Spatiotemporal Variation Characteristics of Drought in the Fen River Basin Based on CWSI: Postprint

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Abstract

Based on MOD16 data, the Crop Water Stress Index (CWSI) was calculated. By integrating meteorological station data, vegetation index data, and land use data from the Fenhe River Basin, and employing the difference method, linear trend method, and correlation analysis, the spatiotemporal variation characteristics of drought in the Fenhe River Basin from 2000 to 2021 were analyzed. The results indicate: (1) CWSI can effectively monitor drought conditions in the Fenhe River Basin, exhibiting a significant negative correlation with 10 cm soil relative humidity; (2) The spatial distribution of CWSI in the Fenhe River Basin shows marked differences, characterized by a pattern of wetter conditions in the south and drier conditions in the north; (3) The interannual variation of CWSI in the Fenhe River Basin is relatively stable, whereas the monthly variation shows substantial fluctuations, with CWSI reaching its annual peak in May; (4) Drought conditions vary significantly across different growth periods within the Fenhe River Basin. During the early growth season (April–May), extreme drought areas account for 48.55% of the total basin area; during the middle growth season (June–August), the entire region is essentially drought-free; and during the late growth season (September–October), drought occurs in only 11.17% of the area; (5) Drought severity differs among land use types, with CWSI values in ascending order as follows: forestland (0.686) $<$ grassland (0.749) $<$ cropland (0.751) $<$ unused land (0.758) $<$ urban areas (0.765). The findings of this study can provide scientific data support for drought monitoring and decision-making regarding drought resistance strategies in the Fenhe River Basin.

Full Text

Abstract

Based on MOD16 global evapotranspiration data, the Crop Water Stress Index (CWSI) was calculated and combined with meteorological station observations, vegetation index data, and land use data for the Fenhe River Basin. Employing difference analysis, linear trend analysis, and correlation analysis, we examined the spatiotemporal variation characteristics of drought in the Fenhe River Basin from 2000 to 2021. The results demonstrated that: (1) CWSI effectively monitored drought conditions in the Fenhe River Basin, showing a significant negative correlation with 10 cm soil relative moisture. (2) The spatial distribution of CWSI exhibited pronounced disparities, characterized by wetter conditions in the south and drier conditions in the north. (3) Interannual CWSI variation remained relatively stable, whereas monthly fluctuations were substantial, peaking in May each year. (4) Drought conditions varied markedly across different growing periods: during the early growing season (April–May), severe and extreme drought areas accounted for 48.55% of the total basin area; during the mid-growing season (June–August), virtually the entire basin was drought-free; and during the late growing season (September–October), only 11.17% of the area experienced drought. (5) Drought occurrence differed significantly among land use types, with mean annual CWSI values ranking from lowest to highest as: forest land (0.686) < grassland (0.749) < cultivated land (0.751) < unused land (0.758) < urban land (0.765). These findings provide critical scientific support for drought monitoring and informed decision-making regarding drought resistance strategies in the Fenhe River Basin.

Keywords: drought; Crop Water Stress Index; spatiotemporal variation; Fenhe River Basin

1 Study Area Overview

The Fenhe River Basin is located in the middle reaches of the Yellow River basin, spanning 110°30’ -113°32’ E and 35°20’ -39°00’ N. The basin crosses six prefecture-level cities—Xinzhou, Taiyuan, Jinzhong, Lüliang, Linfen, and Yuncheng—covering a drainage area of 39,471 km^2, which represents 25.3% of Shanxi Province’ s total area [Figure 2: see original paper]. Situated in a mid-latitude temperate continental monsoon climate zone, the basin experiences an average annual temperature of 8-14 °C, average annual precipitation of 400-550 mm, and average annual potential evaporation of 1,400-1,600 mm. Precipitation exhibits substantial interannual variability and uneven seasonal distribution, with approximately 70% of annual rainfall concentrated in the flood season (June-September), creating a high risk of both drought and flood disasters [11,16]. The basin serves as the primary agricultural production base in Shanxi Province, with agricultural output accounting for over 50% of the provincial total. Cultivated land comprises approximately 11,000 km^2, representing about 50% of the province’ s total arable land area, with wheat and corn as the main crops. Consequently, precise drought monitoring in the Fenhe River Basin holds critical importance for regional agricultural sustainability.

