Spatiotemporal Variation Characteristics of Soil Moisture and Its Influencing Factors in the Xiangride-Qaidam River Basin: Postprint

Authors: Mengyuan Cheng, Cao Guangchao, Zhao Meiliang

Date: 2022-03-28T17:04:34+00:00

Abstract

Soil moisture, as a critical factor of the ecological environment, serves as an important indicator for soil monitoring and ecological environmental change. Based on MOD11A2 LST and MOD13A2 NDVI data, this study analyzes the spatiotemporal distribution characteristics of soil moisture and its influencing factors during the vegetation growing season in the Xiangride-Qaidam River Basin using mathematical statistical methods including the Temperature Vegetation Dryness Index (TVDI), correlation analysis, and regional statistical analysis. The results indicate: (1) The average TVDI value during the vegetation growing season in the Xiangride-Qaidam River Basin for the years 2005, 2010, 2015, and 2020 is 0.61, with the maximum value observed in 2015 (0.64) and the minimum value in 2020 (0.58). Interannual TVDI values exhibit a slow declining trend, though an increase occurred in 2015, suggesting that drought conditions in the study area are unstable and persist at a drought level over the long term. (2) The areal extent of different soil moisture levels, from largest to smallest, follows the order: dry > extremely dry > normal > wet > extremely wet, accounting for 30.63%, 25.77%, 22.16%, 16.44%, and 5.01% of the total study area, respectively. (3) TVDI demonstrates a gradually decreasing spatial trend from northwest to southeast, exhibiting pronounced regional heterogeneity. (4) TVDI values are negatively correlated with elevation, decreasing by 0.11 for every 500 m increase in elevation. TVDI values are positively correlated with mean air temperature, while no significant correlations exist with slope or precipitation.

Full Text

Temporal and Spatial Variation Characteristics of Soil Moisture and Its Influencing Factors in the Xiangride-Qaidam River Basin

CHENG Mengyuan1,2,3, **CAO Guangchao**2,3,4, **ZHAO Meiliang**1,2,3, **DIAO Erlong**1,2,3, **HE Qixin**1,2,3, **GAO Siyuan**1,2,3, **QIU Xunxun**1,2,3, **CHENG Guo**1,2,3

1 College of Geographical Science, Qinghai Normal University, Xining 810008, Qinghai, China
2 Qinghai Province Key Laboratory of Physical Geography and Environmental Process, Xining 810008, Qinghai, China
3 Key Laboratory of Tibetan Plateau Land Surface Processes and Ecological Conservation, Ministry of Education, Xining 810008, Qinghai, China
4 Academy of Plateau Science and Sustainability, People' s Government of Qinghai Province & Beijing Normal University, Xining 810008, Qinghai, China

Abstract

Soil moisture serves as a critical factor in ecological environments and represents an important indicator for soil monitoring and environmental change assessment. This study utilized MOD11A2 LST and MOD13A2 NDVI data from 2005 to 2020, employing mathematical and statistical analysis methods including the Temperature Vegetation Dryness Index (TVDI), correlation analysis, and regional statistical analysis to investigate the spatiotemporal distribution characteristics of soil moisture and its influencing factors during the vegetation growing season in the Xiangride-Qaidam River Basin. The results indicate that the average TVDI value during the vegetation growing season from 2005 to 2020 was 0.61, with a maximum of 0.64 in 2015 and a minimum of 0.58 in 2020. Although the interannual TVDI values showed a gradual declining trend, an increase occurred in 2015, suggesting unstable drought conditions and prolonged drought status in the study area. The area proportions of different soil moisture levels, in descending order, were: drought (30.63%), extremely arid (25.77%), normal (22.16%), humid (16.44%), and extremely humid (5.01%). Spatially, TVDI exhibited a gradually decreasing trend from northwest to southeast, demonstrating distinct regional differences. TVDI values were negatively correlated with altitude, decreasing by 0.11 for every 500 m increase in elevation. TVDI showed a positive correlation with mean temperature but no significant correlation with slope or precipitation.

