Soil moisture retrieval with remote sensing images for debris flow forecast in humid regions

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Abstract

Soil moisture is a key parameter in debris flow prediction for its influence on the critical rainfall triggering debris flow. Soil moisture can be obtained by ground measurement. However, it is difficult to extend these limited observing data to the regional scale because of the heterogeneity of land surface. The Temperature-Vegetation Dryness Index (TVDI) is a common method of estimating regional soil moisture by the images of MODIS, because of its moderate spatial resolution and high temporal resolution. However, because the basic assumption of the TVDI method is that pixels from the study region can cover the entire range of soil moisture conditions and vegetation fractions, it is difficult to determine the actual dry edge of the space in humid regions. The Crop Water Shortage Index (CWSI) calculated by actual evapotranspiration and potential evapotranspiration does not need fitting to the dry edge and wet edge. CWSI further considers about the influence of vegetation. In this paper, we applied both TVDI and CWSI methods to retrieving soil moisture using remote sensing and meteorological data in Zhejiang Province, which has a humid climate. Among CWSI, the actual and potential evapotranspiration are calculated by the SEBS model. CWSI can also directly express the extent of soil moisture. In surface soil (0-10cm), the correlation coefficient of CWSI and measured relative soil moisture (RSM) reached -0.89.
Keywords: remote sensing, soil moisture, TVDI, CWSI, debris flow forecast, humid region.

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1 Introduction

Soil moisture can affect the shear strength and infiltration capacity of soil, which can further influence the critical rainfall triggering debris flow. Therefore, soil moisture monitoring has important significance for debris flow forecasting. Due to lack of soil moisture observation stations, antecedent rainfall is used in debris flow forecast instead at present [1, 2]. Along with the development of remote sensing, the method of retrieving regional soil moisture for debris flow prediction with images of remote sensing is becoming available.

There are two indices for soil moisture estimation, Temperature-Vegetation Dryness Index (TVDI) [3] and Crop Water Shortage Index (CWSI) [4, 5]. Many researches have shown that land surface temperature is negatively related to vegetation cover fraction, and the relationship is affected by soil moisture [6-8]. TVDI is computed through the feature space constituted by vegetation index and surface temperature. It has been widely used for its simple algorithm [9-11] without meteorological data. If the study area is large enough to cover land surfaces with the whole range of soil moisture conditions and vegetation densities, "dry edge" and "wet edge" of the space can be determined by data fitting. The precondition cannot be fully satisfied in humid regions, so the fitted edges are experiential edges. Land surface actual evapotranspiration (*LE*) correlates with soil moisture. It can be estimated by remote sensing data (include vegetation index, surface temperature and albedo) united with meteorological data. So CWSI, which is calculated by *LE* and potential evapotranspiration (LE_{wet}), is also related with soil moisture. The Surface Energy Balance System (SEBS) [12] is one of estimating *LE* model according to the surface energy balance equation. SEBS is first built to estimate atmospheric turbulent fluxes and evaporative fraction using remote sensing and meteorological data. It gives a physical description to the key parameter in surface energy flux estimation-the roughness length for heat transfer, which increases calculation accuracy of *LE*. It has been used in some regions of China [13, 14].This paper will discuss how to use the images of MODIS (Moderate Resolution Imaging Spectroradiometer) and meteorological data to estimate soil moisture. CWSI calculated by SEBS and TVDI are applied to retrieve soil moisture respectively. The results of both retrieving methods are tested by ground soil moisture observations in Zhejiang Province, China.

2 Methodology

2.1 Method of TVDI [3, 6, 7, 15]

Vegetation index provides useful information about vegetation growth status while soil moisture conditions can be reflected by surface temperatures. These provide the basis for regional soil moisture monitoring with remote sensing data. When vegetation is water-stressed, the feature space composed by surface temperature (T_s) and normalized difference vegetation index (*NDVI*) is trapezoidal, otherwise it is triangular. The triangular space can be considered as a special case of trapezoidal spaces, so in this paper we used the trapezoidal space (see Fig. 1). Line 2-4 is dry edge of the space. It defines the relationship between T_s and *NDVI* in drought conditions. Line 1-3 is the wet edge and defines the relationship in wet conditions. For a given point inside the trapezoid, *TVDI* is defined as

$$TVDI = \frac{T_s - T_{s\min}}{T_{s\max} - T_{s\min}} \quad (1)$$

where T_{smin} and T_{smax} are temperature values on the wet edge and dry edge corresponding to the point, respectively. Dry edge and wet edge can be obtained by following fitting equations:

$$T_{s\max} = a + b * NDVI \quad (2)$$

$$T_{s\min} = c + d * NDVI \quad (3)$$

where a, b, c, d are fitting coefficients.