2 Data and Methods

2.1 Data Sources

The global terrestrial evapotranspiration product MOD16 provides both 8-day composite (MOD16A2) and annual composite (MOD16A3) datasets at 500 m spatial resolution. This study utilized MOD16A2 and MOD16A3 data for the Fenhe River Basin from 2000 to 2021, obtaining actual evapotranspiration (ET) and potential evapotranspiration (PET) data for tile numbers h26v05 and h27v05 from the Numerical Terradynamic Simulation Group (http://www.ntsg.umt.edu/). Data preprocessing included mosaicking, reprojection, and format conversion using the MODIS Reprojection Tool. For analytical purposes, 8-day data were aggregated to monthly values using averaging. NDVI data were derived from the annual normalized difference vegetation index dataset (2015-2021) provided by the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/data), which was generated from 10-day maximum value composite (MVC) MODIS data. Soil moisture data at 10 cm depth were obtained from the National Meteorological Information Center’ s (http://data.cma.cn/data) Tianjin crop growth and farmland soil moisture dataset, which includes relative soil moisture measurements at 10 cm, 20 cm, 50 cm, 70 cm, and 100 cm depths. Additional meteorological data included annual precipitation and temperature data for 2000-2021, which were processed from monthly to annual values. Detailed data sources are listed in .

2.2.1 Crop Water Stress Index Method

The Crop Water Stress Index (CWSI), proposed by Jackson et al. [18,19], is an energy balance-based approach for monitoring soil moisture conditions under vegetation cover. The CWSI is calculated as:

$$CWSI = 1 - \frac{ET}{PET}$$

where ET represents actual evapotranspiration and PET represents potential evapotranspiration. The index ranges between 0 and 1, with higher values indicating greater water stress (drier conditions) and lower values indicating wetter conditions.

2.2.2 Analysis Methods

We employed three analytical approaches: (1) Difference analysis to quantify CWSI variability levels; (2) Linear trend analysis to characterize long-term

CWSI trends; and (3) Correlation analysis to examine relationships between CWSI and influencing factors including precipitation, temperature, and NDVI.

3.1 Validation of Drought Monitoring Results

To evaluate the effectiveness and accuracy of CWSI-based drought monitoring, we validated the MOD16-derived CWSI against soil relative moisture measurements. Previous research has identified the 10 cm soil depth as optimal for soil moisture estimation using MODIS data in the Fenhe River Basin [17]. Scatter plot analysis between CWSI and 10 cm soil relative moisture [Figure 10: see original paper] revealed a significant negative correlation: CWSI values were high when soil moisture was low, and vice versa. The correlation coefficient passed the 0.01 significance test, confirming that MOD16-based CWSI is suitable for drought monitoring in the Fenhe River Basin. Based on this validation and following the National Meteorological Administration’ s drought classification standards [27], we established drought severity levels for the Fenhe River Basin .

3.2 Interannual Spatiotemporal Distribution Characteristics of CWSI

Interannual variations in ET, PET, and CWSI for the Fenhe River Basin from 2000 to 2021 are shown in [Figure 3: see original paper]. Actual evapotranspiration (ET) showed relatively small interannual fluctuations, ranging from 278.83 mm (2001) to 429.07 mm (2003), with a mean of 343.15 mm. Potential evapotranspiration (PET) ranged from 1,253.81 mm (2003) to 1,765.40 mm (2001), with a mean of 1,408.33 mm. The difference between PET and ET (DET) exhibited variation trends consistent with both ET and PET. CWSI showed relatively stable interannual variation with fluctuation rates between 0–10%, indicating that drought severity in the basin remained comparatively steady over time. Furthermore, analysis of regional drought area interannual changes [Figure 4: see original paper] revealed that the basin predominantly experienced no drought or slight drought, with no extreme drought events occurring in recent years and a gradual decrease in drought-affected area over time.

