Evapotranspiration Estimation and Irrigation Efficiency Assessment in the Shule River Basin Using the SEBAL Model (Postprint)

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Abstract

Water resources are scarce in the inland river basins of the arid region of Northwest China, where water utilization is primarily dedicated to agricultural production. Accurate estimation of evapotranspiration and agricultural irrigation efficiency in inland river basins is crucial for studying climate change and rational water resources utilization in these basins. Using the SEBAL model based on the surface energy balance equation, this study conducted quantitative estimation and spatiotemporal distribution characteristic analysis of evapotranspiration in the Shule River Basin from 2017 to 2018, and estimated the intra-annual irrigation water use efficiency coefficient of the Changma Irrigation District in the Shule River Basin by incorporating precipitation and net irrigation water volume data. The results indicated that: (1) The daily average ET in the Shule River Basin from 2017 to 2018 exhibited a unimodal variation trend, with a maximum value of 5.03 $\mathrm{mm \cdot d^{-1}}$ in June and a minimum value of 0.55 $\mathrm{mm \cdot d^{-1}}$ in December, along with significant spatial distribution differences. (2) Seasonal ET in the Shule River Basin varied significantly, reaching the highest value of 201.83 mm in summer, followed by spring and autumn, with the lowest value of 53.92 mm in winter; ET gradually decreased from southeast to northwest, and ET in the upper reaches of the basin was significantly higher than that in the middle and lower reaches. (3) Different irrigation water volumes during various irrigation periods in the Changma Irrigation District caused differences in evapotranspiration across irrigation seasons; high ET value areas in the irrigation district were mainly distributed in the central and southeastern regions, while low value areas were primarily located in the northwestern part and at the edges of the irrigation district. (4) The intra-annual irrigation water use efficiency coefficient in the Changma Irrigation District showed a decreasing trend, with values of 0.76, 0.71, 0.69, and 0.55 for spring irrigation, summer irrigation, autumn irrigation, and winter irrigation, respectively, and the annual average irrigation water use efficiency coefficient was 0.67.

Full Text

Preamble

Water resources are scarce in the inland river basins of northwestern China’ s arid regions, where agricultural production accounts for the majority of water consumption. Accurate estimation of evapotranspiration (ET) and agricultural irrigation efficiency in these basins is crucial for understanding climate change impacts and enabling rational water resource utilization. This study employs the Surface Energy Balance Algorithms for Land (SEBAL) model, which is based on the surface energy balance equation, to quantitatively estimate and analyze the spatiotemporal distribution characteristics of ET in the Shule River Basin during 2017–2018. Combining precipitation and net irrigation data, we further estimate the annual irrigation water use efficiency coefficient for the Changma irrigation district within the basin. The results demonstrate: (1) daily ET exhibits a unimodal trend throughout the year, with a maximum value of 5.03 $\mathrm{mm} \cdot \mathrm{d}^{-1}$ and a minimum of 0.55 $\mathrm{mm} \cdot \mathrm{d}^{-1}$; (2) seasonal ET variations are pronounced, with summer ET reaching the highest value of 201.83 mm, followed by spring and autumn, while winter ET is lowest at 53.92 mm; (3) ET decreases gradually from southeast to northwest, with significantly higher values in the upper reaches compared to the middle and lower reaches; (4) different irrigation volumes across seasons create distinct ET patterns in the Changma irrigation district, with high-ET zones concentrated in the central and southeastern areas and low-ET zones in the northwestern and peripheral regions; (5) the annual irrigation water use efficiency coefficient shows a declining trend, with values of 0.76, 0.71, 0.69, and 0.55 for spring, summer, autumn, and winter irrigation periods, respectively, yielding an annual average of 0.67.

