A modified perpendicular drought index in NIR-Red reflectance space

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Abstract. Soil moisture and vegetation index provides valuable information for surface water content and drought assessment with remotely sensed data. In this paper, a new drought monitoring method (MPDI1) with soil moisture and vegetation index is constructed in NIR-Red reflectance space. The relationship between MPDI1 and soil moisture is explored using satellite image and field measure data, and a comparison among MPDI1, the Perpendicular Drought Index (PDI), and the Modified Perpendicular Drought Index (MPDI) is also evaluated. Results indicate that the MPDI1 is highly accordant with the in-situ ground observation with the coefficient of determination ($R^2=0.4905$) between MPDI1 and 5-20 cm mean soil moisture. Moreover, PDI, MPDI and MPDI1 provide quite similar spatial patterns for bare soil or lower vegetated surface, but MPDI1 demonstrates a better performance in measuring densely vegetated surface. This paper concludes that MPDI1 is a useful tool for surface drought estimation under complex underlying conditions.

1. Introduction

Drought might be described as a chronic disaster characterized by a prolonged reduction of water resources, which leads to great social and economical consequences [4]. Quantitative assessment of surface drought has become an important issue to the scientists. Remotely sensed image has proven to be a promising approach for drought estimation over large areas.

Vegetation growth has a close relationship with surface water-energy balance and drought status. The normalized difference vegetation index (NDVI) is the most famous vegetation index for drought estimation and ecosystem monitoring [1]. Considering the interannual variations of NDVI values from both the weather fluctuation and the ecosystem component, the Anomaly Vegetation Index (AVI) and the Vegetation Condition Index (VCI) [5] were derived. Combined the thermal and optical channels from satellite images, the Temperature Condition Index (TCI) [11], the Vegetation Temperature Index (VTI) [6], and the Vegetation Health Index (VHI) [6] were proposed. Due to the obvious difference of water reflectance in near infrared and shortwave infrared (SWIR) bands, the normalized difference water index (NDWI) [2], the normalized difference drought index (NDDI) [12], and the normalized multiband drought index (NMDI) [12] were developed. Moreover, the Perpendicular vegetation index (PVI) was also used to estimate crop water balance in arid region [8].

Soil moisture is crucial in energy balance and water circulation between land and atmosphere. Richardson and Wiegand [10] discovered that the scatter plot of NIR-Red reflectance space conformed
to a typical triangle distribution (also called the feature triangle), and developed the Perpendicular Vegetation Index (PVI) to describe vegetation coverage. The Perpendicular Drought Index (PDI) [3] were derived with the atmospheric corrected reflectance of Landsat ETM+ NIR and Red bands. Qin et al. [9] evaluated the MODIS derived perpendicular drought index for surface dryness estimation over northwestern China. In order to exclude the vegetation interference of a mixed pixel that accounted for soil moisture and vegetation growth, Ghulam et al. [3] introduced vegetation fraction to construct the Modified Perpendicular Drought Index (MPDI) for vegetated surface dryness monitoring.

The paper aims to explore a new drought index with remotely sensed data in NIR-Red reflectance space, which is a continuous work of PDI and MPDI models. The Second Modified Perpendicular Drought (MPDI1) is a combination of two satellite-derived variables - a soil moisture component using PDI, and a vegetation component using PVI. In contrast to the MPDI model of excluding the vegetation interference from PDI in soil-plant continuum, MPDI1 model reflect the drought contribution from both soil moisture and vegetation growth.

2. Methodology

2.1. The perpendicular drought index (PDI)

As shown in Figure 1, point A, B, C, D, and E locate inside the feature triangle. Point B, C, and D are in the straight bottom line (called the soil line), point A is the corresponding vertex of the soil line, and point E is a random point inside the feature triangle. Line L passes point O (the coordinate origin) and is perpendicular to Line BC, which intersects Line BC at point H. And Line EF passes point E and is perpendicular to Line L, which intersects Line L at point F.

Suppose the coordinate of point E in NIR-Red spectral space is $(R_{\text{Red}}, R_{\text{NIR}})$, EF (PDI) represents the distance between point E and line L, which can be expressed by the following equation:

$$PDI = \frac{1}{\sqrt{M^2 + 1}} (R_{\text{NIR}} + MR_{\text{Red}})$$

Where $R_{\text{NIR}}$ and $R_{\text{Red}}$ refer to the atmospherically corrected reflectance of NIR band and Red band respectively, $M$ refer to the slope on vertical axis of the soil line, which can be calculated by linear regression.