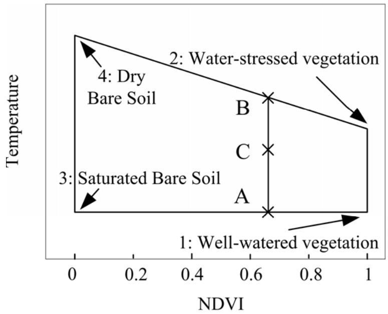

Figure 1: The hypothetical trapezoidal shape that would result from the relation between temperature and NDVI. This sketch map is modified from Moran et al. [15].

2.2 Method of CWSI [4, 5]

CWSI was originally proposed on the basis of the energy balance, and its initial prototype is the ratio of canopy-air temperature difference and air saturation deficit. In this paper, the higher the soil moisture content is, the closer the actual latent heat flux is to LE_{wet}. Otherwise the actual latent heat flux is closer to 0. So we can define CWSI to characterize the soil drought degree:

$$CWSI = 1 - LE / LE_{wet} \quad (4)$$

Different from the previous CWSI calculation method, *LE* is calculated by SEBS model. SEBS[12] is a single-source model based on the energy balance, soil heat flux *G*, net radiation R_n and sensible heat flux *H* are calculated with *NDVI*, T_s, geodata and meteorological data, and then latent heat flux *LE* is computed as:

$$LE = R_n - G - H \quad (5)$$

The Penman-Monteith formula with removing the surface resistance term is used to calculate latent heat flux in wet conditions:

$$LE_{wet} = \frac{\Delta(R_n - G) + \rho C_p (e_*(T_a) - e_a)/r_{ah}}{\Delta + r} \tag{6}$$

$$e_*(T_a) = 0.6108\exp\left(\frac{17.27T_a}{237.3 + T_a}\right) \tag{7}$$

$$\Delta = \frac{4098 e_*(T_a)}{(237.3 + T_a)^2} \tag{8}$$

where ρ is air density, kg/m^3, C_P is specific heat capacity at constant pressure of the air, J/(kg·K), $e_*(T_a)$ is saturation vapour pressure corresponding to T_a, kPa, e_a is actual vapour pressure, kPa, r_{ah} is the aerodynamic resistance for heat transfer, s/m, Δ is the slope of vapour pressure-temperature curve, kPa/K, r is the psychrometer constant, kPa/K.

3 Study area and data sources

3.1 Overview of the study area

Zhejiang Province has a terrestrial area of 101,800 km^2, of which 70.4% are hills and mountains (Fig. 2). The ground elevation ranges from 0 to 1914m. It has mild temperatures, and vegetations grow well. In land-use types, forest land accounts for 62.8%, followed by paddy fields and towns. The average annual

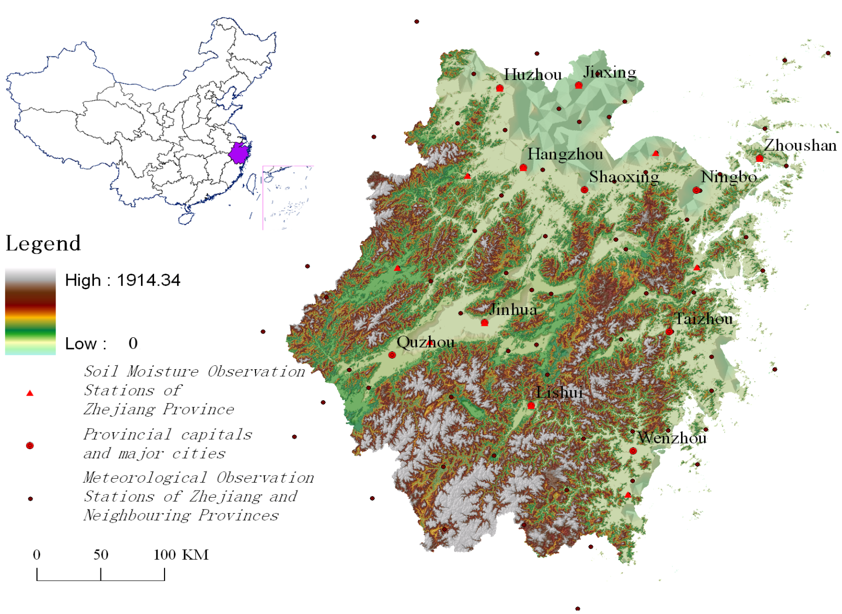

Figure 2: Topographic map of Zhejiang and sampling sites locations.