Evapotranspiration represents a primary component of watershed hydrological cycles and water balance, serving as a critical element of regional energy balance that reflects interactions between water and energy fluxes under varying atmospheric, soil, and vegetation conditions. Consequently, ET research enables deeper understanding of water resource formation processes and variation patterns, playing a vital role in water resource assessment and drought monitoring. In arid northwestern China, accurate ET estimation and monitoring are particularly significant for regional water resource management and utilization. Traditional ET measurement methods include lysimeters, Bowen ratio-energy balance systems, eddy covariance instruments, and scintillometers. However, these methods are labor-intensive, have limited data availability, and cannot provide comprehensive observations of large-scale regions at reasonable costs. Advances in remote sensing technology offer alternative approaches for quantifying regional surface ET. Combining remote sensing data with models for regional ET inversion and application has become an important research direction both domestically and internationally. Widely used models include the Surface Energy Balance Algorithm for Land (SEBAL), Surface Energy Balance System (SEBS), trapezoidal space models based on surface temperature and vegetation indices, and two-source energy balance models (TSEB). Among these, the SEBAL model features a clear physical basis, broad adaptability, and high accuracy, making it suitable for calculating long-term surface ET over large scales. Consequently, it has been widely applied both internationally and domestically. For instance, foreign scholars such as Rahimi et al. and Santos et al. have used different data sources with SEBAL for ET inversion, achieving good results at watershed scales. Domestic researchers including Li Baofu, Liu Chunyu, and Zhou Yanzhao have applied the SEBAL model to ET inversion studies in northwest China’ s arid regions, demonstrating its effectiveness for simulating ET in arid areas. Therefore, this study employs the SEBAL model to investigate ET in the Shule River Basin.

Numerous scholars have conducted extensive research on irrigation efficiency evaluation indicators and their connotations, with specific discussions on the irrigation water use efficiency coefficient. Remote sensing techniques enable rapid acquisition of ET in irrigation districts, using water consumption by irrigated land as the effective irrigation water amount for efficiency estimation. This approach avoids the complexity and monitoring difficulties of traditional irrigation efficiency measurement, providing technical support for efficient agricultural water use. Scholars both domestically and internationally have utilized remote sensing ET models for water consumption analysis and irrigation evaluation in irrigation districts, demonstrating that remote sensing-based irrigation water use efficiency evaluation methods can rapidly and accurately assess irrigation efficiency with strong applicability.

1 Data and Methods

1.1 Study Area Overview

The Shule River Basin is located in the arid region of northwestern China, between 38°00 -42°48 N and 92°11 -98°30 E, covering an area of approximately 1.25\$×10^{5}\$ km^2. It represents one of the three major inland river basins in the Hexi Corridor. The upper reaches of the basin consist of high-altitude mountainous areas with typical continental glaciers and permafrost distribution. The middle and lower reaches feature low-lying terrain with extensive desert distribution and severe land desertification. Land use types are dominated by low-coverage grassland, sandy land, and desert, with sparse vegetation and a fragile ecological environment. The basin experiences a typical arid desert climate characterized by scarce precipitation and strong evaporation, with average annual rainfall below 60 mm and maximum annual evaporation reaching 3000 mm, classifying it as a severely arid region. The basin contains three major irrigation districts: Changma, Shuangta, and Huahai. Following years of water conservancy construction and implementation of comprehensive ecological protection planning projects, the Shule River irrigation district has significantly improved its irrigation efficiency and has been designated as a demonstration area for effective irrigation water use in Gansu Province. Water resources are scarce in the basin, with the primary conflict existing between limited water availability and rapidly increasing population, cultivated land, and agricultural-ecological water demands, making rational water allocation particularly critical. Agricultural water use accounts for approximately 80% of the basin' s annual water resources, relying primarily on irrigation from water conservancy projects. Therefore, rapid and accurate evaluation and improvement of agricultural water use efficiency in the basin are urgently needed. Clarifying the spatial pattern of actual ET and irrigation water use efficiency is essential for sustainable water resource utilization in this region.

Current ET research in the Shule River Basin primarily involves traditional measurement methods and short-term scale inversion based on remote sensing models. Studies on the Shule River irrigation district have focused on irrigation systems and techniques, with few analyses of annual ET variation characteristics or evaluations of irrigation efficiency across different irrigation seasons. This study utilizes MODIS data and meteorological observations to quantitatively estimate surface ET in the Shule River Basin during 2017-2018 using the SEBAL model, clarifying annual ET variation characteristics. Combining irrigation water data for each irrigation season in the Changma irrigation district, we estimate the annual irrigation water use efficiency coefficient to more realistically reflect actual irrigation efficiency, providing a basis for water resource management and allocation in the Shule River Basin.

