Evaluation of Water Use Efficiency for Farmland in the Yanqi Basin, Xinjiang (Postprint)

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Abstract

Due to factors such as scarcity of monitoring data, it is difficult to achieve regional-scale evaluation of water resource consumption effectiveness in Northwest arid regions. Using MODIS remote sensing data to drive the Hybrid Dual-Source Trapezoidal Evapotranspiration Model (HTEM), the spatiotemporal process of land surface evapotranspiration in the Yanqi Basin was continuously simulated, and the effectiveness of water consumption in the irrigation district was evaluated. The results show that: (1) The multi-year average evapotranspiration in the Yanqi Basin irrigation district from 2013 to 2020 was 624.4 mm, with evapotranspiration during the crop growing season (April–October) accounting for 89.6% of the annual total. (2) The multi-year average vegetation transpiration and soil evaporation in the Yanqi Basin irrigation district were 508.9 mm and 115.5 mm, respectively, accounting for 81.5% and 18.5% of the total evapotranspiration. (3) The multi-year average evapotranspiration water consumption in the Yanqi Basin irrigation district was 13.82\$×10^{8}\$ m^3, of which high-efficiency, medium-efficiency, and low-efficiency water consumption accounted for 81.5%, 5.6%, and 12.9% of the total water consumption, respectively, and water consumption effectiveness was closely related to vegetation coverage. This study reveals the effectiveness of evapotranspiration water consumption in the Yanqi Basin irrigation district in a spatiotemporally continuous manner at the regional scale, providing a reliable theoretical basis for water resource management and control in arid regions.

Full Text

Effectiveness Evaluation of Water Consumption in Agricultural Land of Yanqi Basin, Xinjiang

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Abstract: Due to factors such as scarce monitoring data, it is difficult to evaluate water resource consumption effectiveness at a regional scale in arid northwestern China. This study uses MODIS remote sensing data to drive a hybrid dual-source trapezoidal evapotranspiration model (HTEM) for continuous simulation of land surface evapotranspiration processes in the Yanqi Basin of Xinjiang, and evaluates the effectiveness of water consumption in the irrigation area. The results show that: (1) The multiyear average evapotranspiration in the Yanqi Basin irrigation area from 2013 to 2020 was 624.4 mm, with evapotranspiration during the crop growth period (April–October) accounting for 89.6% of the annual total. (2) The multiyear average vegetation transpiration and soil evaporation in the irrigation area were 508.9 mm and 115.5 mm, respectively, comprising 81.5% and 18.5% of total evapotranspiration. (3) The multiyear average evapotranspiration water consumption in the irrigation area was 13.82$×10^{8}$ m^{3}, of which high-efficiency, medium-efficiency, and low-efficiency water consumption accounted for 81.5%, 5.6%, and 12.9% of total water consumption, respectively, with water consumption effectiveness closely related to vegetation coverage. This study reveals the effectiveness of evapotranspiration water consumption in irrigation areas at a regional scale in a spatiotemporally continuous manner, providing a reliable theoretical basis for water resource management in arid zones.

Keywords: evapotranspiration; hybrid dual-source trapezoidal evapotranspiration model (HTEM); water consumption effectiveness; Yanqi Basin

1. Introduction

In the water cycle of arid and semi-arid regions of northwestern China, evapotranspiration (ET) represents the primary pathway of water consumption. Comprising vegetation transpiration and soil evaporation, ET accounts for over 90% of water consumption in these regions, with the vast majority occurring through farmland irrigation. The Yanqi Basin, a typical arid region in northwestern China, serves as an important oasis area and economic crop and grain production base in Xinjiang. Agricultural and ecological ET consumption constitutes the main form of water consumption within the oasis. With the implementation of major strategies such as rural revitalization, the contradiction between high-quality economic and social development and ecological water security has become increasingly prominent, making water resources a controlling factor for ecological protection and economic and social development in the Yanqi Basin. However, traditional water-saving concepts primarily focus on the total amount of water actually saved before and after implementing different measures at the terminal water use stage, without further subdividing the consumption amount in the water cycle process. This approach emphasizes only the magnitude of water savings while neglecting the actual effectiveness of water resource consumption. Therefore, investigating water use efficiency during the consumption process and implementing targeted water-saving measures in the water cycle are crucial for intensive water resource management in the Yanqi Basin.