Keywords: soil moisture; temperature vegetation drought index; correlation analysis; Xiangride-Qaidam River Basin

Introduction

Soil moisture constitutes a vital component of the terrestrial water cycle and plays a crucial regulatory role in surface energy balance, serving as an important research indicator in meteorology, hydrology, and agriculture [?]. Current methods for obtaining soil moisture information primarily include two approaches [?]. The first is field measurement using ground observation stations or field sampling, which offers high data accuracy but only represents local conditions at observation points and is unsuitable for large-scale monitoring [?]. The second approach employs multi-source remote sensing technology to rapidly acquire large-scale, spatially continuous soil moisture information through retrieval, which has become the primary method for monitoring soil moisture [?]. Remote sensing retrieval methods mainly include thermal inertia, microwave remote sensing, and vegetation index methods [?]. Thermal inertia is significantly affected by weather conditions, while microwave remote sensing, though highly accurate, is influenced by vegetation cover and surface roughness, making data acquisition difficult [?]. The vegetation index method indirectly reflects soil moisture conditions by obtaining vegetation spectral characteristics [?]. For instance, utilizing the NDVI-LST spectral feature space enables precise monitoring of soil drought [?]. Liu et al. [?] employed MODIS TVDI and fuzzy mathematics to monitor spring and summer drought dynamics in northern Tibet, demonstrating that this method can provide data support for drought monitoring in the region. Cao et al. [?] studied drought spatiotemporal variations on the Mongolian Plateau using TVDI, revealing widespread drought conditions and impacts on ecosystem distribution and biodiversity. Numerous studies have demonstrated the good applicability of TVDI for retrieving soil moisture in plateau regions.

The Xiangride-Qaidam River Basin is located in a high-altitude inland basin with relatively scarce water resources. Due to its special geographical location and arid climate, vegetation is sparse with low coverage, and soil suffers from severe wind erosion and salinization, representing a typical fragile ecosystem [?]. Large amounts of surface runoff are used for irrigation, leading to deteriorating downstream ecological conditions and weak overall drought resistance in the basin. As an important grain and oil crop production area in the Qaidam Basin [?], soil moisture in the Xiangride-Qaidam River Basin is a key factor affecting local agricultural and pastoral production and serves as an important indicator for crop yield estimation and drought monitoring. However, meteorological stations are sparse in the study area, lacking long-term, large-scale soil moisture observation data, making it difficult to obtain relevant information through observations. Currently, no studies have investigated drought variation trends in this basin using the TVDI method. Therefore, this research applied MODIS data to calculate TVDI through the Ts-NDVI feature space, examining the spatiotemporal variation characteristics of soil moisture during the vegetation growing season and exploring its relationship with terrain and meteorological factors, providing references for agricultural and pastoral production, rational water resource utilization, ecological project construction, and environmental protection planning in the Xiangride-Qaidam River Basin.

1.1 Study Area Overview

The Xiangride-Qaidam River Basin is located in the Haixi Mongolian and Tibetan Autonomous Prefecture, southeastern Qaidam Basin, Qinghai Province. The terrain slopes from southeast to northwest, featuring both basin and mountainous landforms. The southern region features continuous high mountains with average elevations above 4000 m, while the northwestern area consists of alluvial plains at 2900-3100 m [?]. The region has a continental climate with abundant sunshine, large diurnal temperature variations, low annual precipitation, and strong evaporation. The multi-year average temperature ranges from 3.1 to 4.4°C, annual evapotranspiration reaches 2525.3 mm, and multi-year average precipitation is 150-200 mm [?]. The southeastern mountainous area is dominated by grasslands, including *Stipa purpurea* steppe, *Phragmites australis* meadows, and *Potentilla parvifolia* shrublands. Farmland and construction land are located at the mountainous margins, while the central and northwestern regions are mostly bare land, including salt marshes and *Artemisia sieversiana* gravel deserts [?].