1.2 Data Sources

The primary data used in this study include remote sensing data, meteorological data, land use/cover data, and irrigation statistics. Input parameters for the ET inversion model were obtained from NASA' s MODIS products (https://ladsweb.nascom.nasa.gov/search/). Clear-sky MODIS remote sensing images with minimal cloud cover and good quality were selected for the Shule River Basin. Meteorological data were obtained from the China Meteorological Data Sharing Service System (//cdc.cma.gov.cn/home/), including conventional surface meteorological observations such as air temperature, wind speed, relative humidity, and atmospheric pressure corresponding to satellite overpass times. The ASTER GDEM V2 product with 30 m spatial resolution was sourced from the Geospatial Data Cloud (//www.gscloud.cn/). Land use/cover data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (//www.resdc.cn/). Irrigation management data for calculating irrigation efficiency were provided by the Gansu Shule River Basin Water Resources Management Bureau (//slt.gansu.gov.cn/slhglj/).

1.3 SEBAL Model Calculation Principles

The SEBAL model is a remote sensing-based land surface energy balance model that estimates regional actual ET by calculating various energy components using remote sensing data and meteorological parameters. The regional land surface energy balance equation is expressed as:

$$\lambda ET = Rn - G - H$$

where λET is the latent heat flux ($\mathrm{W \cdot m^{-2}}$), Rn is the net radiation flux ($\mathrm{W \cdot m^{-2}}$), G is the soil heat flux ($\mathrm{W \cdot m^{-2}}$), H is the sensible heat flux ($\mathrm{W \cdot m^{-2}}$), and λ is the latent heat of vaporization ($\mathrm{J \cdot kg^{-1}}$).

1.3.1 Surface Net Radiation Flux Rn

$$Rn = (1-\alpha) \cdot Rs + R_L \downarrow - R_L \uparrow - (1-\varepsilon) \cdot R_L \downarrow$$

where α is the surface albedo, Rs is the total solar shortwave radiation ($\mathrm{W \cdot m^{-2}}$), $R_L \downarrow$ is the atmospheric longwave radiation ($\mathrm{W \cdot m^{-2}}$), $R_L \uparrow$ is the ground longwave radiation ($\mathrm{W \cdot m^{-2}}$), and ε is the surface emissivity.

1.3.2 Soil Heat Flux G

$$G = Rn \cdot \frac{TS}{\alpha} \cdot (0.0038\alpha + 0.0074\alpha^2) \cdot (1 - 0.98 \cdot NDVI^4)$$

where TS is the surface temperature (K) and $NDVI$ is the normalized difference vegetation index.

1.3.3 Sensible Heat Flux H

$$H = \frac{\rho_{air} C_p dT}{rah}$$

where ρ_{air} is the air density ($\mathrm{kg \cdot m^{-3}}$), C_p is the specific heat capacity of air at constant pressure (taken as 1004 $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), dT is the temperature difference between two heights, and rah is the aerodynamic resistance ($\mathrm{s \cdot m^{-1}}$). Both rah and dT are calculated through iterative selection of hot and cold pixels.

1.3.4 Evaporation Ratio and Daily Evapotranspiration Since satellite observations represent instantaneous ground data, the instantaneous ET is extended to daily ET using the constant evaporation ratio method:

$$\phi = \frac{\lambda ET}{Rn - G}$$

$$ET_{24} = \frac{Rn_{24} \times \phi \times 86400}{\lambda}$$

$$\lambda = 2.501 - 0.002361 \times (TS - 273.15)$$

where ϕ is the evaporation ratio, ET_{24} is the daily ET ($\mathrm{mm \cdot d^{-1}}$), Rn_{24} is the daily net radiation ($\mathrm{W \cdot m^{-2}}$), and TS is the surface temperature (K).

1.4 Evapotranspiration Time Scale Extension and Validation

1.4.1 Reference Crop Evapotranspiration ET_0 Based on ground meteorological observations, reference crop evapotranspiration was calculated using the FAO Penman-Monteith equation for long-term scale extension of simulated ET:

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is the reference crop evapotranspiration ($\mathrm{mm \cdot d^{-1}}$), Δ is the slope of the saturation vapor pressure curve ($\mathrm{kPa \cdot ℃^{-1}}$), Rn is the net radiation ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), G is the soil heat flux ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), T is the daily mean air temperature (℃), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), γ is the psychrometric constant ($\mathrm{kPa \cdot ℃^{-1}}$), and u_2 is the wind speed at 2 m height ($\mathrm{m \cdot s^{-1}}$).

1.4.2 Monthly Evapotranspiration Monthly actual ET was calculated by combining the SEBAL model and reference crop evapotranspiration:

$$ET_c = ET_{0F} \times ET_0$$

where ET_c is the actual evapotranspiration ($\mathrm{mm \cdot d^{-1}}$) and ET_{0F} is the reference evapotranspiration ratio, obtained from the ratio of ET calculated by SEBAL to ET_0 on satellite overpass days. For non-satellite overpass days, ET_{0F} can be obtained through time series interpolation. Continuous daily actual ET values were accumulated to obtain corresponding monthly ET.