precipitation ranges from 980 mm to 2000mm. Affected by the plum rains and typhoons, the precipitation mainly occurs between April and October. The high-intensity rainfall and great elevation difference result in a frequent occurrence of landslide and debris flow.

3.2 Data sources

The MODIS instrument has moderate spatial resolution (250m, 500m and 1000m), high temporal resolution (four times per day), and high spectral resolution (36 spectral bands range from 0.62μm to 14.385μm).

The 6 days of MODIS data used in this paper were downloaded from the website of NASA. They were obtained on clear days from July to September, 2008. The data include surface reflectance product (MOD09), surface temperature product (MOD11) and normalized difference vegetation index products (MOD13).

Air temperature, wind speed and vapour pressure data of the satellite transit time were obtained from 72 meteorological stations in Zhejiang Province and 11 stations in the neighbouring provinces (Fig. 2). Soil moisture data were also obtained from 10 meteorological stations of Zhejiang Province for verification. In addition, land use classification maps and digital elevation model (DEM) data were used in this paper.

4 Data processing and TVDI and CWSI retrieving

4.1 Data processing

4.1.1 TVDI data processing

4.1.1.1 Surface temperature adjustment TVDI is based on the negative relationship between T_s and *NDVI*. An even and stable atmosphere is essential for the computation of this index. In this paper, T_s values need to be adjusted because atmosphere is non uniform in the study region. In the troposphere, air temperature drops 0.65 ℃ when the height increases by 100m. As a result, T_s values were adjusted as follows:

$$T_s' = T_s + 0.0065Z \tag{9}$$

where Z is ground elevation, m.

4.1.1.2 Determination of the dry edge and wet edge T_s' was plotted versus *NDVI* in Fig.3. We can see that T_s' increases with *NDVI* when *NDVI* is less than 0.3, which is contrary to the theory of feature space. It induces some difficulty to determining the dry edge. According to the land-use map, we found that pixels with *NDVI* values less than 0.3 are mostly mixed pixels. Few pure pixels can be found at the 1km pixel scale. It results in a lack of bare ground pixels. Therefore, we only used pixels with *NDVI* values greater than 0.3 to determine the dry edge. The maximum T_s' value was selected for each *NDVI* interval of 0.01, then they are used to fit the dry edge (see Table 1).

Table 1: Wet and dry edges for *Ts-NDVI* Feature Space.

Time	Dry edge	Wet edge
7/6/2008	y = -7.8671x + 48.259	y = 28.04
7/17/2008	y = -8.4107x + 45.676	y = 27.95
7/27/2008	y = -7.1457x + 41.768	y = 23.79
8/12/2008	y = -6.499x + 40.548	y = 25.77
9/10/2008	y = -3.579x + 37.467	y = 24.01
9/22/2008	y = 0.4521x + 35.907	y = 25.62

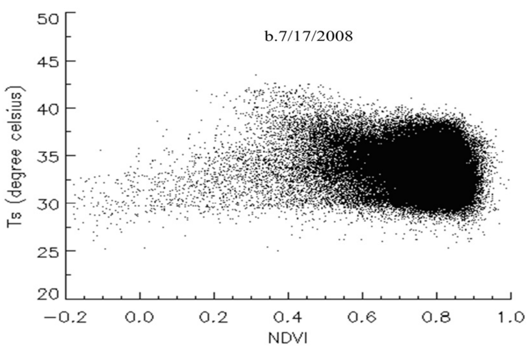

Figure 3: Scatter point TVDI image of Zhejiang (case study of July 17th 2008).

