Spatiotemporal Variation Characteristics of Actual Evapotranspiration and Its Environmental Impact Factors in the Ili River-Balkhash Lake Basin Postprint

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Abstract

Based on multiple remote sensing datasets, this study employs the Mann-Kendall test, Theil-Sen median trend analysis, Pearson correlation analysis, and the water balance principle to investigate the spatiotemporal variation patterns of actual evapotranspiration and its main influencing factors in the Ili River-Balkhash Lake basin from 2000 to 2020, and discusses the changes in water resource supply of the basin ecosystem. The results show that: (1) The multi-year average annual evapotranspiration in the upper, middle, and lower reaches of the basin is 439.0 mm, 317.9 mm, and 201.1 mm, respectively; the daily evapotranspiration in the upper and middle reaches is highest in summer, while in the lower reach it is highest in spring; the intra-annual distribution of evapotranspiration in the upper and middle reaches follows a "unimodal pattern" with peaks in July and June, respectively, whereas the lower reach exhibits a "bimodal pattern" with peaks in March and November. (2) The annual evapotranspiration in both the upper and lower reaches shows a significant increasing trend, with significant areas mainly distributed in the Ili River Valley and Tianshan Mountains in the upper reach and near the Ili River Delta in the lower reach; compared with 2000-2010, the multi-year average annual evapotranspiration in the Ili River Valley and Ili River Delta increased by more than 10% during 2010-2020. (3) Evapotranspiration in the upper and middle reaches shows a high positive correlation with air temperature and NDVI; evapotranspiration in the lower reach shows a high positive correlation with soil moisture. (4) The total water resource supply service of the basin ecosystem decreased during 2000-2020, with deficits occurring multiple times in the upper reach and beginning to emerge in the middle and lower reaches in 2020; it is necessary to ensure water supply-demand balance by controlling total water consumption and improving water use efficiency.

Spatial and Temporal Variation Characteristics of Actual Evapotranspiration and Its Environmental Impact Factors in the Ili River-Balkhash Lake Basin

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Abstract

Based on multiple remote sensing datasets from 2000 to 2020, this study employed the Mann-Kendall method, Theil-Sen median trend analysis, Pearson correlation analysis, and water balance principles to investigate the spatiotemporal patterns of actual evapotranspiration (ET) in the Ili River-Balkhash Lake Basin and identify its primary controlling factors. The analysis also examined changes in ecosystem water supply services. The results reveal: (1) The multi-year average annual ET in the upper, middle, and lower reaches of the basin was 439.0 mm, 317.9 mm, and 201.1 mm, respectively. Daily ET peaked in summer in the upper and middle reaches, while the lower reach experienced maximum daily ET in spring. The intra-annual distribution of ET was unimodal in the upper and middle reaches, with peaks in July and June, respectively, whereas the lower reach exhibited a bimodal pattern with peaks in March and November. (2) Annual ET showed significant increasing trends in both the upper and lower reaches, with the most pronounced changes occurring in the Ili River Valley of the upper reach, the Tianshan Mountains, and the Ili River Delta region of the lower reach. Compared to the 2000–2010 period, the average annual ET in the Ili River Valley and Delta increased by more than 10% during 2010–2020. (3) Pearson correlation analysis indicated that ET in the upper and middle reaches had strong positive correlations with temperature and NDVI, while ET in the lower reach showed a strong positive correlation with soil moisture. (4) The total water supply service of the basin’ s ecosystem declined from 2000 to 2020, with the upper reach experiencing multiple deficits and the middle and lower reaches beginning to show deficits after 2020. Maintaining the balance between water supply and demand will require controlling total water consumption and improving water use efficiency.

Keywords: Ili River-Balkhash Lake Basin; evapotranspiration; spatiotemporal variation; driving factors; Pearson correlation analysis

1. Introduction

Actual evapotranspiration (ET), which includes soil evaporation, plant interception evaporation, and vegetation transpiration, constitutes a critical component of terrestrial water and energy cycles. The Ili River-Balkhash Lake Basin (hereafter referred to as the "Ili-Balkhash Basin") is an important transboundary watershed between China and Kazakhstan located in an arid to semi-arid region, characterized by a large drainage area and substantial differences in geomorphology and climate. In recent years, fluctuations in the water level of Balkhash Lake [1] and ecological changes in the Ili River Delta [2] have made water resource allocation an extremely sensitive issue. As ET represents the largest water balance expenditure in arid and semi-arid regions, understanding its spatiotemporal evolution and driving factors is crucial for water resource management and allocation in the Ili-Balkhash Basin under global climate change and intensifying human activities.

