Estimation of surface soil moisture content in the Siaya catchment

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Abstract

Regression equations are developed to calculate surface soil moisture of bare lands in the Siaya catchment which is located on the coastal belt of Zululand. Soil moisture was measured at depths of 25 mm and 75 mm along with 15 soil and terrain variables at each site. Six representative sites were selected and five samples of each depth were collected. At the time of the experiment colour and infrared aerial photographs of the catchment were taken with the intention of relating, at a later date, digitised images to variations in measured and calculated soil moisture. Factor analysis, correlation analysis and regression analyses were used to develop the equations. These equations were found to be unsatisfactory predictors of soil moisture content, particularly at 75 mm. The poor regression results were attributed to the extremely dry soil moisture conditions on the day of the study.

Background

Soil moisture has long been ascribed a prominent role in the hydrological cycle (Henninger, Petersen and Engman, 1976). The major dynamic storage component of a catchment is the soil matrix and generally soil moisture variations need to be considered in both time and space for hydrological modelling. Temporal variations in soil moisture at different depths in the soil horizon are controlled by different mechanisms. Tischendorf (1969) concluded that the deeper soil moisture changes were related to season while researchers such as Carlson, Reinhart and Horton (1956) found soil moisture in the surface 300 mm to depend primarily on the sequence of rainfall amounts, findings which have been substantiated in South Africa by Hope and Schulze (1979). The depth to which daily fluctuations in evapotranspiration affect soil moisture is determined by the rooting depth of the vegetation (e.g. Grindley, 1967 and Jones, 1976). Research findings, particularly in the United States of America, generally attribute spatial differences in soil moisture to one or more of the following; climate, soils, vegetation and topographical position (e.g. Wild and Scholz, 1930; Platt, 1955; Kovner, 1955; Stoeckeler and Curtis, 1960; Whipkey, 1965; Tischendorf, 1969 and Helvey, 1971).

The measurement of catchment soil moisture is time consuming and at best point readings are made at selected sites. In view of the highly variable nature of soil moisture in a catchment estimates of total soil moisture content are usually crude even when numerous point samples are taken (Blyth, 1981). Over the past decade much attention has been given to remote sensing techniques for the estimation of soil moisture (e.g. Schmugge, Meneely, Rango and Neff, 1977; Schmugge, Blanchard, Anderson and Want, 1978; Price, 1980; Newton, 1981 and Heilman and Moore, 1981). Reflectances in the green-yellow band (0,5μm – 0,6μm) and near infrared band (0,8μm – 0,9μm) have been found to be correlated with surface soil moisture conditions of bare land (Morris, Blyth and Clarke, 1980; Hardy, 1980 and Marcolongo, 1980).

An aerial survey of the Siaya catchment is made annually in order to monitor land-use changes in the catchment. This survey includes both colour and infrared photography and attempts are to be made at relating digitised multispectral images to the surface soil moisture of bare lands in this area. Thus, surface soil moisture measurements at representative sites in the catchments are required at the time of the photography. This study was designed to provide information on the surface soil moisture of bare soil in the Siaya catchment on August 30, 1982 when aerial photographs of the catchment were being taken.

Aims and Data

In order to relate remotely sensed data to surface soil moisture conditions it is necessary to sample soil moisture at sites which represent the variety of conditions found in the study area. Data from these control sites may then be used to establish a relationship between the appropriate spectral signature (combination of wavelengths) and surface soil moisture. Should such a relationship be found then the soil moisture of other bare fields in the catchment could be classified from the remotely sensed data.

The principal aim of this investigation was to develop regression equations from readily measurable soil and terrain variables which could be used at a later date to calculate surface soil moisture conditions which prevailed at the time of the flight. Estimates of surface soil moisture could then be made in areas of the catchment which were not included in the original sampling and assist in the interpretation of the aerial photographs.

An initial consideration in this study was to select six sites which were representative of the physical characteristics of the Siaya catchment and then to determine the surface soil moisture of each site at the time of the aerial data collection (between 11h00 and 13h00).