1.2 Data Sources and Preprocessing

1.2.1 Remote Sensing Data Remote sensing data were selected from MOD11A2 LST and MOD13A2 NDVI products (https://ladsweb.modaps.eosdis.nasa.gov/) for the vegetation growing season (May-September) from 2005 to 2020, with a spatial resolution of 1 km. DEM data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn) as SRTMDEM UTM digital elevation data.

1.2.2 Meteorological Data Meteorological data included daily average temperature and precipitation from five meteorological stations: Dulan and Nuomuhong within the basin, and Wulan, Chaka, and Maduo in the surrounding areas, sourced from the China Meteorological Data Network (http://data.cma.cn/).

1.2.3 Data Preprocessing MRT software was used for mosaicking, reprojection, and format conversion of MOD11A2 LST and MOD13A2 NDVI data. ENVI software performed data restoration to obtain true values, and ArcGIS was used to clip raster images for the study area. For subsequent analysis, all data were resampled to a 500 m resolution in ArcGIS.

1.3 Methods

1.3.1 Temperature Vegetation Dryness Index Soil moisture variation is influenced by numerous factors including temperature, vegetation growth status, and soil properties, which interact in complex ways [?]. Sandholt et al. [?] found a significant negative correlation between vegetation index and land surface temperature, leading to the construction of the Ts-NDVI feature space and the proposal of the Temperature Vegetation Dryness Index (TVDI) for estimating soil moisture. Based on the Ts-NDVI feature space, TVDI is defined as [?]:

$$TVDI = \frac{T_s - T_{s,min}}{T_{s,max} - T_{s,min}}$$

where T_s is the land surface temperature of any pixel; $T_{s,max}$ and $T_{s,min}$ represent the maximum and minimum land surface temperatures at the same NDVI value, respectively. A smaller TVDI indicates wetter conditions, while a larger TVDI indicates drier conditions.

1.3.2 Dry-Wet Edge Equation Fitting Using NDVI values as the horizontal axis and corresponding T_s values as the vertical axis, scatter plots were created for linear fitting. Since vegetation coverage affects NDVI values, excessively high or low NDVI can impact soil moisture monitoring results. Therefore, effective NDVI values were selected within the 0.2-0.8 range [?]. The calculation formulas are:

$$T_{s,max} = a_1 + b_1 \times NDVI$$

$$T_{s,min} = a_2 + b_2 \times NDVI$$

where a_1 and b_1 are coefficients for the dry edge fitting equation, and a_2 and b_2 are coefficients for the wet edge fitting equation.

1.3.3 Correlation Analysis To investigate relationships between TVDI and other factors in the Xiangride-Qaidam River Basin, Pearson correlation analysis was employed. This correlation coefficient tests relationships between two variables and is widely used in meteorology, hydrology, and ecological research. The calculation formula is [?]:

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where R_{xy} is the correlation coefficient ranging from [-1, 1]; n is the sample size; x_i and y_i are pixel values for variables x and y in month i; and $\bar{x}$ and $\bar{y}$ are the average values. A positive R_{xy} indicates positive correlation, negative R_{xy} indicates negative correlation, and larger absolute values indicate more significant correlations.

Results

2.1 Dry-Wet Edge Equation Fitting Results

The Ts-NDVI feature space for the Xiangride-Qaidam River Basin (Fig. 2) shows similar characteristics across years, presenting triangular or trapezoidal shapes consistent with previous studies [?, ?]. As NDVI increases, the maximum temperature on the dry edge decreases linearly, while the minimum temperature on the wet edge increases but remains unstable. Analysis of dry-wet edge equations during the vegetation growing season (Table 1) reveals that all dry edge equations have negative slopes, showing negative correlations with R^2 values of 0.75-0.93, indicating good fitting performance. Wet edge equations show weaker correlations, with R^2 values below 0.7 in most cases, suggesting unstable relationships between T_s and NDVI in the study area.