Spatial distribution analysis [Figure 5: see original paper] showed a pattern of wetter conditions in peripheral mountainous areas and drier conditions in central basin regions, with southern areas being relatively wetter and northern areas drier. Specifically, drought was more pronounced in the northern Taiyuan-Jinzhong region, reaching slight to moderate drought levels, while the southern Yuncheng area experienced only slight drought. The drought-free zone accounted for 71.36% of the basin area, mainly distributed in southern basin regions. Slight drought areas covered 22.71% of the basin, concentrated in Lanxian, Loufan, Yangqu, Shouyang, Qixian, Pingyao, and Wanrong. Moderate drought areas occupied 5.93% of the basin, primarily in Jinzhong. Pixel-based trend analysis [Figure 6: see original paper] revealed an overall upward CWSI trend across the basin, with more significant increasing trends in southern basin areas and around Taiyuan. Correlation analysis between annual CWSI and climatic factors showed that CWSI was negatively correlated with precipitation and NDVI but positively correlated with temperature, with the strongest correlation observed between CWSI and NDVI.

3.3 Intra-annual Spatiotemporal Distribution Characteristics of CWSI

Intra-annual variations in ET, PET, and CWSI [Figure 7: see original paper] exhibited distinct seasonal patterns. ET and PET showed unimodal curves, with ET peaking at 219.07 mm in July and PET reaching 1,765.40 mm in June. CWSI displayed a bimodal pattern: the first peak occurred in May, indicating maximum drought severity during this month; the second, smaller peak appeared in October, concentrated in northern basin regions including southern Xinzhou, Taiyuan, and Jinzhong. Drought type area proportions [Figure 8: see original paper] confirmed that drought was concentrated in April–May, with severe and extreme drought dominating during this period before transitioning to predominantly no drought conditions after June.

To characterize drought conditions during different crop growth stages, we calculated CWSI for the early growing season (April–May), mid-growing season (June–August), and late growing season (September–October). Spatial distributions [Figure 9: see original paper] and area proportions revealed significant differences in drought severity across these periods. During the early growing season, 48.55% of the basin experienced extreme drought and 25.08% experienced severe drought, with drought-free areas comprising only 6.83% of the basin. During the mid-growing season, 93.87% of the basin was drought-free, with slight and moderate drought areas accounting for just 5.97% and 0.16%, respectively. In the late growing season, drought intensity increased again compared to mid-season, with slight and moderate drought areas covering 11.17% of the basin. This late-season increase is associated with reduced precipitation, crop harvest, and diminished vegetation cover and transpiration. Correlation analysis for intra-annual variations showed that CWSI was negatively correlated with precipitation and NDVI and positively correlated with temperature, though correlations were moderate. However, ET showed strong correlations with both precipitation and temperature, while PET showed the strongest correlation with temperature, indicating that drought causation is complex and cannot be fully explained by precipitation, temperature, and NDVI alone.

3.4 Analysis of CWSI Characteristics Under Different Land Use Types

CWSI is closely related to soil moisture, which varies by land use type. Analysis of annual mean CWSI across land use types [Figure 10: see original paper] revealed relatively small differences, with values concentrated between

0.6–0.8. However, distinct patterns emerged: forest land showed the lowest CWSI (0.686), followed by grassland (0.749), cultivated land (0.751), unused land (0.758), and urban land (0.765). This ranking reflects differences in water retention capacity and vegetation characteristics. Forests, typically located in mountainous areas with higher elevations and adequate precipitation, possess diverse vegetation and strong water conservation capacity, resulting in higher ET but lower PET and consequently lower CWSI and drought risk. Grassland, with shorter and denser vegetation, experiences faster water evaporation and weaker water retention than forests. Cultivated land in the Fenhe River Basin is dominated by summer corn and winter wheat; after harvest in the late growing season, exposed surfaces reduce ET and increase CWSI. Urban areas exhibit the highest drought risk due to low vegetation cover, high temperatures, and impervious surfaces that accelerate water loss.