Soil moisture is high in the study area in summer because of plenty of precipitation, so we can get wet pixels for different *NDVI* values. For the selected 6 days, standard deviation of the minimum temperatures in each *NDVI* interval is 1.34 ℃, 1.28 ℃, 1.29 ℃, 1.50 ℃, 1.20 ℃ and 1.08 ℃ respectively. It proves the low discrete degree of the data. As a result, the wet edge is expressed by the average value (see Table1).

4.1.2 CWSI data processing

4.1.2.1 Input data of model Input data of the model include 3 categories: (1) Remote sensing data: surface albedo, *NDVI*, and surface temperature; (2) Meteorological data: air temperature, vapour pressure and wind speed; (3) Geographical data: altitude, slope, flow direction, latitude, and land use. These data are directly or indirectly used in the model.

4.1.2.2 Spatial interpolation of meteorological data We got the raster data of air temperature, wind speed and vapour pressure through the Kriging interpolation with single-station data. The resolution is 1km×1km. In order to eliminate the impact of elevation and make two-dimensional interpolation to one-dimensional, air temperatures were revised to the sea level temperatures according to Equation (9) before interpolation. They were revised to the actual altitude after interpolation.

4.2 Results of TVDI and CWSI retrieving

The results are retrieved by TVDI and CWSI (Fig.4-5). The majority values of results are between 0 and 1, and the region's values less than 0 are under the cloud coverage.

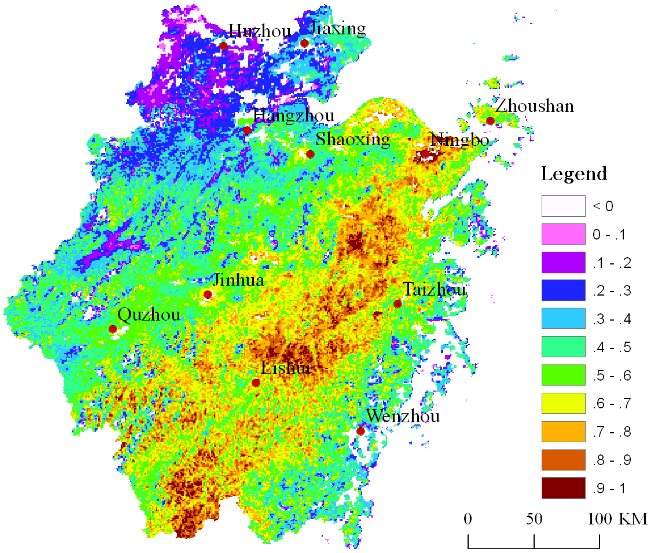

Figure 4: Retrieving results of TVDI (case study of July 17th 2008).

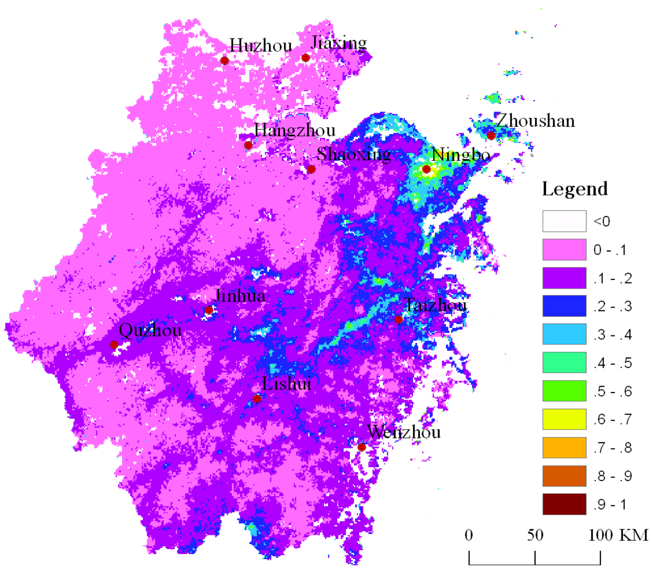

Figure 5: Retrieving results of CWSI (case study of July 17th 2008).

4.3 Examination and comparison of retrieving results

4.3.1 Examinations of retrieving results with observation data

We got soil moisture from 11 stations in the study area. 5 Urban stations were excluded during the data processing because of the complexity in land use as well as the mixed pixels of MODIS images. TVDI and CWSI were compared with relative soil moisture (RSM) observations at different depths, separately.

The correlation coefficients (Table 2) are negative. According to the average correlation coefficient, CWSI has a closer relationship with soil moisture than TVDI.