2.2 Spatiotemporal Variation of TVDI in the Xiangride-Qaidam River Basin

The average TVDI value during the vegetation growing season from 2005 to 2020 was 0.61, with a maximum of 0.64 in 2015 and a minimum of 0.58 in 2020. Although TVDI values gradually decreased over time, an increase in 2015 indicates unstable drought conditions with prolonged drought status. According to the soil moisture classification method [?], five levels were defined: extremely humid ($0 \leq \text{TVDI} < 0.2$), normal ($0.2 \leq \text{TVDI} < 0.4$), drought ($0.4 \leq \text{TVDI} < 0.6$), arid ($0.6 \leq \text{TVDI} < 0.8$), and extremely arid ($0.8 \leq \text{TVDI} \leq 1$). The area proportions of different levels, from largest to smallest, were drought (30.63%), extremely arid (25.77%), normal (22.16%), humid (16.44%), and extremely humid (5.01%).

Spatially, TVDI showed a gradually decreasing trend from northwest to southeast, with distinct regional differences. High TVDI values were primarily distributed in alluvial plains downstream, where desert vegetation coverage is low [?] and rainfall is scarce, 不利于 soil moisture storage. Low TVDI values occurred in upstream areas and around Nuomuhong, where lakes and rivers are distributed with relatively high vegetation coverage and soil moisture. Temporally, the most significant changes occurred in July, when solar radiation is strongest, temperatures peak, and vegetation water demand is maximal, leading to reduced soil moisture content. From May to July, extremely arid areas converted to arid and normal levels, with extremely arid area decreasing from 19.01% to 3.07%. The most obvious changes in July occurred in southeastern and southwestern areas, where drought levels converted to normal, decreasing from 20.56% to 12.42%.

2.3 Influencing Factors

2.3.1 Terrain Factors Altitude and slope are important influencing factors of TVDI. The Xiangride-Qaidam River Basin has large elevation differences and slope variations. Following mountain classification standards [?], the basin is dominated by mid-high mountains (3500-5500 m) and low-mid mountains (2500-3500 m). Further dividing altitude into 500 m intervals for regional statistical analysis and correlation analysis revealed that TVDI is significantly negatively correlated with altitude ($P < 0.01$), decreasing by 0.11 for every 500 m increase in elevation. Mid-high mountains had higher soil moisture than high mountains. According to slope classification standards, slopes were divided into plain to gentle slope (0°-2°), gentle slope (2°-5°), steep slope (5°-15°), sharp slope (15°-25°), very sharp slope (25°-35°), and vertical slope (>35°). TVDI values were largest on sharp and very sharp slopes and smallest on vertical slopes, with overall unclear variation patterns. Altitude directly affects topography and hydrothermal conditions, while increased elevation enhances freeze-thaw processes and vegetation coverage, thereby increasing soil moisture.

2.3.2 Meteorological Factors The Xiangride-Qaidam River Basin has a typical plateau continental climate with extremely uneven precipitation distribution, decreasing from east to west and from surrounding mountains to the basin center. Correlation analysis between TVDI and meteorological station data revealed positive correlations between TVDI and mean temperature at all stations ($P < 0.01$), with R^2 values above 0.5. Monthly variations in mean temperature and TVDI showed similar trends, indicating that increased temperature enhances surface evaporation, raising TVDI values and reducing soil moisture. However, no significant correlation was found between cumulative precipitation and TVDI ($R^2 = 0.09$-0.467), likely due to the basin’ s complex terrain, sparse meteorological stations, low precipitation, and strong evaporation. Precipitation effects on TVDI have certain lag effects [?], consistent with findings from the Qiangtang Plateau [?].