The Siaya catchment is located on the northern coastal belt of Zululand and covers an area of 15,3 km^2 (Figure 1). Altitudes range from 90 m in the west to sea level at the outlet of the catchment. Mean annual rainfall for the area is approximately 1350 mm and most of the catchment is covered by sugar cane. The selection of sites for this study was restricted by the location of fallow fields. However, an attempt was made to select sites which were representative of the soils, slopes and aspects found in the catchment. Furthermore, attention was given to providing a good spatial cover within the catchment which would include sites at various altitudes and distances from the sea. The locations of the selected sites are given in Figure 1.

At each site five sampling points were selected and samples of the soil at depths of 25 mm and 75 mm were taken. The five

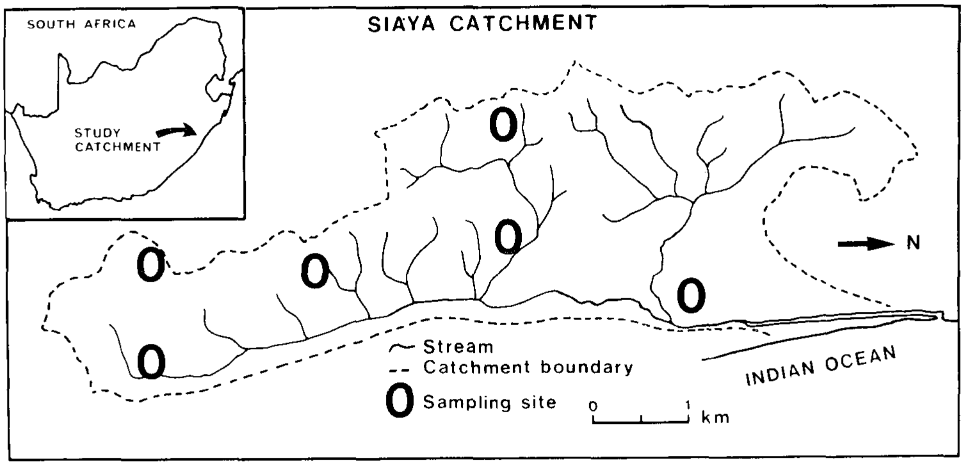

Figure 1
The Siaya catchment and location of sampling sites

individual sampling points were located at least 75 m apart so as to represent the local features of each site such as topographical position, soil and altitude. At least 100 g of soil was collected for each sample and placed in an air-tight bag and soil moisture (per cent by mass) was determined by gravimetric analysis in a laboratory. Besides expressing soil moisture as a per cent by mass, the variable was also converted to a relative value as is defined in the following expression:

$$RSM = \frac{SM_{ij} - SM_L}{SM_L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

RSM = relative soil moisture (–),
SM_{ij} = soil moisture at the i'th sample point of site j (%) and
SM_L = the lowest soil moisture value for any sample point for the chosen depth (%).

The concept of relative soil moisture was introduced so that the relationship between catchment variables, soil variables and the relative difference in soil moisture on the selected day could be evaluated. Independent variables were correlated with the variations in relative soil moisture rather than absolute soil moisture values.

Fifteen independent variables were measured at each sampling point for possible inclusion in the regression equations to calculate soil moisture at the two selected depths. Although not included in the regression analysis, soil temperature was measured at 25 mm (TEMP 1) and 75 mm (TEMP 2) to determine whether aspect and slope affected the temperatures of these depths.

Antecedent rainfall was not included as an independent variable in this study since no rain had fallen for fifteen days prior to the day of the flight. Furthermore, Hope and Mulder (1979) have established that rainfall amounts in this region are correlated highly with altitude and distance from the sea, both these variables being recorded at each sample point. Since the six selected sites were all located in ploughed fields, soil texture and organic matter were found to be very similar. Textural analyses were thus conducted using the combined samples from the two depths. A summary of all the variables used in this study is given in Table 1 while the mean, standard deviation and coefficient of variation of each variable is presented in Table 2.

TABLE 1
SELECTED INDEPENDENT AND DEPENDENT VARIABLES.