4 Conclusions

This study calculated CWSI for the Fenhe River Basin using MOD16 data and integrated meteorological observations, land use, and vegetation index data to reveal spatiotemporal drought characteristics. The main conclusions are:

(1) CWSI demonstrated a significant negative correlation with 10 cm soil relative moisture, confirming its effectiveness for drought monitoring in the Fenhe River Basin.

(2) Spatially, CWSI exhibited strong spatial heterogeneity, with wetter conditions in peripheral mountainous areas and drier conditions in central basin regions, and relatively wetter conditions in the south compared to the north. The northern Taiyuan-Jinzhong region represents a drought-prone area and should be prioritized for drought prevention and mitigation efforts.

(3) Temporally, interannual CWSI variation was relatively stable, while monthly fluctuations were substantial. The early growing season (April-May) represents a critical period for drought prevention, with CWSI reaching its annual peak in May.

(4) Across different land use types, mean annual CWSI ranked from lowest to highest as: forest land < grassland < cultivated land < unused land < urban land. Forest land demonstrated the strongest drought resistance, while urban areas exhibited the highest drought risk.

These findings provide scientific support for drought monitoring and management strategies in the Fenhe River Basin.

References

[1] Zhang Qiang, Han Lanying, Zhang Liyang, et al. Analysis on the character and management strategy of drought disaster and risk under the climatic

warming[J]. Advances in Earth Science, 2014, 29(1): 80-91.

[2] Tian Guozhen, Wu Yongli, Liang Yachun, et al. Drought monitoring and timeliness based on evapotranspiration model[J]. Arid Land Geography, 2016, 39(4): 721-729.

[3] Wu Mengquan, Cui Weihong, Li Jinggang. Monitoring drought in mountainous area based on temperature/vegetation dryness index (TVDI)[J]. Arid Land Geography, 2007, 30(1): 30-35.

[4] Wang Zuo, Wang Fang, Zhang Yun. Spatiotemporal distribution characteristics and influencing factors of drought in Anhui Province based on CWSI[J]. Journal of Natural Resources, 2018, 33(5): 853-866.

[5] Zhang Qiang, Ju Xiaosheng, Li Shuhua. Comparison of three drought indicators and identification of new indicators[J]. Meteorological Science and Technology, 1998(2): 49-53.

[6] Wang Jinsong, Guo Jiangyong, Qing Jizu. Application of a kind of K drought index in the spring drought analysis in Northwest China[J]. Journal of Natural Resources, 2007, 22(5): 709-717.

[7] Zou Xukai, Ren Guoyu, Zhang Qiang. Droughts variations in China based on a compound index of meteorological drought[J]. Climatic and Environmental Research, 2010, 15(4): 371-378.

[8] Zhang Jie, Wu Jianjun, Zhou Lei, et al. Comparative study on remotely sensed methods of monitoring agricultural drought based on MODIS data[J]. Remote Sensing Information, 2012, 27(5): 48-54.

[9] Zhang Qiang, Zou Xukai, Xiao Fengjin, et al. GB/T 20481-2006. The Grade of Meteorological Drought[S]. Beijing: China Standard Press, 2006.

[10] Ma Zice. Spatial and Temporal Characteristics of Drought and Its Influencing Factors in North China[D]. Hohhot: Inner Mongol Normal University, 2020.

[11] Liu Xiuhong, Li Zhicai, Liu Xiuchun, et al. Features and causes of spring drought in Shanxi[J]. Journal of Arid Land Resources and Environment, 2011, 25(9): 156-160.

[12] Mu Q Z, Heinsch F A, Zhao M S, et al. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data[J]. Remote Sensing of Environment, 2007, 111(4): 519-536.

[13] Mu Q Z, Zhao M S, Running S W. Improvements to a MODIS global terrestrial evapotranspiration algorithm[J]. Remote Sensing of Environment, 2011, 115(8): 1781-1800.

[14] Zhang Jing, Ren Zhiyuan. Spatiotemporal characteristics of evapotranspiration based on MOD16 in the Hanjiang River Basin[J]. Scientia Geographica Sinica, 2017, 37(2): 274-282.