4.3.2 Comparison of retrieving results between two methods

In the study area, drought degree is defined as follows. RSM in 0%~20% represents extremely severe drought, 20%~40% represents heavy drought, 40%~60% represents slight and medium drought, 60%~90% represents suitable, and >90% represents extreme wetness. All of the RSM values used in this study are over 40%. Some of them even arrive at 100%. Generally, extremely severe drought and heavy drought didn't occur in the selected days.

Qi [16] defined five drought levels according to TVDI and four drought levels of CWSI, as listed in Table 3. When TVDI values in Zhejiang Province are classified with this method, results are quite different with the real conditions (Table 4). CWSI is more suitable for the actuality. Simulated values of CWSI are between 0-0.7. Table 4 lists mean values of the RSM observations corresponding to different CWSI intervals. It can be seen that CWSI can reflect the overall trend of soil moisture distribution.

Table 2: Correlation coefficients between RSM and TVDI and CWSI in different soil layers.

Soil depth	TVDI	CWSI
0-10cm	-0.74	-0.89
10-20cm	-0.62	-0.77
20-30cm	-0.80	-0.64
Average	-0.72	-0.77

Table 3: Drought classifications according to TVDI [16] and CWSI [17].

TVDI	CWSI*	Description
0～0.2	<0.4	Moisture
0.2～0.4	0.4～0.6	Normal
0.4～0.6	0.6～0.8	slight and medium drought
0.6～0.8	/	Drought
0.8～1	0.8～1	Severe Drought

Note: "/" No data in this range. "*" Classification refers to the Water Deficit Index (WDI) partition method based on the CWSI theory.

Table 4: Mean RSM values for different TVDI and CWSI intervals.

Intervals	Mean RSM values for TVDI			Mean RSM values for CWSI		
	0-10cm	10-20cm	20-30cm	0-10cm	10-20cm	20-30cm
0	/	/	/	90.7	92.0	96.0
0-0.1	/	/	/	73.5	84.2	81.4
0.1-0.2	/	/	/	/	/	/
0.2-0.3	/	/	/	76.8	78.6	75.6
0.3-0.4	90.7	92.0	96.0	49.5*	60.8*	67.5*
0.4-0.5	59.0*	63.0*	78.0*	50.0	77.0	79.0
0.5-0.6	72.8	81.6	82.2	/	/	/
0.6-0.7	74.2	86.8*	80.6	/	/	/
0.7-0.8	56.2	70.4	72.9	/	/	/
0.8-0.9	41.0	54.0	55.0	/	/	/
0.9-1	/	/	/	/	/	/

Note: "/" No observations in this range. "*" The value is small due to lack of samples.

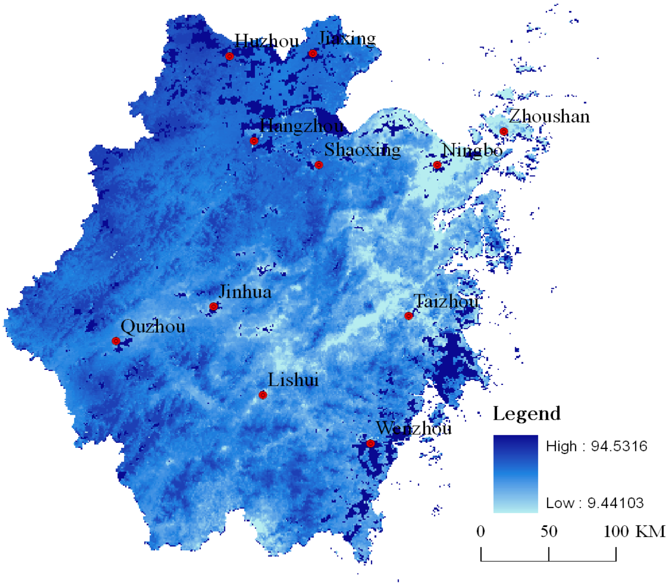

Figure 6: Estimated 0-10cm RSM of Zhejiang on July 17th 2008 using correlation equation $y_{0\text{-}10cm} = -93.586x + 85.173$.