Independent Variables

Variable	Description	
CSAC	coarse sand (%)	TEXTURE
CSAM	medium sand (%)	
CSAF	fine sand (%)	
CSI	silt (%)	
CC	clay (%)	
CSSI	sand + clay (%)	
CSIC	silt + clay (%)	
CO	organic matter (%)	
SB	soil surface slope (deg.)	TERRAIN
H	height above nearest drainage channel (m)	
L	distance to nearest drainage channel (m)	
AL	altitude read from topographical map (m)	
ALB	altitude determined by barometer (m)	
DS	distance from sea (km)	
AZ	azimuth (°N)	

Dependent Variables

Variable	Description
SM1	soil moisture at 25 mm (%)
SM2	soil moisture at 75 mm (%)
RSM1	relative soil moisture at 25 mm (–)
RSM2	relative soil moisture at 75 mm (–)

TABLE 2
MEANS ($\bar{x}$), STANDARD DEVIATIONS (s) AND COEFFICIENTS OF VARIATION (CV) OF SELECTED INDEPENDENT AND DEPENDENT VARIABLES

Variable		$\bar{x}$	s	CV (%)
CSAC	(%)	34,945	11,754	33,6
CSAM	(%)	47,225	11,018	23,3
CSAF	(%)	9,314	3,613	38,8
CSI	(%)	3,271	3,218	98,4
CC	(%)	5,304	4,271	80,5
CSSI	(%)	94,755	4,319	4,6
CSIC	(%)	8,575	7,139	83,3
CO	(%)	2,010	1,633	81,4
SB	(deg.)	5,068	2,312	45,6
H	(m)	5,603	6,149	109,7
L	(m)	109,883	62,866	59,9
AL	(m)	45,057	16,243	36,0
ALB	(m)	55,087	18,977	34,4
DS	(km)	2,226	0,957	43,0
AZ	(°N)	164,967	91,848	55,7
SM1	(%)	1,055	0,808	76,6
SM2	(%)	6,188	3,796	61,3
RSM1	(–)	1,681	1,981	117,8
RSM2	(–)	1,242	1,375	110,7

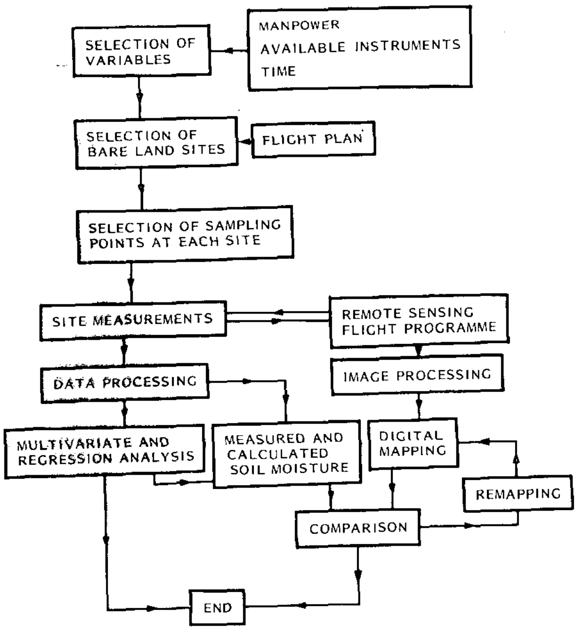

Figure 2
Flow chart of data collection procedure, analytical steps and intended remote sensing application

Analytical Procedures

A fundamental principle of regression analysis is that the independent variables contained in a regression equation should not be intercorrelated. The application of principal components factor analysis to hydrological problems is described by Seyhan (1981) and this procedure was adopted to identify the underlying independent dimensions or factors which explain the variance in the 21 selected variables measured for this study (Table 1). An examination of the correlation matrix used for the principal components factor analysis may reveal some association between variables included in different factors. This would also be seen if the factor matrix were presented without simplification. However, each factor would contain those variables which are least related to variables in other factors and are, for practical purposes, taken as independent of variables in these factors.

The degree of association between a single variable and the other variables in a factor is given by the factor loading. This loading may be taken to have a similar meaning to that of a correlation coefficient in a correlation matrix. Since it is difficult to interpret a factor matrix which contains all the factor loadings, it is necessary to retain only those variables having a loading greater or less than a set value (Seyhan, 1981). The selection of this threshold value is arbitrary and depends largely on the experience of the investigator. However, in many analyses there is a sharp transition between the group of high/low factor loadings and the group of values close to zero which assists in the selection of the critical value. For each factor the cumulative eigenvalue is given which represents the cumulative amount of variance explained by successive factors. The communality, h_i^2, gives the percentage of variance of the *i*th variable in the matrix of *m* factors.