Extensive research has been conducted on ET theory and experiments both domestically and internationally. With the rapid development of satellite remote sensing technology, remote sensing-based ET models grounded in energy balance principles have gradually become the mainstream method for large-scale land surface ET simulation and estimation. Representative models include single-source models such as SEBAL and SEBS, dual-source models such as TSEB and DTD, and feature space-based models like STSEB and TTME. Although single-source models have achieved good results in arid regions such as the Hetao Irrigation District in Inner Mongolia and the Kaidu River Basin, they cannot separate vegetation transpiration from soil evaporation, limiting their effectiveness in evaluating water consumption based on ET. The HTEM model hybridizes the "layered" and "patch" energy allocation methods of dual-source models, achieving land surface ET simulation and component separation through construction of a surface temperature-vegetation index feature space. This approach better reflects vegetation characteristics' influence on ET and is more suitable for non-uniform, incompletely vegetated underlying surfaces in arid and semi-arid regions. Applications of this model in central Iowa, USA, the Heihe River Basin, and the Hetao Irrigation District of Inner Mongolia have demonstrated higher accuracy compared to MOD16 products, single-source models, and the SEBAL model, with good separation of vegetation transpiration and soil evaporation.

Limited by sparse monitoring stations and scarce measured data, ET-based water use efficiency assessments in the Yanqi Basin have been confined to site and irrigation district scales. This study employs high-temporal-resolution and medium-spatial-resolution MODIS data to construct a hybrid dual-source trapezoidal evapotranspiration (HTEM) model, achieving spatiotemporally continuous simulation of daily-scale land surface ET and its components (vegetation transpiration and soil evaporation) in the Yanqi Basin. The study further evaluates the effectiveness of farmland ET water consumption, providing a basis for ET-based water resource management in the region.

2. Materials and Methods

2.1 Study Area

The Yanqi Basin (41°45 -42°29 N, 85°47 -87°32 E) is a semi-enclosed intermontane basin in the northeastern Tarim Basin (Fig. 1). The plain area of the basin (excluding Bosten Lake) is approximately 5,436 km^2, encompassing Yanqi County, Bohu County, Hejing County, Heshuo County, and five regiments of the Xinjiang Production and Construction Corps Second Division. Located deep inland at the climatic transition zone between southern and northern Xinjiang, the region features a typical continental arid climate characterized by: severely cold winters with daily average temperatures below 0°C from December to February; rapid spring warming with daily average temperatures rising from below 0°C to above 20°C between March and May; mild summers with daily temperatures of 20-30°C; and rapid autumn cooling. The basin exhibits typical arid oasis characteristics including low precipitation, long sunshine hours, large diurnal temperature variations, and strong evaporation. Land use structure primarily comprises cultivated land (45.2%), forestland (41.0%), grassland (10.6%), water bodies, construction land, and unused land.

2.2 Data Sources

The main data used in this study include MODIS remote sensing products, meteorological data, land use data, and water diversion data (Table 1). For MODIS remote sensing satellite data, we selected MOD09GA, MOD09GQ, and MOD11A1 products. These data were processed using Google Earth Engine (GEE) for resampling, masking, and projection transformation, with spatial resolution unified to 250 m. Meteorological data and land use data were also resampled to the same 250 m spatial resolution as the MODIS data.

2.3 Research Methods

This study constructs the HTEM model by combining surface energy balance principles with surface temperature-vegetation index feature space, using MODIS data to drive the model for land surface ET simulation and estimation and component separation of vegetation transpiration and soil evaporation, thereby deriving ET-based water consumption effectiveness evaluation.

2.3.1 HTEM Model In models based on surface energy balance principles, the energy consumed by the ET process can be expressed as the residual of the surface energy balance equation:

$$LE = R_n - G - H$$

where LE is the latent heat flux consumed by evapotranspiration ($\mathrm{W \cdot m^{-2}}$), R_n is the net radiation flux at the surface ($\mathrm{W \cdot m^{-2}}$), G is the soil heat flux ($\mathrm{W \cdot m^{-2}}$), and H is the sensible heat flux ($\mathrm{W \cdot m^{-2}}$).