Discussion

This study demonstrates that MODIS data effectively retrieves soil moisture in the Xiangride-Qaidam River Basin, confirming TVDI as a suitable monitoring index. Spatially, soil moisture shows minor variation, with arid and extremely arid areas concentrated in northwestern desert regions, where vegetation cover and terrain likely dominate. Temporally, high TVDI values in July reflect long sunshine duration, rising temperatures, and increased vegetation water demand. Correlation analysis identified altitude and temperature as key factors affecting soil moisture, consistent with drought factor analyses in Inner Mongolia [?]. However, precipitation showed no significant correlation with TVDI, possibly due to the basin’ s low vegetation coverage, strong evaporation, and limited precipitation. The lag effect of precipitation on soil moisture [?] may also contribute to this weak correlation.

This research is limited to the vegetation growing season and considers only four influencing factors. Future work should expand temporal scales and incorporate additional factors such as land use type, evapotranspiration, and anthropogenic influences. Overall, soil moisture in the Xiangride-Qaidam River Basin is predominantly dry, with periodic variations and slight interannual improvement in drought conditions.

Conclusions

1. MODIS data effectively retrieves soil moisture in the Xiangride-Qaidam River Basin during the vegetation growing season, indicating that the TVDI index is suitable for soil moisture monitoring in this region.
2. The basin is primarily characterized by drought conditions during the vegetation growing season, with TVDI values showing spatial patterns of higher dryness in the northwest and center, and relatively humid conditions in the southeast, demonstrating obvious regional differences.
3. Correlation analysis between TVDI and topographic and meteorological factors reveals that TVDI is negatively correlated with altitude and positively correlated with mean temperature, but shows weak correlation with slope and precipitation. This indicates that altitude and temperature are the most significant factors influencing soil moisture variation in the Xiangride-Qaidam River Basin.

References

[1] Li Haixia, Yang Jing, Chen Yaning, et al. Retrieval of soil moisture information in Xinjiang using MODIS[J]. Journal of Acta Prataculturae Sinica, 2017, 26(6): 16-27.

[2] Deng Yawen, Ling Ziyan, Sun Na, et al. Daily estimation of soil moisture over Beijing Tianjin Hebei Region based on General Regression Neural Network Model[J]. Journal of Geo-information Science, 2021, 23(4): 749-761.

[3] Wang Na, Yi Guihua, Zhang Tingbin, et al. Spatio-temporal and climate related variations in soil moisture during the growing season in the hinterland of the Qinghai Tibet Plateau: An analysis using the temperature vegetation dryness index[J]. Pratacultural Science, 2020, 37(11): 2185-2197.

[4] Yang Ling, Yang Yanzhao. The spatial and temporal pattern of soil moisture in the west Liaohe river basin based on TVDI method and its influencing factors[J]. Journal of Arid Land Resources and Environment, 2016, 30(2): 76-81.

[5] Nie Yan, Ma Zeyue, Zhou Xiaofeng, et al. Soil moisture retrieval and monitoring in the Aksu River basin[J]. Acta Ecologica Sinica, 2019, 39(14): 5138-5148.

[6] Wang Jing, Fang Feng, Huang Pengcheng, et al. Evaluation of advanced microwave scanning radiometer for EOS(AMSR-E) soil moisture products over China and its application in drought monitoring[J]. Arid Zone Research, 2021, 38(3): 650-664.

[7] Li Zhanjie, Chen Jipei, Liu Yanmin, et al. Soil moisture retrieval from remote sensing[J]. Journal of Beijing Normal University(Natural Science), 2020, 56(3):

474-481.

[8] Li Yi, Chen Xinguo, Zhao Huichao, et al. Latest advances of soil drought and its monitoring based on remote sensing[J]. Journal of Water Resources and Architectural Engineering, 2021, 19(1): 1-7.

[9] Liu Yizhe, Feng Wenlan, Zhaxi Yangzong, et al. Remote sensing monitoring of drought level in north Tibet based on MODIS TVDI and Fuzzy Mathematics[J]. Arid Zone Research, 2020, 37(1): 86-96.