Numerous studies have investigated spatiotemporal ET variations and their driving factors in arid and semi-arid regions. Li Xiucang [3] found that ET in China' s northwestern arid region increased from 1960 to 2010, primarily influenced by temperature, relative humidity, and wind speed. Liu et al. [4] reported high correlations between ET and precipitation in the Xilingol grassland of Inner Mongolia. Zhang et al. [5] identified relative humidity as the main driver of ET variation in central and western Inner Mongolia. Yan et al. [6] analyzed grassland ET in the Ili River Valley from 2001 to 2015 and found that reduced vegetation cover, precipitation, and temperature all contributed to ET decline. Deng et al. [7] observed that decreasing ET trends in the Tianshan Mountains from 2000 to 2014 were caused by reduced regional precipitation. Liang et al. [8] reported uneven ET distribution in the Ili River Basin, with an average annual ET of 401.18 mm within China—significantly higher than the 194.45 mm in Kazakhstan—identifying water shortage as the primary constraint on vegetation ET.

These studies demonstrate that ET changes in different arid and semi-arid basins are driven by various factors. Although previous research on ET in the Ili-Balkhash Basin has yielded valuable insights, systematic characterization of ET evolution patterns and their controlling factors has been limited by differences in data sources and spatiotemporal scales. This study addresses this gap by delineating the upper, middle, and lower reaches of the Ili-Balkhash Basin based on the Ili River' s contribution to Balkhash Lake, then analyzing long-term remote sensing data to reveal ET variation patterns under environmental changes and quantify the effects of multiple environmental factors through correlation analysis. The findings provide a scientific basis for water resource planning and management and for rational transboundary water allocation between China and Kazakhstan.

2. Study Area and Methods

2.1 Study Area Overview The geographical location of the Ili-Balkhash Basin is shown in [Figure 1: see original paper]. Balkhash Lake is an inland lake in Kazakhstan, with Ili River runoff providing its most important water source, accounting for 78.4% of total inflow [9]. The upper reach of the Ili River in the Tianshan Mountains is the runoff generation zone, while the lower reach in Kazakhstan is the runoff dissipation zone. Using the Sandaozihe hydrological station and the Kapchagay hydrological station (formerly Yili Village station) in Kazakhstan as boundaries, the basin is divided into upper, middle, and lower reaches, with the lower reach also including the catchment areas of the Karatal, Aksu, Lepsy, and Ayaguz rivers [10].

The spatial distribution of elevation, land use, NDVI, and precipitation in the basin is shown in [Figure 2: see original paper]. The basin exhibits extreme elevation differences, with precipitation decreasing markedly from mountains to plains. Multi-year average precipitation exceeds 1000 mm in high mountain areas, 400 mm in low mountain areas, and only 150 mm along the Balkhash Lake coast. High NDVI values are primarily located in high-altitude areas of the upper and middle reaches and at the middle-lower reach junction, while vegetation cover around Balkhash Lake is extremely low except in the Ili River Delta. The spatial distribution of land use mirrors these NDVI patterns.

2.2 Data Sources 2.2.1 Evapotranspiration Data

MOD16A2GF ET data (monthly temporal resolution, 500 m spatial resolution) and MOD13C2 NDVI data (monthly temporal resolution, 0.05° spatial resolution) were obtained from NASA' s LP DAAC via the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) portal (https://lpdaacsvc.cr.usgs.gov/appeears/). After preprocessing (removing invalid values, resampling, extracting the study area, and merging data), annual and seasonal ET datasets at 500 m resolution were generated through pixel-by-pixel calculations in ArcMap.

2.2.2 Meteorological Data

Monthly precipitation, temperature, relative humidity, and wind speed data at 0.1° spatial resolution from 2000 to 2020 were extracted from the Famine Early Warning Systems Network Land Data Assimilation System (FLDAS) dataset.

2.2.3 Soil Moisture Data

Global Land Data Assimilation System (GLDAS) monthly soil moisture data at 0.25° resolution were used, with soil layer thicknesses of 0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm. To reflect water availability for vegetation root systems, the 10-40 cm layer data were resampled to 500 m resolution. After preprocessing, area-averaged values were calculated for the upper, middle, lower, and entire basin.

2.2.4 Land Use Data

Land cover data from the European Space Agency Climate Change Initiative (ESA CCI) and Copernicus Climate Change Service (C3S) at 300 m resolution were reclassified into six categories following Li et al. [11]: grassland, forest, bare land, water body, permanent ice/snow, and human-occupied land (including cropland).