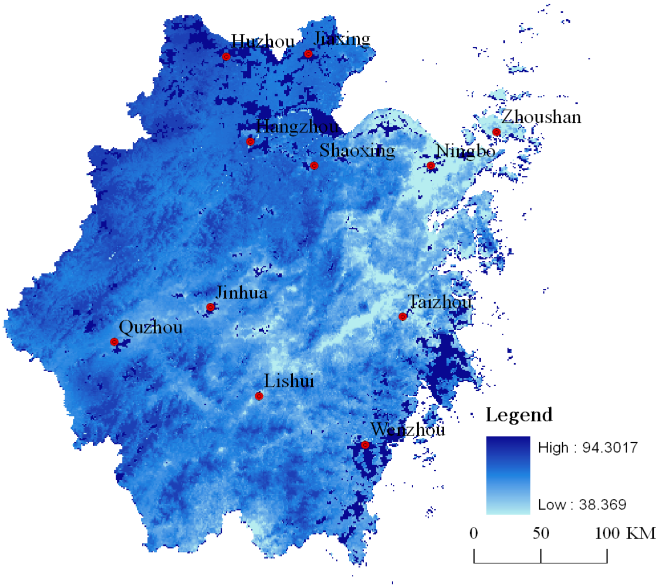

Figure 7: Estimated 20-30cm RSM of Zhejiang on July 17th 2008 using correlation equation $y_{10\text{-}20cm} = -61.517x + 88.15$.

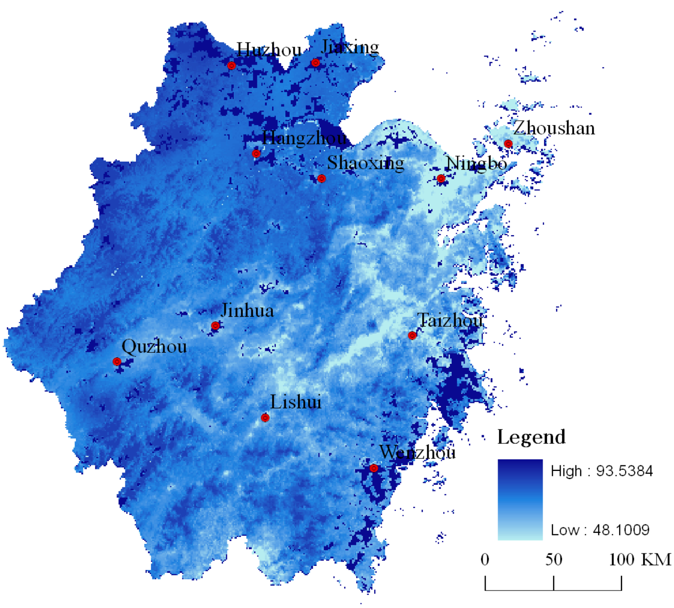

Figure 8: Estimated 20-30cm RSM of Zhejiang on July 17th 2008 using correlation equation $y_{20\text{-}30cm} = -49.974x + 88.541$.

4.4 Soil moisture retrieval using CWSI

CWSI has a closer relationship with soil moisture than TVDI, so it was selected to retrieve RSM in Zhejiang Province. Both fitting equations between CWSI and RSM observations and calculated RSM sketch maps are shown in Figure 6-8 for each soil layer. As illustrated, RSM shows higher in south, west and north, while lower in central and east on July 17, 2008. Three levels of soil moisture distribution have the same trend. The RSM will further provide the basis for debris flow forecast.

5 Conclusions

In this paper, MODIS data were used to retrieve soil moisture in Zhejiang Province, China. In humid regions with high vegetation cover, the experiential dry edge of TVDI may be not the actual dry edge. It can lead to higher estimation in TVDI and severer extent in draught judgement. So TVDI cannot be directly used to express draught degree in this area. However, TVDI has indeed closely relationship with soil moisture, and TVDI does not require meteorological data. If we can find actual dry edge in humid region, it may have more broad application prospects.

CWSI simulated with SEBS can be used in humid regions with high vegetation cover and has more potential to retrieve soil moisture, because SEBS has more advantages in calculating evapotranspiration. It is more objective to determine CWSI because wet and dry edges are not required. CWSI can better reflect soil moisture conditions, especially in the surface layer.

Soil moisture retrieval with remote sensing images resolves the uncertainty with antecedent rainfall and provides an important basis for debris flow forecast. It has far-reaching significance in debris flow prediction.

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