2.2. The modified perpendicular drought index (MPDI)
MPDI can be expressed by the following equation [3]:  
\[ MPDI = \frac{R_{\text{red}} + MR_{\text{NIR}} - f_v(R_{\text{red}} + MR_{\text{NIR}})}{(1 - f_v)\sqrt{M^2 + 1}} \]  
(2)

Where \( R_{\text{NIR}} \) and \( R_{\text{Red}} \) refer to the atmospherically corrected reflectance of NIR band and Red band respectively, \( M \) refer to the slope on vertical axis of the soil line, \( f_v \) refer to the vegetation fraction, \( R_{v,NIR} \) and \( R_{v,\text{Red}} \) refer to vegetation reflectance in the NIR band and Red band respectively.

According to Ghulam et al. (2008), \( R_{v,NIR} \) and \( R_{v,\text{Red}} \) are determined as 0.05 and 0.5 by field measurements respectively.

The vegetation fraction (\( f_v \)) is the fraction of ground surface covered by vegetation, which can be expressed by the following equation:

\[ f_v = 1 - \left(\frac{\text{NDVI}_{\text{max}} - \text{NDVI}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}}\right)^{0.4175} \]  
(3)

Where \( \text{NDVI}_{\text{min}} \) and \( \text{NDVI}_{\text{max}} \) refer to NDVI for a surface with 100% vegetation (\( f_v = 1 \)) and bare soil (\( f_v = 0 \)) respectively. They are determined by finding fully vegetated or bare soil pixels in image.

2.3. The second modified perpendicular drought index (MPDI)

It is speculated that soil moisture and vegetation coverage are two independent variables describing surface drought status. In NIR-Red reflectance space, suppose soil moisture is constant, where vegetation coverage shifts from point A, point E to point D along with line AED, surface dryness is increased gradually. Moreover, suppose vegetation coverage is constant, where soil moisture shifts from point B, point D to point C along with line BDC, surface dryness is also elevated gradually. So the combination of soil moisture and vegetation coverage is acceptable in surface drought estimation.

(1) Soil moisture component - the Perpendicular Drought Index (PDI)

See Chapter 2.1 for more details.

(2) Vegetation coverage component - the Perpendicular Vegetation Index (PVI)

Suppose the coordinate of point E in NIR-Red spectral space is \( (R_{\text{red}}, R_{\text{NIR}}) \), ED (PVI) represents the distance between point E and line BC, which can be expressed by the following equation:

\[ PVI = \frac{1}{\sqrt{M^2 + 1}}(R_{\text{red}} + MR_{\text{NIR}} - I) \]  
(4)

Where \( R_{\text{NIR}} \) and \( R_{\text{Red}} \) refer to the atmospherically corrected reflectance of NIR band and Red band respectively, \( M \) and \( I \) refer to the slope and interception on vertical axis of the soil line respectively, which can be calculated by linear regression.

The Second Modified Perpendicular Drought Index (MPDI) might be defined as the distance between point H and E, which can be expressed by the following equations [7]:  

\[ MPDI = \sqrt{PDI^2 + PVI^2} \]  
(5)

Where PDI refer to its soil moisture component and PVI refer to its vegetation coverage component.

3. Test site and data processing

This paper selects the Zhanghe irrigation system as the test site. It is located at Hubei Province, P. R. China (figure 2) within the latitude of 30°20'-31°10' and the longitude of 112°00'-112°40'. The length along the east-west and of north-south directions is approximately 1600 km and 400 km respectively. Land elevation drops mildly from 800 m to 600 m above sea level. This region has mild climate and a long frost-free period. Its annual average precipitation is about 800 mm, but the rainfall mainly
concentrates in April to October, which results in winter drought and spring drought with severe impact on crop growth and agricultural production.

A satellite-surface synchronous observation champion was conducted in the test site from March to May, 2006. Many surface variables, such as soil moisture, land cover, air temperature, albedo, and vegetation index, were collected. The test site was divided equally into four sample fields, and ten sample points were deployed equally in each sample fields. The distance among each sample points was no less than 100 m. Soil moisture from different soil depths of 5, 10 and 20 cm were collected by direct measurement method. And soil moisture content (%) was calculated by dividing the water content of a 1000 g sample by its dried counterpart and then multiplying by 100.