2.3 Research Methods Seasons were defined according to Xia et al. [10]: spring (March-May), summer (June-August), autumn (September-November), and winter (December-February). The Theil-Sen median trend analysis [12,13] was applied to calculate interannual trends in ET and environmental factors at different temporal scales. Mann-Kendall significance tests were performed on each grid cell to assess trend significance. Land use change maps were produced using the land use transition matrix principle [14,15] to analyze impacts on ET. Pearson correlation analysis [16] was used to quantify relationships between ET and five environmental factors (temperature, wind speed, relative humidity, soil moisture, and NDVI). Correlation coefficients (r) were interpreted as: $|r| < 0.3$ (weak), $0.3 \leq |r| < 0.5$ (moderate), and $|r| \geq 0.8$ (strong). Water balance principles [17] were applied to analyze changes in ecosystem water supply services.

3. Results

3.1 Spatiotemporal Variation Characteristics of ET 3.1.1 Annual Scale

The spatial distribution of multi-year average annual ET from 2000 to 2020 shows a distinct pattern of high values in the southeast and low values in the northwest, ranging from 117.6 mm to 1028.6 mm [Figure 3: see original paper]. High-ET areas are concentrated in regions with high vegetation cover, including the upper Karatal and Aksu rivers, south of Almaty, and the Kashi and Kunes river basins, where land use is predominantly forest or cropland. Low-ET areas are mainly distributed in the plains around Balkhash Lake and low-altitude regions of the middle reach.

The basin-wide multi-year average annual ET is 249.7 mm, with the upper, middle, and lower reaches averaging 439.0 mm, 317.9 mm, and 201.1 mm, respectively—a ratio of approximately 4:3:2. The spatial distribution of Mann-Kendall trend test Z-values shows increasing ET trends across most of the basin [Figure 4: see original paper]. In the upper reach, the Ili River Valley and most Tianshan Mountain areas exhibit significant increases ($p < 0.05$), while surrounding areas show non-significant decreasing trends. The middle reach shows predominantly non-significant trends, whereas the lower reach' s Ili River Delta and northeastern Balkhash Lake region display significant increasing trends ($p < 0.05$).

Time series analysis reveals increasing ET trends in the upper, lower, and entire basin, with average increases of 18.32 $\text{mm} \cdot \text{decade}^{-1}$, 10.35 $\text{mm} \cdot \text{decade}^{-1}$, and

12.22 mm • decade^{-1}, respectively [Figure 5: see original paper]. The upper and lower reach trends are statistically significant ($p < 0.05$), while the middle reach trend is not.

3.1.2 Seasonal Scale

Multi-year average daily ET values for spring, summer, autumn, and winter are 0.91 mm, 0.92 mm, 0.72 mm, and 0.60 mm basin-wide, respectively. Seasonal patterns vary by region: the upper and middle reaches peak in summer (1.36 mm and 1.37 mm, respectively), while the lower reach peaks in spring (0.67 mm). High-ET areas in all seasons correspond to high-elevation, high-vegetation-cover regions, though the Ili River Valley also shows high summer and autumn ET due to extensive cropland [Figure 6: see original paper].

Spatial trend analysis shows that the upper reach Ili River Valley has significant ET increases in spring, summer, and autumn, while the Tianshan Mountains show increases in spring, summer, and autumn [Figure 7: see original paper]. The middle reach exhibits non-significant increasing trends across all seasons. In the lower reach, areas around Balkhash Lake show significant increasing trends in spring, summer, and autumn, while some northern lake areas have significant decreasing trends in winter.

3.1.3 Monthly Scale

The intra-annual distribution of ET differs among reaches [Figure 8: see original paper]. The upper and middle reaches show unimodal distributions peaking in July (81.1 mm) and June (43.5 mm), respectively. The lower reach displays a bimodal pattern with peaks in March (29.9 mm) and November (24.4 mm). Monthly interannual trends show that most months have positive slopes, particularly June–September in the upper reach and March–November in the lower reach . Winter months contribute little to the overall annual trend due to small ET values.

Interdecadal changes between the 2000s and 2010s show ET increases exceeding 10% in the upper reach Ili River Valley and lower reach delta regions [Figure 9: see original paper]. Decreases exceeding 10% occur in areas south of the Kapchagay Reservoir, likely due to conversion of high-ET cropland to lower-ET natural vegetation after 2000 [12,27]. Land use change analysis reveals extensive conversion from bare land to grassland north of Balkhash Lake and in the delta, while forest degradation to grassland occurs within the delta [Figure 10: see original paper]. In the upper reach, grassland-to-forest conversion in the Tianshan Mountains and grassland-to-human-occupied land conversion contribute to ET increases.