1.4.3 Accuracy Evaluation Quantitative indicators including Root Mean Square Error (RMSE), coefficient of determination (R^2), and Mean Relative Error (MRE) were used for model validation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(ET_{m_i} - ET_{SEBAL_i})^2}{n}}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(ET_{m_i} - ET_{SEBAL_i})^2}{\sum_{i=1}^{n}(ET_{m_i} - \overline{ET_{m_i}})^2}$$

$$MRE = \frac{\sum_{i=1}^{n} |ET_{m_i} - ET_{SEBAL_i}|/ET_{m_i}}{n} \times 100\%$$

where n is the number of observation samples, ET_{m_i} is the measured ET, and ET_{SEBAL_i} is the ET calculated by the SEBAL model.

1.5 Water Balance and Irrigation Water Use Efficiency Coefficient Calculation

Based on ET estimation for the Changma irrigation district in the Shule River Basin, combined with actual irrigation and precipitation data, the irrigation water use efficiency coefficient was estimated for different irrigation periods. A water balance equation was established for the irrigation district, excluding water leakage and recharge due to hydraulic gradient effects:

$$\Delta w = (ET_n + ET_i + R) - (P_n + P_i + I)$$

where Δw is the change in soil water content during the period (mm), P_n and P_i are precipitation on non-irrigated and irrigated land during the period (mm), I is the net irrigation amount during the period (mm), ET_n and ET_i are evapotranspiration from non-irrigated and irrigated land during the period (mm), and R is surface runoff from the irrigation district during the period (mm).

The Changma irrigation district is located in an arid plain region with low annual precipitation, so surface runoff from precipitation is negligible. Changes in soil water content within the study period are also minor and thus not considered. The water balance equation can be simplified as:

$$I = (ET_i - P_i) + (ET_n - P_n)$$

Water consumed by irrigated land is typically considered effective irrigation water use. The ratio of effective irrigation water consumption $(ET_i - P_i)$ to net irrigation amount (I) is defined as the irrigation water use efficiency coefficient η:

$$\eta = \frac{ET_i - P_i}{I} = \frac{ET_i - P_i}{(ET_i - P_i) + (ET_n - P_n)}$$

where $(ET_i - P_i)$ is water consumption on irrigated land (mm), $(ET_n - P_n)$ is water consumption on non-irrigated land (mm), and η is the irrigation water use efficiency coefficient.

2 Results Analysis

2.1 Model Validation

Two methods were employed to validate ET simulation results. The first method used meteorological observation data from four stations (Dunhuang, Yumen, Mazongshan, and Guazhou) within the basin to calculate daily reference crop evapotranspiration for March-October using the FAO Penman-Monteith equation. Actual crop evapotranspiration was then obtained using crop coefficients during the growing season to validate ET simulation values. The second method applied evaporation pan coefficients to convert measured pan evaporation values at each station, which were then compared with ET simulation results.

Validation results from both methods are shown in [Figure 2: see original paper]. When extracting ET values for validation sites, the average value within a 3$\times$3 pixel window centered on each station was used. Both validation methods yielded R^2 values greater than 0.75, indicating good correlation and consistent trends between calculated/measured values and model inversion values. Root mean square errors were relatively small at 0.49 $\mathrm{mm \cdot d^{-1}}$, showing close agreement between calculated and inversion values. Mean relative errors were 8.4% for both methods, indicating that simulated values closely approximate actual conditions and are reliable. These validation results demonstrate that the SEBAL model can effectively simulate actual evapotranspiration in the Shule River Basin.