Landsat Enhanced Thermatic Mapper Plus (ETM+) image acquired on March 26, 2006 were introduced as satellite sources. DNs values were converted to spectral radiance and top of atmosphere (TOA) reflectance, and the atmospheric correction was performed using 6S model to eliminate the atmospheric perturbation and obtain the reflectance at ground level. NIR-Red reflectance space was constructed with the atmospherically corrected ground reflectance of Landsat ETM+ Red (band 3: 630-690 nm) and NIR (band 4: 755-900 nm) bands. More details about the approach is available in Ghulam et al. [4] and Qin et al. [9].

4. Result and discussion

4.1. Relationship between MPDI and soil moisture

Drought status is directly linked to soil water content, so it is available to monitor surface drought with soil moisture data. The correlation analysis between MPDI and soil moisture is conducted to validate the availability of the proposed method. As shown from the results that there is a significant negative correlation between MPDI and soil moisture at different depths (Figure 3). MPDI is negatively correlated to 10 cm soil moisture with the coefficient of determination (R²=0.4204). Moreover, MPDI is also negatively correlated to 5-20 cm soil moisture with the coefficient of determination (R²=0.4905). Although the number of field measurements was limited, it is suggested that MPDI model provides correct information in surface drought assessment.

Figure 3. Relationship between MPDI and soil moisture at different depths.

4.2. Comparison among PDI, MPDI and MPDI

A comparative study among these candidate drought indices was also conducted to the furtherly understanding of MPDI model in surface drought estimation. As shown from the results that PDI, MPDI and MPDI manifest roughly similar spatial patterns over these sample points (Figures 4). Note that PDI values are close to MPDI values at sample point 7, 9, 13 and 14, which demonstrates that these sample points have lower vegetation coverage. MPDI values are also close to PDI and MPDI values at these points, which indicates that MPDI is consistent with PDI and MPDI for bare soil or lower vegetated surface. Importantly, PDI values are a litter far away from MPDI values at sample point 10, 11, 12 and 15, which indicates that these points have larger vegetation coverage. MPDI
values are also higher than PDI and MPDI values at these points, which suggests MPDI1 is more sensible than PDI and MPDI for surface drought estimation under higher vegetation cover condition. Although it might theoretically overestimate surface drought status to some extent, it is speculated that MPDI1 demonstrates a better performance in measuring densely vegetated surface, which requires further exploration.

5. Conclusion
The main objective of this paper is to explore a new drought monitoring model with remotely sensed data. A famous drought index in NIR-Red reflectance space is the PDI model, which describes the typical triangular distribution of soil water content. In order to protrude the soil information and exclude the vegetation interference from the mixed pixels in soil-plant continuum, the MPDI model is constructed with the introduction of the vegetation fraction ($f_v$) to the PDI model. Considering that both soil moisture and vegetation index are acceptable in surface drought modeling, a new drought index (MPDI1) is developed in NIR-Red reflectance space, which is a continuous work of PDI and MPDI models. Model validation is performed using satellite remotely sensed image (Landsat ETM+) and in-situ field measurements. The relationship between MPDI1 and soil moisture observation at different depths is explored. Results indicate that the MPDI1 is highly consistent with the ground observation. The correlation between MPDI1 and 5-20 cm mean soil moisture observation is the coefficient of determination ($R^2=0.4905$), which is slightly higher than the correlation between MPDI1 and 10 cm soil moisture observation with the coefficient of determination ($R^2=0.4204$). A comparative study among these candidate drought indices (PDI, MPDI, MPDI1) is also conducted. It is evident from the results that MPDI1 values are close to PDI and MPDI values under lower vegetation coverage conditions, which provide quite similar spatial patterns for bare soil or lower vegetated surface. Interestingly, MPDI1 values is higher than PDI and MPDI values under higher vegetation coverage conditions, which demonstrates a better performance in measuring densely vegetated surface.

It is noted that MPDI1 is not entirely superior than PDI and MPDI models, for it might theoretically overestimate surface drought status to some extent. From the aspect of algorithmic complexity and calculation efficiency, MPDI1 is almost the same with PDI, but is much simper than MPDI [7]. Despite these shortcomings, this paper concludes that MPDI1 provides correct and sufficient information on surface drought status in soil-plant continuum, which appears to have great potential for surface drought estimation under complex underlying conditions.

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