[15] Wu Guiping, Liu Yuanbo, Zhao Xiaosong, et al. Spatiotemporal variations of evapotranspiration in Poyang Lake Basin using MOD16 products[J]. Geographical Research, 2013, 32(4): 617-627.

[16] Wen Yuanyuan, Zhao Jun, Wang Yanqiang, et al. Spatiotemporal variation characteristics of surface evapotranspiration in Shanxi Province based on MOD16[J]. Progress in Geography, 2020, 39(2): 255-264.

[17] Li Qing, Yang Pengnian, Peng Liang, et al. Study of the variation trend of evapotranspiration in the Yanqi Basin based on MOD16 data[J]. Arid Zone Research, 2021, 38(2): 351-358.

[18] Jackson R D, Idso S B, Reginato R J, et al. Canopy temperature as a crop water stress indicator[J]. Water Resources Research, 1981, 17(4): 1133-1138.

[19] Jackson R D, Kustas W P, Choudhury B J. A reexamination of the crop water stress index[J]. Irrigation Science, 1988, 9(4): 309-317.

[20] Liu Anlin, Li Xingmin, He Yanbo, et al. Simplification of crop shortage water index and its application in drought remote sensing monitoring[J]. Chinese Journal of Applied Ecology, 2004, 15(2): 210-214.

[21] Wang Lingling, Zhang Youjing, She Yuanjian, et al. Analysis and comparison of drought monitoring methods by remote sensing[J]. Remote Sensing of Information, 2010, 25(5): 49-53.

[22] He Huijuan, Zhuo Jing, Li Hongmei, et al. Spatial temporal distribution characteristics of drought in Guanzhong region of Shaanxi Province based on MOD16 products[J]. Agricultural Research in the Arid Areas, 2016, 34(1): 236-241.

[23] Kang Ligang, Jing Yuxin, Bao Yuhai. Comparative agricultural drought monitoring based on three machine learning methods[J]. Arid Zone Research, 2022, 39(1): 322-332.

[24] Wang Xiaoyan, Li Jing, Xing Liting. Temporal and spatial changes of evapotranspiration in the Shaliu River Basin of Qinghai Lake[J]. Arid Zone Research, 2023, 40(3): 358-372.

[25] Chen Jianing, Sun Huaiwei, Wang Jianpeng, et al. Improvement of comprehensive meteorological drought index and its applicability analysis[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(16): 71-77.

[26] Wu Bowei, Yang Shengtian, Shao Nanfang, et al. Effects of land use change on ecosystem service value in fragile ecological area of the Loess Plateau: A case study of Fenhe River Basin[J]. Research of Soil and Water Conservation, 2019, 26(5): 340-345.

[27] Li Jingjing, Lv Zhemin, Shi Xiaoping, et al. Spatiotemporal variations analysis for land use in Fen River Basin based on terrain gradient[J]. Transactions of the Chinese Society of Agricultural Engineering, 2016, 32(7): 230-236.

[28] Tong S, Zhang J, Bao Y. Interdecadal spatiotemporal variations of aridity based on temperature and precipitation in Inner Mongolia, China[J]. Polish Journal of Environmental Studies, 2017, 26(2): 807-816.

[29] Zhang Yalin, Zhao Haiyan, Wang Chunling, et al. Temporal and spatial characteristics of drought from 1979 to 2014 in Fen River Basin[J]. Chinese Agricultural Science Bulletin, 2018, 34(3): 145-151.

[30] Su Yingqing, Zhang Enyue, Liu Yuan, et al. Land use changes and ecological environment effects on Fen River Basin[J]. Arid Zone Research, 2022, 39(3): 968-977.

[31] Shi Lijiang, Liu Min, Li Yanping, et al. The spatiotemporal evolution and influencing factors of economic difference at county level in Fenhe River Basin[J]. Geographical Research, 2020, 39(10): 2361-2378.

[32] Pearson K. Note on regression and inheritance in the case of two parents[J]. Proceedings of the Royal Society of London, 1895, 58: 240-242.

Note: Figure translations are in progress. See original paper for figures.