The HTEM model consists of two modules (Fig. 2). The first module partitions the available energy for each pixel and estimates surface energy fluxes using a hybrid dual-source scheme. The "layered" method first partitions net radiation flux into canopy and soil components, then the "patch" method partitions available energy into soil heat flux, sensible heat flux, and latent heat flux. This approach enables separate calculation of evaporation from vegetated and bare soil areas, making it suitable for sparsely vegetated arid and semi-arid regions and providing high accuracy for farmland during sowing periods.

To solve for latent heat flux, vegetation canopy temperature and soil surface temperature must be obtained. The HTEM model decomposes surface temperature into these components by constructing a trapezoidal F_c-LST feature space (Fig. 2). This method assumes four ideal extreme points representing soil moisture conditions and evaporation rates exist within the space, forming a trapezoidal framework. Points c_{wet} and s_{wet} represent non-water-stressed points for fully vegetated and bare soil areas, respectively, forming the "wet edge" with evaporation rate at potential rate. Points c_{dry} and s_{dry} represent completely dry points for fully vegetated and bare soil areas, forming the "dry edge" with evaporation at potential rate. For the wet edge, maximum evaporation corresponds to minimum sensible heat flux, so the average air temperature is considered the wet edge. Between the dry and wet edges, inclined lines within the trapezoidal space represent soil moisture isolines, obtainable through linear interpolation of dry and wet edge slopes. Under specific meteorological and surface characteristic conditions, setting canopy latent heat flux to maximum yields the temperature of theoretically fully vegetated land (c_{max}); similarly, setting soil latent heat flux to minimum yields the temperature of theoretically driest bare land (s_{max}). Finally, vegetation canopy temperature and soil surface temperature can be calculated using isoline slopes.

2.3.2 Temporal Scaling of Evapotranspiration As satellite remote sensing provides surface information only during satellite overpass times, instantaneous ET (ET_{inst}) must be scaled to daily values (ET_{day}). This study assumes the reference evapotranspiration fraction (F_{ref}) remains constant throughout the day:

$$ET_{\mathrm{day}} = \frac{ET_{\mathrm{inst}}}{ET_{\mathrm{r,inst}}} \times ET_{\mathrm{r,day}}$$

where $ET_{\mathrm{r,inst}}$ is the instantaneous reference crop evapotranspiration at satellite imaging time, and $ET_{\mathrm{r,day}}$ is the cumulative daily reference crop evapotranspiration calculated using the FAO Penman-Monteith formula. Due to cloud cover and missing images, remote sensing data are not daily continuous. For periods lacking remote sensing data, F_{ref} can be obtained through linear interpolation between days with remote sensing data.

2.3.3 Water Consumption Effectiveness Evaluation Indicators Based on soil water resource consumption utility evaluation indicators proposed by Wang et al. and methods from Tu et al., this study defines water consumption during the ET process as three types: (1) High-efficiency water consumption: vegetation transpiration that directly participates in plant dry matter formation and is essential for crop production; (2) Medium-efficiency water consumption: inter-plant evaporation (soil evaporation under vegetation cover) that regulates plant growth microclimate and affects crop yield, though with lower efficiency than transpiration; (3) Low-efficiency water consumption: soil evaporation under near-zero vegetation cover that occurs without surface vegetation, minimally utilized despite some ecological effects. These three indicators are used to evaluate water consumption effectiveness in the Yanqi Basin farmland.