The factor analysis in this study was based on a symmetrical correlation matrix (of Pearson's product-moment correlation coefficients) with variance orthogonal rotation criterion (Seyhan, 1981). Following the identification of independent factors, correlation, multiple linear regression and step-wise multiple linear regression analyses were used to develop the regression equations with only a single variable from each factor being permitted to enter each equation. Thus, the results of the factor analysis are used in an explanatory mode (Seyhan, 1981). No new independent variables (with factor scores) were developed from the factor analysis for inclusion in the regression analysis since similar studies have failed to show an increase in the significance of the regression equations when this procedure is adopted (Seyhan and Keet, 1981). All data were transformed logarithmically since, according to Seyhan (1981), this transformation generally results in a better approximation of the normal distribution, this distribution being assumed in all the statistical procedures adopted for this study.

A flow chart of the data collection procedure, analytical steps and intended remote sensing applications is given in Figure 2. The flow chart in Figure 2 gives an indication of the constraints under which such an investigation is invariably conducted.

Results and Discussion

The surface soils of bare fields in the Siaya catchment were found to be exceptionally dry on the day of the study with the mean soil moisture content at depths of 25 mm and 75 mm being 1,055% and 6,188% respectively (Table 2). The greater soil moisture content at 75 mm may have been expected since losses occur from above and rainfall had not occurred for 15 days. The coefficient of variation for soil moisture in the upper zone was 76,6% while that for the lower zone was 61,3%. These differences in variability suggest that localised factors, such as microtopography, have a more pronounced effect on soil moisture closer to the surface. Quantification of factors affecting soil moisture could thus be expected to be more difficult for the shallower depth. The two relative soil moisture indices, RSM1 and RSM2, also reflect the greater relative variability in soil moisture at 25 mm. However, the coefficients of variation for both indices are markedly higher than the associated values for soil moisture content (RSM1 : CV = 117,8%; RSM2 : CV = 110,7%).

The simplified rotated factor matrix of the 21 selected variables (Table 1) is given in Table 3. Six underlying dimensions or factors were identified and accounted for 84,8% of the variance in the correlation matrix. Factor I is clearly the most important dimension explaining 31,9% of the variance. This factor represents the strong relationship between soil texture and distance to the nearest drainage channel (L). The negative sign associated with L indicates that there is an inverse relationship between this variable and the silt content (CSI), clay content (CC) and organic matter content (CO) of the soils. Since these fine particles are generaly transported downslope by the movement of water, a greater concentration in each of these fractions would be expected closer to the drainage channels.

Factor II is a dimension which may be broadly described as the altitude factor. The variables included in this factor are either direct measures of altitude (AL, ALB) or related to altitude (H, DS). The coarse, medium and fine sand textural components constitute an independent dimension, factor III. Factor IV is the independent dimension of soil moisture containing soil moisture content and relative soil moisture for the two depths. The high positive factor loadings in factor IV indicates that soil moisture at the two depths is highly related. Soil temperatures, TEMP1 and TEMP2, were included in a single factor (V) and did not include azimuth (AZ) or slope SB as was expected. Finally, the soil surface slope (SB) was found to be an independent factor (VI) which accounted for 10,61% of the observed variance in the correlation matrix.

TABLE 3
SIMPLIFIED ROTATED FACTOR MATRIX OF SOIL, TERRAIN AND SOIL MOISTURE VARIABLES
(factor loadings ≥ 0,65 and ≤ – 0,65 retained)

Variables	Factors						h_i^2(%)
	I	II	II	IV	V	VI	
CSAC			0,945				90,18
CSAM			0,873				84,54
CSAF			– 0,930				94,33
CSI	0,650						48,03
CC	0,883						89,59
CSSI	– 0,934						95,18
CSIC	0,937						93,60
CO	0,805						93,89
SB						– 0,809	85,44
H		0,813					88,69
L	– 0,808						87,94
AL		– 0,967					93,98
ALB		– 0,954					95,93
DS		– 0,930					96,23
AZ							74,36
SM1				0,690			82,42
SM2				0,794			79,64
RSM1				0,806			79,31
RSM2				0,871			80,66
TEMP1					– 0,635		82,00
TEMP2					– 0,799		64,81
Eigen-value	6,70	3,69	3,50	1,40	1,39	1,18	
Explained Variance (Cu. %)	31,90	49,48	66,15	72,18	79,18	84,80	