3.2 Variation Characteristics of ET Impact Factors Environmental factors show varying trends from 2000 to 2020 . Basin-wide wind speed decreased significantly at -0.01 m • s^{-1} • decade^{-1} ($p < 0.05$). Precipitation and temperature decreased in the middle reach (-5.77 mm • decade^{-1} and -0.13°C • decade^{-1}, respectively; $p < 0.05$). Relative humidity, soil moisture, and NDVI increased across the basin, with relative humidity increases in the lower reach ($0.37\% \cdot \text{decade}^{-1}$) and NDVI increases in the upper reach ($0.02\ \text{decade}^{-1}$) being statistically significant ($p < 0.05$). The decreasing precipitation and increasing soil moisture trends suggest that irrigation activities may be enhancing soil moisture, promoting vegetation growth and increasing ET.

The intra-annual distribution of ET correlates with different factors by region [Figure 11: see original paper]. In the upper and middle reaches, ET distributions closely match temperature and NDVI patterns, while the lower reach ET distribution aligns with soil moisture. This suggests that temperature and vegetation activity control ET in the upper/middle reaches, whereas soil moisture is the primary control in the lower reach.

3.3 Influencing Factors of ET in Different Regions The MOD16 ET product is calculated using the Penman-Monteith equation, which requires meteorological, vegetation, and soil moisture conditions [28,29]. Previous studies have identified region-specific dominant factors [30,31]. Pearson correlation analysis reveals that temperature and NDVI have moderate positive correlations with ET in the upper and middle reaches ($r > 0.5$, $p < 0.05$), indicating these are primary controlling factors . In the lower reach, soil moisture shows a low positive correlation with ET ($r = 0.33$, $p < 0.05$), suggesting soil moisture limitation.

Spatial correlation patterns show that temperature-ET correlations are significant in the Ili River Valley, while both temperature and NDVI correlate positively with ET in the Tianshan Mountains [Figure 12: see original paper]. In the lower reach, soil moisture-ET correlations are significant in specific areas: low correlation north of Balkhash Lake, moderate correlation south of the lake, and moderate correlation in the delta wetland and upstream forest/cropland areas. Wind speed shows significant correlations with ET only in localized areas, indicating it is not a major basin-wide factor.

4. Discussion

Liang et al. [8] previously reported decreasing ET trends in the Ili-Balkhash Basin with continued future decline. In contrast, this study finds significant increasing trends, with average annual ET values of 334.26 mm (2000-2010) and 427.91 mm (2011-2020) in the upper reach, 311.36 mm and 317.90 mm in the middle reach, and 217.38 mm and 311.36 mm in the lower reach—all significantly higher than the 2000-2010 baseline. This discrepancy likely stems from different data sources and time periods.

The sustained ET increase directly impacts ecosystem water supply services. Water balance calculations show that while basin precipitation is decreasing (TABLE:2), ET is increasing (FIGURE:5), causing a decline in total water supply services [Figure 13: see original paper]. The middle reach shows the most pronounced decline. The upper reach has experienced negative water supply values in several years, with a deficit reaching 100 mm in 2020. The middle and lower reaches also showed negative values beginning in 2020.

Recent land use changes have exacerbated water consumption. In the upper reach, conversion of grassland to cropland in the Ili River Valley has increased water demand [32]. In the middle reach, establishment of the Kapchagay Reservoir converted surrounding grasslands to agricultural land, intensifying water consumption and potentially affecting Balkhash Lake levels [33]. After 2015, many croplands were abandoned, but subsequent land reforms increased cultivated area again [34], while bare lands near Balkhash Lake converted to grassland, further driving ET increases [35].

5. Conclusions

This study analyzed ET evolution and its environmental drivers in the Ili-Balkhash Basin using MOD16, meteorological, and soil moisture data from 2000 to 2020. The main conclusions are:

1. **Spatial Distribution**: ET decreases progressively from upstream to downstream, with multi-year averages of 439.0 mm, 317.9 mm, and 201.1 mm in the upper, middle, and lower reaches, respectively. Daily ET peaks in summer in the upper and middle reaches but in spring in the lower reach. The intra-annual distribution is unimodal in the upper (July peak) and middle (June peak) reaches, and bimodal in the lower reach (March and November peaks).
2. **Temporal Trends**: Annual ET increased significantly in the upper and lower reaches, with the most pronounced changes in the Ili River Valley, Tianshan Mountains, and Ili River Delta. Compared to the 2000s, average annual ET increased by over 10% in the Ili River Valley and Delta during the 2010s.
3. **Controlling Factors**: Temperature and NDVI showed moderate positive correlations with ET in the upper and middle reaches ($p < 0.05$), while soil moisture had a low positive correlation with ET in the lower reach ($p < 0.05$).
4. **Water Supply Implications**: The combination of increasing ET and decreasing precipitation has reduced the basin' s ecosystem water supply services. The upper reach has experienced multiple deficits, and the middle and lower reaches began showing deficits in 2020. Controlling total water consumption and improving water use efficiency are urgently needed to maintain water supply-demand balance.

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