Study on Remote Sensing Retrieval of Soil Moisture in Arid Desert Area Based on FTVDI

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Abstract. In this study, the desert oasis area of Minqin, Gansu Province was taken as the study area, and China Gaofen-6(GF-6) satellite and China-Brazil Earth Resource Resources Satellite - 04 (CBERS-04) were involved as remote sensing data sources. The soil moisture was retrieved by using Forward Temperature Vegetation Dryness Index (FPVDI), and the spatial distribution of soil moisture was analyzed. The result showed that FTVDI could be directly and accurately retrieve soil moisture.

1. Introduction

Soil moisture, which affects the energy and material exchange between atmosphere and land surface, is an important physical parameter for monitoring climate change, and is widely used in weather prediction and climate change prediction [1]. Soil moisture is another important part of hydrological model construction. Many studies showed that soil moisture played an important role in regional water cycle planning, hydrological simulation, drought and flood, etc [2-3]. Traditional methods of obtaining soil moisture mainly used meteorological or hydrological departments to measure and obtain soil moisture at measuring points through professional instruments. Although this method has high observation accuracy, the observation range is limited, and the measurement results cannot effectively reflect the soil information in the region. It also consumes a lot of manpower and material resources. Remote sensing technology has numerous advantages, such as high spatial resolution, wide monitoring range, which has gradually become an important technical means to obtain soil moisture in regional scope [4]. After years of development, methods of retrieving surface humidity based on remote sensing technology have been enriched. According to the source of remote sensing data, remote sensing methods can be divided into microwave remote sensing [5] and optical remote sensing [6]. Microwave remote sensing inversion methods can be divided into active microwave remote sensing inversion method, passive microwave remote sensing inversion method and the active and passive fusion inversion method. The advantage of microwave remote sensing inversion method is that there are few inversion parameters, and the remote sensing data can be acquired all day without the influence of weather and other factors, while the disadvantage is that the spatial resolution of remote sensing data is low, and the inversion accuracy and range are limited.
Optical remote sensing inversion method is mainly based on the reflection characteristics of surface soil to visible light band and near infrared band, and constructs the correlation model between soil moisture and various indices. These indices include Vertical Drought Index (PDI) [7], Temperature Vegetation Drought Index (TVID) [8], and so on. The advantages of this method are high spatial resolution and abundant remote sensing data sources. Its disadvantage is that it is easily disturbed by natural conditions. The main data sources of optical remote sensing are MODIS [9], Landsat[10], EOS-Terra [11], etc.

Among many models and methods, TVID is widely used by researchers in many remote sensing inversion studies of land surface temperature. Minqin, Gansu Province is a desert oasis area, with sparse vegetation coverage and many areas covered by sandy soil. The purpose of this study is to explore the applicability of FTVDI, which evolved from TVDI.

2. Study area and data source

2.1. Study area

The study area (38°19′47″–38°44′50″N, 102°48′15″–103°19′1″E) is located in Minqin County, Wuwei City, Gansu Province, China, with an area of about 2100 km² (Figure 1). It is adjacent to the Tengger Desert in the east and the Badain Jaran Desert in the west, where is belonging to a typical arid desert climate.

![Figure 1. The image on the left figure(a) is the regional distribution of Gansu Province, and the red rectangle in the image is the geographic location of the study area. The image on the right figure (b) is the true color image of GaoFen-6 satellite (GF-6) image after preprocessing.](image)

2.2. Remote sensing date

The WFV data of GaoFen-6 (GF-6) satellite and the thermal infrared data of CBERS-04 satellite were used in the study. The GF-6 satellite was officially put into use on March 21, 2019. It is a low–orbit optical remote sensing satellite, using the CAST 2000 platform. The satellite is equipped with a 2 m panchromatic/8 m multi–spectral high–resolution camera (PMS) and a 16 m multi–spectral medium–resolution wide field view (WFV) camera. The observation width of PMS is 90km, and that of WFV is 800km. The return period is two days. The CBERS-04 satellite was jointly developed by China and Brazil and launched in December 2014. The satellite carries four imaging payloads, namely 5 meters panchromatic (PAN)/10 meters multi–spectral (MUX) camera, 20 meters multi–spectral (MUX) camera, 40m/80m infrared (IRS) camera, and 73m wide-field imager (WFI). Both two satellite data used by the institute are all from China observation satellite data service platform. IRS data of CBERS-04 satellite was acquired on September 27, 2019, and WFV data of GF-6 satellite was acquired on September 29, 2019. The spatial resolution of CBERS-04 IRS data is 80 meters, and that of GF-6 WFV data is 16 meters. To meet the need of inversion, on the basis of atmospheric correction, radiometric calibration and image clipping of satellite data, CBERS-04 IRS data should be resampled to adjust its spatial resolution to 16 meters.
3. Method

3.1. Forward temperature vegetation dryness index (FTVDI)

Sandholt put forward the temperature vegetation drought index (TVDI) [12], and thought that the feature space constructed by normalized difference vegetation index (NDVI) and land surface temperature (LST) was the existence of isolines reflecting soil moisture.