2.3.4 HTEM Model Validation To verify the reliability of HTEM-estimated land surface ET, validation is necessary. Although various remote sensing ET products such as MOD16A2 exist, data gaps and underestimation in arid and semi-arid regions limit their applicability at watershed scales. Therefore, following previous research, this study conducts accuracy analysis at both site and regional scales. At the site scale, validation uses: (1) daily observations from meteorological station evaporators converted to large water surface evaporation using conversion coefficients, comparing monthly average daily evaporation with HTEM-simulated water surface evaporation; (2) Penman-Monteith formula calculations using multiple reference crops area-weighted within farmland scope, comparing monthly average daily actual ET with HTEM results. At the regional scale, the water balance equation calculates regional ET for comparison: $ET_W = P + R - \Delta W$, where ET_W is regional annual total ET (m^3), P is regional annual precipitation (m^3), R is regional annual water diversion (m^3), ΔW is regional annual outflow (m^3), and for annual equilibrium, water storage change is zero. Regional average ET is calculated as $\overline{ET_W} = ET_W/A$, where A is study area (m^2).

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3. Results

3.1 Evapotranspiration Simulation Accuracy Assessment

Comparison results at site and regional scales are shown in Fig. 3. At the site scale (Fig. 3a), HTEM simulation compared with large evaporator observations yields RMSE of 0.38 $\mathrm{mm \cdot d^{-1}}$, R^2 of 0.91, and MRE of 14.7%. Comparison with Penman-Monteith calculations shows RMSE of 0.58 $\mathrm{mm \cdot d^{-1}}$, R^2 of 0.82, and MRE of 17.4% (Fig. 3b). At the regional scale, HTEM versus water balance calculation shows RMSE of 14.7 mm and MRE of 5.6% (Fig. 3c). These errors are within reasonable ranges and similar to other validation results, indicating good HTEM applicability in the Yanqi Basin for subsequent spatiotemporal ET pattern analysis.

3.2 Spatiotemporal Distribution Characteristics of Evapotranspiration

Spatial distribution of ET and land use types in the Yanqi Basin (Fig. 4) shows significant spatial variation. High values concentrate in central basin cropland, water bodies, and wetlands near Bosten Lake, where abundant water supply from proximity to water bodies and irrigation activities leads to higher ET. Low values concentrate in piedmont plains and gobi desert areas around the basin periphery, where low precipitation and high solar radiation result in insufficient water supply and lower ET. To assess farmland water use efficiency, this study extracted and analyzed farmland areas.

Interannual and monthly trends of farmland ET from 2013-2020 are shown in Fig. 5. Annual farmland ET fluctuated between 570-660 mm, with a multiyear average of 624.4 mm, showing an overall increasing trend. Monthly variations show a unimodal pattern, with ET continuously increasing to peak in July and then decreasing to minimum in January. The period from April-October (crop growth period) accounts for 89.6% of annual ET.

3.3 Component Evaluation of Vegetation Transpiration and Soil Evaporation

Spatial distributions and proportions of vegetation transpiration and soil evaporation (Fig. 6) show that vegetation transpiration primarily occurs in central basin cropland, forestland, and grassland with vegetation cover, while soil evaporation shows opposite distribution patterns, with high values in unused land and construction sites without vegetation cover, and low values in vegetated areas. Proportion analysis reveals vegetation transpiration varies between 8-92% of total ET, while soil evaporation varies between 0-92%, showing opposite trends and significant complementary effects, both closely related to vegetation distribution.

Interannual and monthly trends of farmland vegetation transpiration and soil evaporation from 2013-2020 are shown in Fig. 7. Vegetation transpiration multiyear average is 508.9 mm (81.5% of total ET), while soil evaporation is 115.5 mm (18.5%). Interannual trends show increasing vegetation transpiration and soil evaporation that first decreases then increases. Monthly variations show vegetation transpiration following a unimodal pattern consistent with vegetation cover, peaking in July and minimizing in January. Soil evaporation shows a bimodal pattern: small during winter frozen soil period, increasing after March thaw to peak in April, then decreasing with crop growth and surface coverage to minimum in August, followed by a second peak after harvest and traditional winter irrigation.

3.4 Water Consumption Effectiveness Evaluation

Based on water consumption utility evaluation indicators, effectiveness of farmland water consumption from 2013-2020 was assessed (Table 3). The multiyear average water consumption in basin farmland was 13.82$×10^{8}$ m^3, comprising high-efficiency (11.27$×10^{8}$ m^3, 81.5%), medium-efficiency (0.77$×10^{8}$ m^3, 5.6%), and low-efficiency (1.79$×10^{8}$ m^3, 12.9%) consumption. High-efficiency water consumption far exceeds medium and low efficiency, with interannual variation matching total water consumption trends, while medium and low efficiency show some divergence.