[10] Cao Xiaoming, Feng Yixing, Shi Zhongjie. Spatio-temporal variations in drought with remote sensing from the Mongolian Plateau during 1982-2018[J]. Chinese Geographical Science, 2020, 30(6): 1055-1068.

[11] Wang Jiaxin, Sa Chula, Mao Kebiao, et al. Temporal and spatial variation of soil moisture in the Mongolian Plateau and its response to climate change[J]. Remote Sensing for Land and Resources, 2021, 33(1): 231-239.

[12] Mao Jun. Study on the Impact of Irrigation on Groundwater and its Ecological Response of Xiangride Oasis in Qaidum Basin[D]. Beijing: Beijing Forestry University, 2007.

[13] Wang Fake, Lei Yuhong, Du Zhanliang, et al. Climate change affects major crops yield in Qaidam Basin[J]. Chinese Agricultural Science Bulletin, 2020, 36(14): 107-112.

[14] Zhang Jiahao. Groundwater Resource Evaluation of Xiangride-Nuomuhong Piedmont Plain[D]. Beijing: China University of Geosciences, 2013.

[15] Zhu Mingbang. Study on Lycium barbarum Land Use Change and Spectral Recognition of L. Area Based on Technique in Dulan County[D]. Qinghai: Qinghai University, 2017.

[16] Xiao Yang, Zhang Xiang, Zhu Cairong, et al. Research on the dynamics of soil moisture[J]. China Rural Water and Hydropower, 2014, 56(12): 9-12, 16.

[17] Sandholt I, Rasmussen K, Andersen J. A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status[J]. Remote Sensing of Environment, 2002, 79(2): 213-224.

[18] Ye Weilin, Zhou Ziqiang, Shi San' e, et al. Analysis of spatio-temporal distribution of soil moisture and influencing factors in Heifangtai area based on TVDI[J]. Journal of Gansu Sciences, 2020, 32(6): 50-58.

[19] Xu Jianhua. Mathematical Methods in Modern Geography[M]. 2th Ed. Beijing: Higher Education Press, 2002.

[20] Wang Hanwen, Yuan Xizhong, Lei Shengyou, et al. Study on soil moisture trend of different land types based on TVDI[J]. Journal of Henan Polytechnic University(Natural Science), 2020, 39(5): 50-60.

[21] Yang Ru, Gao Chao, Zha Qianyu, et al. Application of different vegetation indexes in soil moisture inversion based on TVDI[J]. Geomatics & Spatial

Information Technology, 2020, 43(2): 33-37.

[22] Li Caiying, Yan Jianzhong, Liu Linshan, et al. Analysis of soil moisture variation in summer of Qiangtang Plateau based on TVDI[J]. Geographical Research, 2017, 36(11): 2101-2111.

[23] Wu Yingjie, Quan Qiang, Chen Xiaojun, et al. Temporal and spatial variations of drought and climatic response in the Xilingol grassland from 2000 to 2018[J]. Arid Land Geography, 2020, 43(5): 1289-1297.

[24] Gao Ya, Wang Xiaofei, Gao Maofang, et al. Drought monitoring in Qujing based on temperature vegetation drought index[J]. Chinese Agricultural Science Bulletin, 2020, 36(9): 37-45.

[25] Zhong Xianghao, Liu Shuzhen. Research on the mountain classification in China[J]. Mountain Research, 2014, 32(2): 129-140.

[26] Qin Yi, Zhang Tingbin, Yi Guihua, et al. Remote sensing monitoring and analysis of influencing factors of drought in Inner Mongolia growing season since 2000[J]. Journal of Natural Resources, 2021, 36(2): 459-475.

[27] Waston K, Pohn H A. Thermal inertia mapping from satellite discrimination of geology unit in Oman[J]. Journal of Research of the U. S. Geological Survey, 1974, 2(2): 147-158.