The calculation of TVDI is [6]:

\[
TVDI = \frac{LST - LST_{\text{min}}}{LST_{\text{max}} - LST_{\text{min}}}. \tag{1}
\]

In this formula, \(LST_{\text{min}}\) is the lowest surface temperature corresponding to the same NDVI, which represents the wet edge of feature space, and \(LST_{\text{max}}\) is the highest surface temperature corresponding to the same NDVI, which represents the dry edge of feature space. By analyzing the pixels in feature space, the equation of wet edge and dry edge can be obtained on the basis of linear fitting, and the formulae are expressed as:

\[
LST_{\text{max}} = a_1 + b_1 \times NDVI \tag{2}
\]

\[
LST_{\text{min}} = a_2 + b_2 \times NDVI. \tag{3}
\]

In formula 2 and 3, \(a_1, a_2, b_1\) and \(b_2\) are the coefficients of the equation of dry edge and wet edge respectively. TVDI values range from 0 to 1, with TVDI on the dry side being 1 and TVDI on the wet side being 0. The value of TVDI can be used to express the soil moisture, and the closer it is tantamount to 1, the lower the soil moisture content. The closer the TVDI value is 0, the higher the water content of soil. Because TVDI has a negative correlation with soil moisture, which is not conducive to conventional understanding. A new index with positive correlation humidity is defined in the study, and its expression is as:

\[
FTVDI = 1 - TVDI. \tag{4}
\]

3.2. NDVI

NDVI is an index that can reflect the growth of plants by combining the data detected by satellites in different bands. The calculation of NVDI is:

\[
NDVI = \frac{NIR - RED}{NIR + RED}. \tag{5}
\]
In Equation (5), NIR and RED are the reflectance of pixels in the near infrared band and red band, respectively. Figure 3 was the NDVI extraction result of the study area.

3.3. Land surface temperature
Single channel method (SC) was used to retrieve the land surface temperature (LST) based on CBERS-04 IRS data. Through the meteorological data obtained, the key parameters of land surface temperature inversion can be obtained, and the LST inversion results in the study area could be obtained.

![Figure 3. Extraction results of NDVI](image1)

![Figure 4. Inversion LST results of SC based on CBERS-04 IRS data](image2)

3.4. Classification of soil moisture retrieval results
In order to clearly show the soil moisture, the inversion results obtained by different indexes were divided into five humidity levels according to the histogram of inversion results[13].

| Grade | Type   | Standard         |
|-------|--------|------------------|
| 1     | Very dry | 0≤Index<0.2     |
| 2     | Dry    | 0.2≤Index <0.4   |
| 3     | Moderate | 0.4≤Index <0.6  |
| 4     | Moist  | 0.6≤Index <0.8   |
| 5     | Very wet | 0.8≤Index≤1     |

4. Results and discussion

4.1. Construction of feature space
On the basis of LST data and NDVI data obtained in the previous chapters, the feature space of NDVI and LST was constructed by the IDL programming language, so that the dry edge equation and wet edge equation of the feature space can be fitted. As showning in figure 5.
It can be seen from figure 5 that the scatter plot presents a triangle shape, and the maximum value of surface temperature $T_{\text{max}}$ decreases with the increase of NDVI, while the minimum value of surface temperature $T_{\text{min}}$ increases with the increase of NDVI, and the difference between the two values was also decreasing, which was consistent with the research results of many scholars. 

From the dry fitted edge equation and wet edge equation, the slope of the dry edge equation was less than 0, and the slope of the wet edge equation was greater than 0. From the slope rule, we can know the change rule of land surface temperature with NDVI. At the same time, the absolute slope value of dry edge equation was larger than that of wet edge equation, which means that the surface temperature fitted by dry edge equation was more sensitive to the change of the vegetation index. The determination coefficient $R^2(0.864817)$ of dry edge equation was larger than $R^2(0.738757)$ of wet edge equation, indicating that the fitting effect of dry edge equation is better.

4.2. FTVDI in the study area

According to the calculation results of feature space, the TVDI inversion results of the study area were obtained. It can be seen from the figure 6 that there were noticeable differences in soil moisture in the study area. Among them, the blue mark area was water body, the light blue mark area was mainly concentrated near water body, and the red area was mainly desert. In order to analyze the inversion effect of each index more concretely, the pixels included in the drought grade were counted. The results were presented in table 2.

| Grade | Type       | Number of pixels | Proportion (%) |
|-------|------------|------------------|----------------|
| 1     | Very dry   | 3576056          | 45.23          |
| 2     | Dry        | 3399286          | 42.99          |
| 3     | Moderate   | 800519           | 10.12          |
| 4     | Moist      | 35894            | 0.45           |
| 5     | Very wet   | 95489            | 1.21           |

From the inversion results, the distribution range of FPDI is 0.1833~0.9968. Among them, drought and very drought grades include most pixels in the study area, reaching 88.22%. The research area was a typical desert arid area. Coupled with the land classification results obtained from the actual investigation, the FTVDI obtained from this inversion can reflect the gradient change of surface humidity.
4.3. Accuracy analysis of inversion result

Because some reasons, the inversion results can not be verified by the measured surface humidity in time. In the same period of 2020, combined with the meteorological conditions in the same period of 2019, the soil moisture in the study area was collected on the spot from September 26 to 27, 2020.

In the measured data, the sampling points with higher surface relative humidity were located near Hong Yashan Reservoir, while the sampling points with lower surface relative humidity were mainly concentrated in Tengger Desert. It can be seen from figure 7 that the measured surface humidity was far lower than FTVDI. Although the measured data in the same period can not be used as verification data, the measured data in the same period can reflect the change trend and difference of humidity at different points.

The measured soil moisture at the sampling sites was in good agreement with the change trend of FTVDI, which can better reflect the different characteristics of soil moisture.

![Figure 6. The FTVDI grading results of the study area](image)

![Figure 7. comparison between measured surface humidity and FTVDI](image)

5. Conclusion

In this study, NDVI obtained from GF-6 WFV data and LST obtained from CBERS-04 IRS data were used to construct the feature space, thus obtaining FTVDI of the study area. The measured data for the same period in 2020 and the land classification results showed that FTVDI can better reflect the difference of soil moisture in the study area.

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