Monthly proportions of multiyear average high-, medium-, and low-efficiency water consumption (Fig. 9) show: high-efficiency varies 11.6–98.0% with unimodal pattern, peaking during crop growth period; medium-efficiency varies 1.3–27.4% with bimodal pattern, peaking during early growth and harvest periods; low-efficiency varies 0.7–84.2% with unimodal (valley) pattern opposite to high-efficiency, peaking during non-growth periods when vegetation cover is minimal.

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4. Discussion

4.1 Evapotranspiration Model Inversion

Validation at site and regional scales shows errors within reasonable ranges, with results similar to Yu et al.' s simulations in the Kaidu River Basin, confirming HTEM' s rationality and good applicability in the Yanqi Basin. Spatial ET distribution shows high consistency with land use types, with high values in central basin cropland, water bodies, and Bosten Lake wetlands, and low values in peripheral piedmont plains and gobi areas lacking water supply. This aligns with Ning et al.' s conclusions that water bodies and vegetation have high ET while sand and bare land have minimum ET. This method accurately simulates ET, overcoming traditional limitations of crop growth period-only simulations, and provides richer data for ET-based water consumption research.

4.2 Evapotranspiration Water Consumption Effectiveness Evaluation

This study decomposes farmland ET water consumption in the Yanqi Basin into high-, medium-, and low-efficiency components based on consumption utility. Results show that of the 624.4 mm average annual ET, 508.9 mm is vegetation transpiration (high-efficiency) and 115.5 mm is soil evaporation (18.5% of total ET). Of the soil evaporation, 80.7 mm (1.79$×10^{8}$ m^3) is low-efficiency consumption occurring mainly during non-growth periods, primarily from water stored during winter irrigation. Winter irrigation stores and freezes water in soil, which upon spring thaw increases soil moisture for salinity control. However, excessive large-scale winter irrigation not only causes substantial evaporation and increases low-efficiency water consumption but also leads to soil fertility loss. With implementation of strictest water resource management, quota water supply will become normalized, making large-area winter irrigation unsustainable. Moderate, rational limited winter irrigation will be the future trend. Given the current declining soil salinization in Yanqi Basin farmland, appropriately reducing winter irrigation area or extending winter irrigation intervals could alleviate conflicts between agricultural and ecological water use.

5. Conclusions

Based on the status of scarce monitoring data limiting regional-scale water use efficiency evaluation in the Yanqi Basin, this study used MODIS data to drive the HTEM model for regional-scale, spatiotemporally continuous ET simulation and component separation, revealing temporal and spatial variation characteristics of vegetation transpiration and soil evaporation, and quantitatively evaluating irrigation area ET water consumption effectiveness. This provides a reliable theoretical basis for water resource management in arid zones. Main conclusions are:

1) The 2013–2020 average ET in the Yanqi Basin irrigation area was 624.4 mm, showing an overall increasing interannual trend and unimodal monthly variation, with April–October crop growth period ET accounting for 89.6% of annual ET. Spatial distribution showed significant variation, with high values in central basin cropland, water bodies, and Bosten Lake wetlands, and low values in peripheral piedmont plains and gobi areas.
2) Multiyear average vegetation transpiration and soil evaporation were 508.9 mm and 115.5 mm, respectively (81.5% and 18.5% of total ET). Interannual vegetation transpiration increased while soil evaporation first decreased then increased. Monthly vegetation transpiration followed unimodal pattern peaking in July, while soil evaporation showed bimodal pattern peaking in April and November.
3) Multiyear average ET water consumption was 13.82$×10^{8}$ m^3, with high-, medium-, and low-efficiency consumption of 11.27$×10^{8}$ m^3, 0.77$×10^{8}$ m^3, and 1.79$×10^{8}$ m^3, respectively (81.5%, 5.6%, and 12.9%). With improved irrigation efficiency, high- and medium-efficiency consumption increased while low-efficiency consumption decreased. Water consumption effectiveness is closely related to and increases with vegetation coverage.

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