Following the correlation, multiple linear regression and stepwise multiple linear regression analyses two equations were developed for caltulating soil moisture content at a depth of 25 mm (SM1), viz.

$$\mathrm{SM1} = 0{,}534\,(\mathrm{CO})^{0{,}886};\ r^2 = 0{,}563 \qquad (2)$$

and

$$\mathrm{SM1} = 0{,}038\,(\mathrm{CO})^{0{,}834}(\mathrm{CSAF})^{0{,}759};\ r^2 = 0{,}631 \qquad (3)$$

These equations indicate that organic content (CO) has the greatest association with moisture content in the upper zone accounting for 56,3% of the observed variance in SM1 (Equation 2). By including the fine sand content (CSAF) in the equation the explained variance increases by less than 7 per cent to 63,1 per cent. Since the standard error of estimate for both equations was greater than 30 per cent and the explained variances were low, the equations were not regarded as satisfactory models for calculating SM1.

A single equation was developed for soil moisture content at the depth of 75 mm (SM2) and took the following form:

$$\mathrm{SM2} = 0{,}232\,(\mathrm{CO})^{0{,}497};\ r^2 = 0{,}430 \qquad (4)$$

The standard error of estimate for this equation also exceeded 30 per cent of the mean and a mere 43 per cent of the observed variance in SM2 was explained by the model (Equation 4). These statistics were not improved by including additional independent variables and Equation 4 was also considered unsatisfactory for calculating soil moisture content.

The importance of organic matter (CO) in retaining moisture in the soil under dry conditions was illustrated in this regression analysis, being important at both depths. Generally, adsorptive forces are important in retaining soil moisture under dry conditions and despite the greater specific surface associated with silt and clay, fine sand was the only textural component included in the regression equations. Contrary to expectations, the equations developed for SM1 were better than the equation for SM2.

Attempts to develop regression equations for relative soil moisture at the two depths (RSM1, RSM2) were not successful. The best equation was for RSM1 and was of the form:

$$\mathrm{RSM1} = (0{,}13 \times 10^{-4})(\mathrm{CO})^{3{,}221}(\mathrm{ALB})^{2{,}116};\ r^2 = 0{,}429 \ldots \qquad (5)$$

Besides the low coefficient of determination ($r^2 = 0{,}429$) the standard error exceeded 30 per cent. It may thus be concluded that the relative soil moisture as defined by these indices had a limited relationship with the independent variables measured. However, organic matter (CO) was also a significant independent variable in this equation at the 95% level.

Conclusions

Soil moisture contents determined for the 30 sample points on bare land and at two depths in the Siaya catchment revealed that the soil moisture conditions for the selected day were particularly dry. The major findings of this investigation may be summarised as follows:

- Soil moisture contents at the depth of 75 mm were markedly higher than those at the depth of 25 mm and exhibited less variability.
- The 21 variables measured in this study were reduced, successfully, to six independent dimensions using principal components factor analysis.
- Organic matter was found to be the most important independent variable affecting soil moisture contents at both depths investigated.
- Regression equations for calculating surface soil moisture were not satisfactory, particularly for estimates at a depth of 75 mm. These equations were characterised by poor coefficients of determination (r^2) and high values of the standard error of estimate.
- Expressing soil moisture as a quantity relative to the lowest recorded value resulted in weaker regression equations and could not be related successfully to the selected independent variables.

The results and conclusions of this investigation may have been dominated by the dry soil moisture conditions on the day of the study. Different results may be found under wetter conditions where factors such as antecedent rainfall could be included in the analysis. Furthermore, independent variables which were found to be unimportant in this study could be significant under wetter conditions and may result in more accurate predictive equations. The results of the regression analysis for these dry conditions are inadequate for the proposed application to remote sensing. However, the measured values of the 30 sample points could be used as a training sample for digitised images. The procedures adopted in this investigation were considered to be satisfactory and suitable for repeated analyses of this nature.

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