2.2 Evapotranspiration Simulation Results

2.2.1 Daily Evapotranspiration Variation Characteristics [Figure 3: see original paper] shows the spatial distribution of daily ET in the Shule River Basin during 2017-2018 (using Julian day numbers to represent dates). Daily ET in January was low, with a regional average of 0.58 $\mathrm{mm \cdot d^{-1}}$ and overall low values. Daily ET gradually increased in March, May, and April, reaching 1.21 $\mathrm{mm \cdot d^{-1}}$, 3.00 $\mathrm{mm \cdot d^{-1}}$, and 3.52 $\mathrm{mm \cdot d^{-1}}$, respectively. Daily ET reached its maximum of 5.03 $\mathrm{mm \cdot d^{-1}}$ in late July. Daily ET began to decline in September and October but remained at relatively high levels of 4.85 $\mathrm{mm \cdot d^{-1}}$ and 4.62 $\mathrm{mm \cdot d^{-1}}$, respectively. Daily ET decreased significantly in November to 1.62 $\mathrm{mm \cdot d^{-1}}$, with the area of high ET values noticeably shrinking. Daily ET reached its annual minimum in December at 1.1 $\mathrm{mm \cdot d^{-1}}$. Overall, daily ET in the study area showed an initial increase followed by a decrease, with the maximum occurring in late July and annual daily ET fluctuating between 0.55–5.03 $\mathrm{mm \cdot d^{-1}}$. The high-value area in the upper reaches decreased significantly, while spatial distribution characteristics remained similar, showing a gradual decrease from southeast to northwest.

2.2.2 Seasonal Evapotranspiration Characteristics Based on monthly ET estimates, seasonal ET values were obtained as shown in [Figure 4: see original paper]. Spring (March-May), summer (June-August), autumn (September–November), and winter (December–February) ET spatial distributions are presented. Seasonal ET differences in the Shule River Basin are significant, with summer ET reaching the highest value of 201.83 mm, followed by spring at 165.51 mm, autumn at 100.51 mm, and winter at 53.92 mm. The spatial heterogeneity of seasonal ET is pronounced. Temporally, differences between summer and autumn ET are more significant than those between spring and winter. Spatially, ET decreases from southeast to northwest, with ET in the upper reaches significantly higher than in the middle and lower reaches. The spatial distribution of ET shows high consistency with land cover types. High ET values are concentrated in high-coverage grassland and water areas in the upper reaches, where seasonal precipitation from mountainous areas provides water supply, maintaining moist soil favorable for evaporation. The middle and lower reaches are dominated by extensive sandy land and desert with small oases interspersed, representing the main low-ET distribution area. The extreme water scarcity in desert regions, combined with sparse groundwater resources and reliance on precipitation and groundwater recharge, results in minimal ET from bare sand and Gobi surfaces.

2.3 Water Balance and Irrigation Water Use Efficiency Coefficient Results

The remote sensing ET model was applied to the Changma irrigation district, the largest in the Shule River Basin, to estimate irrigation water use efficiency and evaluate irrigation performance. Located in the middle reaches, the Changma district primarily contains cultivated land and some forest land ([Figure 1: see original paper]). High ET areas in all seasons are concentrated in the upper reaches, distributed in grassland and forest near mountainous areas, along riverbanks, and in water bodies. ET in the middle and lower reaches remains relatively low throughout the basin.

Irrigation periods in the Changma district are divided as: spring irrigation (March–May), summer irrigation (June–August), autumn irrigation (September–November), and winter irrigation (December–February). Seasonal ET results for these periods are shown in [Figure 5: see original paper]. Due to varying irrigation volumes and planting conditions across seasons, significant spatiotemporal differences in ET are evident. Summer irrigation (June–August) shows the highest ET, followed by autumn and spring irrigation, with winter irrigation showing the lowest ET. Spatially, high-ET zones during different irrigation periods are mainly distributed in the central and southeastern parts of the district, while low-ET zones are primarily in the northwestern and peripheral areas.

Monthly ET and precipitation variations in the Changma district are shown in [Figure 6: see original paper]. ET shows an initial increase followed by a decrease, gradually rising from March and peaking in July at 129 mm, then declining and reaching a minimum in December at 20 mm. Monthly precipitation varies significantly, with the highest precipitation in July and August exceeding 30 mm, while remaining below 15 mm in other months. These ET and precipitation components significantly influence irrigation efficiency across different seasons.

[Figure 7: see original paper] presents variations in parameters for each irrigation season. Calculated irrigation water use efficiency coefficients for spring, summer, autumn, and winter irrigation are 0.76, 0.71, 0.69, and 0.55, respectively, with an annual average of 0.67. The coefficient shows a gradually decreasing trend throughout the year, with spring irrigation having the highest efficiency, followed by summer and autumn, and winter irrigation the lowest. This pattern reflects the combined effects of net irrigation amount, precipitation, and ET, as well as irrigation technology and water delivery systems.

