /genetic type and the spatiability of the profile/, and the geomorphology of the area. Regardless of whether there is access to sophisticated tools for mechanical analysis, the reasoning and the association of information that result from general soil sciences is important, especially findings on the relations between the water characteristics of the soil, the structure of the soil profile and the distribution of the soil in a given geomorphological unity.

For the analysed area it will thus be possible to create certain patterns of correlation between the soil picture on the photograph, the structure of the soil profile /information from the soil map/, the relief /information from the topographical map or from stereoscopic model/ and water status categories. After checking the correctness of the established patterns it is possible to mark out the contours of their range as based on the remotely sensed data. In this way, a classification map can be drawn, which on some scales requires field verification, after which a map of water status can be compiled.

The procedure described above is shown in Fig. 10.

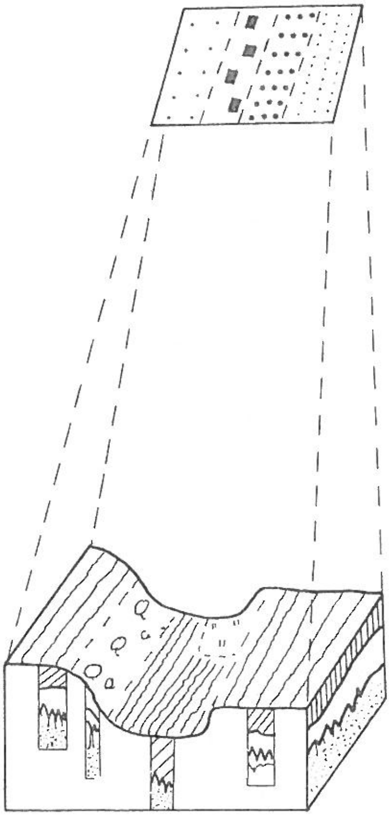


Fig. 10
Elaboration of a soil water status map with the use of remotely sensed data

Summary

Soil moisture can be determined by means of remote sensing methods using registration in the visible band or the near to infrared /photographic/ band or in the thermal and microwave bands.

Photographic registration gives qualitative but not quantitative information about soil moisture. Quantitative information can be obtained from the thermal and microwave band registration, but this information requires calibration based on direct moisture measurements. These pieces of information concern the surface layer of the soil.

To pass from these single remote sensing registration data, which provide information about the moisture level at a given moment of time, to the estimation of water status, consideration must be given to the structure of the soil profile and the geomorphology of the area.

The models for water status categories are created on the basis of this information. A determination is then made of the relations between these models and the remotely sensed data. If these relations are confirmed in the field, recommendations can be made for soil contours according to water status categories as shown by remotely sensed data.

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