3 Discussion

3.1 Evapotranspiration Model Inversion

This study used MODIS remote sensing data and the SEBAL model to quantitatively estimate ET in the Shule River Basin during 2017–2018 and analyze its spatial distribution characteristics. Results show that annual daily ET exhibits a unimodal trend, fluctuating between 0.55–5.03 $\mathrm{mm} \cdot \mathrm{d}^{-1}$, with summer ET being the highest, followed by spring and autumn, and winter the lowest. Previous studies by Chang et al. using SEBAL obtained daily ET values of 1.5–6.5 $\mathrm{mm} \cdot \mathrm{d}^{-1}$ for the upper Shule River in July 2012, while Zhou et al. obtained July multi-year average daily ET of 8.52 $\mathrm{mm} \cdot \mathrm{d}^{-1}$. These findings are similar to our results for corresponding periods, confirming the reasonableness of our calculations. Annual ET variation is influenced by temperature, precipitation, solar radiation, vegetation growth status, and soil moisture content, showing clear seasonality. Summer represents the peak vegetation growth period, where abundant water and strong radiation maximize evaporation from water bodies and transpiration from vegetation. In contrast, winter ET is low due to low temperatures, weak radiation, minimal precipitation, and reduced evaporation from surface vegetation and soil moisture.

The spatial distribution of ET shows high consistency with land cover types. High-ET zones are mainly distributed in high-coverage grassland and water areas in the upper reaches, where seasonal mountain precipitation provides water supply. The middle and lower reaches of the Shule River Basin feature extensive sandy land and desert with small interspersed oases, representing the primary low-ET distribution area. The extreme water scarcity in desert regions, combined with sparse vegetation and bare surfaces, results in minimal ET. These findings align with Jin et al.’ s ET estimation results for the Heihe River Basin in arid regions, where water bodies and grassland had high ET while sandy and bare land had minimal ET.

3.2 Irrigation Water Use Efficiency Coefficient Calculation

This study estimated the irrigation water use efficiency coefficient for the Changma irrigation district using a remote sensing ET model. The precipitation, actual irrigated area, and net irrigation amount used in calculations were obtained from measured statistical data, ensuring certain accuracy in the derived coefficient. The calculated annual average irrigation water use efficiency coefficient for 2017-2018 was 0.67, indicating relatively high irrigation efficiency in the Changma district.

The irrigation water use efficiency coefficient is simultaneously influenced by net irrigation amount, precipitation, and ET, as well as irrigation technology and water delivery systems. Therefore, different water-saving irrigation measures and rational irrigation volumes can be adopted according to seasonal ET characteristics and irrigation water use patterns to improve irrigation efficiency. As ET constitutes an important component in calculating irrigation water consumption and efficiency, accurate ET estimation is crucial for understanding crop water use characteristics. Future research should improve model parameters based on actual conditions and combine high-resolution imagery to enhance ET inversion accuracy for the basin and irrigation district, thereby enabling more accurate estimation of irrigation water use efficiency.

4 Conclusions

1) ET in the Shule River Basin shows an overall unimodal trend, with annual average daily ET fluctuating between 0.55–5.03 $\mathrm{mm \cdot d^{-1}}$. Daily ET increased from March, peaked in late July, then decreased, reaching its minimum from December to the following February.

2) Seasonal ET variations in the Shule River Basin are significant, with values decreasing in the order: summer (201.83 mm) $>$ spring (165.51 mm) $>$ autumn (100.51 mm) $>$ winter (53.92 mm). The spatiotemporal heterogeneity of seasonal ET is pronounced, with more obvious temporal differences between summer and autumn than between spring and winter. Spatially, ET decreases from southeast to northwest, with upper reach ET significantly higher than middle and lower reaches. The spatial distribution of ET shows high consistency with land cover types.

3) Due to different irrigation volumes and planting conditions across seasons, the Changma irrigation district exhibits distinct spatial distribution differences in ET for irrigated land. High-ET zones are mainly distributed in the central and southeastern parts of the district, while low-ET zones are primarily in the northwestern and peripheral areas.

4) Based on water balance calculations, the irrigation water use efficiency coefficient for the Changma district shows a decreasing trend throughout the year. The coefficients for spring, summer, autumn, and winter irrigation periods are 0.76, 0.71, 0.69, and 0.55, respectively, with an annual average of 0.67. The coefficient is influenced by net irrigation amount, precipitation, and ET, as well as irrigation technology and water delivery systems. Different water-saving irrigation measures and rational irrigation volumes

should be adopted according to seasonal ET characteristics to improve irrigation efficiency.

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