Estimation of Groundwater Evapotranspiration Using the Diurnal Water Level Fluctuation Method: A Case Study of Typical Oases in the Hexi Corridor (Postprint)

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Abstract

Using multiple diurnal water table fluctuation methods (White method, Hays method, Loheide method), groundwater evapotranspiration (ETg) was calculated for typical periods during the growing season in the shallow groundwater area of the desert-oasis ecotone in the middle reaches of the Heihe River, and correlation analysis was conducted between the estimated results and potential evapotranspiration (PET) obtained by the Penman method, water surface evaporation measured by E-601 (ET0), and water surface evaporation measured by Φ20 (ET1). The results indicate that among these algorithms, the Hays method exhibits the highest accuracy, followed by the White method, while the Loheide method demonstrates the lowest computational accuracy. Therefore, the Hays method is recommended for priority use in calculating daily ETg, and ET0 is suggested for verifying calculation accuracy. The Loheide method can achieve relatively high accuracy ($R=0.821$, $P<0.01$) for ETg calculation, but exhibits a significant time-lag effect with a lag time of approximately 3 h. These computational results possess certain reference significance and application value for the rational allocation and sustainable development and utilization of local water resources.

Full Text

Estimation of Groundwater Evapotranspiration Using Diurnal Water Level Fluctuation Methods: A Case Study of Typical Oasis in the Hexi Corridor

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Abstract

Multiple diurnal water level fluctuation methods (White, Hays, Loheide) were employed to estimate daily groundwater evapotranspiration (ETg) during the growing season in the shallow groundwater area of the desert-oasis ecotone in the middle reaches of the Heihe River basin. The estimated results were correlated with potential evapotranspiration (PET) obtained by the Penman method, water surface evaporation measured by E-601 pan (ET_0), and water surface evaporation measured by Φ20 pan (ET_1). The results demonstrated that among these algorithms, the Loheide method exhibited the lowest accuracy. Therefore, the Hays method is recommended for calculating daily ETg, and ET_0 is recommended for validating calculation accuracy. The Loheide method can achieve relatively high accuracy ($R=0.821$, $P<0.01$) for ETg calculation, but exhibits a significant time lag effect of approximately 3 hours. These findings provide valuable scientific support for rational allocation and sustainable development and utilization of regional water resources in the Heihe River basin.

Keywords: desert oasis; groundwater; diurnal water level fluctuation method; groundwater recharge

Introduction

Oases represent the core geographical units in arid regions. Shallow groundwater areas (groundwater depth <5-10 m) are significantly influenced by groundwater dynamics, concentrating scientific issues such as groundwater irrigation, soil water-salt balance, and ecological water levels, thereby serving as health indicators of oasis ecosystems [1]. Groundwater constitutes a crucial water source for vegetation in shallow groundwater environments, and groundwater-supported evapotranspiration (ETg) represents an important groundwater discharge pathway in arid zones [2]. Accurate ETg estimation is of great significance for groundwater-soil-plant-atmosphere continuum (GSPAC) research, ecological water demand estimation, and groundwater resource assessment, providing scientific support for rational groundwater utilization and curbing oasis ecological degradation.

Numerous environmental factors influence ETg, and the process is rather complex, making precise estimation challenging under actual conditions [3]. Existing ETg estimation methods generally fall into three categories: (1) Water balance method: calculates ETg based on water balance principles, but its accuracy is constrained by other water balance components besides ETg, and the numerous influencing factors make high-temporal-resolution ETg estimation difficult; (2) Limiting depth method: also known as empirical formula method, with the White method being the most classical, which requires satisfying four preconditions [4]; and (3) Diurnal water level fluctuation method: calculates ETg based on diurnal groundwater level fluctuation patterns, requiring only specific yield and groundwater level data (depth), without needing to consider regional soil heterogeneity and surface crop types that are difficult to quantify precisely. This method offers advantages of fewer required parameters, lower cost, and easy data availability, and has thus developed rapidly in recent years [5].

The diurnal water level fluctuation method was first proposed by White [6]. Many scholars have improved upon the "four assumptions," such as Gribovszki et al. [7] who refined groundwater recharge rate and specific yield calculations using hydraulic methods to make results more realistic; Meyboom [8] who proposed using "readily available specific yield" to replace specific yield, recommending half the specific yield value as readily available specific yield; Hays [9] who improved recharge rate estimation by dividing the water level change process into rising and falling periods to calculate recharge and consumption rates separately; Loheide [10] who introduced groundwater level superposition principle and detrending methods for specific yield calculation, enabling precise hourly ETg estimation; and Soylu et al. [11] who used Fourier transform to fit groundwater level data and establish quantitative relationships between ETg and water level amplitude, avoiding recharge rate calculation but with more complex computation. Currently, diurnal water level fluctuation methods have been rarely applied in domestic arid zone research, with insufficient investigation.

This study applies diurnal fluctuation methods to the Hexi Corridor region for the first time, using high-resolution data (hourly scale) to calculate ETg and conducting comparative analysis across four typical surface landscapes in desert-oasis areas (farmland, old oasis, shelterbelt, and desert edge). The research findings can provide scientific basis for water resource evaluation in the "Belt and Road" region, improvement of water use strategies in desert-oasis areas, and prevention of soil salinization.

1 Study Area Description

The study area is located in the desert-oasis ecotone of Linze County in the middle reaches of the Heihe River basin in the Hexi Corridor of western Gansu (99°51 -100°30 E, 38°57 -39°42 N, elevation 1304–2196 m). The region features a typical semi-arid desert steppe climate with a mean annual temperature of 7.6°C. Precipitation is scarce and seasonally distinct, with an average annual precipitation of only 110 mm and annual potential evaporation exceeding 2000 mm, yielding an aridity index of approximately 18.2 and extremely fragile ecological conditions. The terrain is high in the north and south but low in the middle. Regional groundwater is primarily recharged by river channels, with surface soil moisture mainly derived from lateral seepage of farmland irrigation and shallow groundwater recharge [12].

The study area is extensively covered by gray-brown desert soil, with corn as the main crop. Due to scarce precipitation, farmland irrigation relies primarily on river water and groundwater, resulting in shallow groundwater depth (generally 1-5 m) and serious salinization [13]. Vegetation growth is closely related to groundwater, with most being groundwater-dependent species, including *Populus gansuensis*, *Elaeagnus angustifolia*, *Caragana microphylla*, *Haloxylon ammodendron*, and *Salix mongolica* [14]. Vegetation type differences are mainly caused by variations in groundwater depth. The study area exhibits a mosaic distribution pattern of new oasis farmland (approximately 30 years) in the south, old oasis in the north, and shelterbelts (approximately 3 m width) in between [15].

2 Methods

2.1 Data Sources

Groundwater depth data were obtained from monitoring wells constructed using PVC pipes (diameter ~5 cm) installed in the study area. Groundwater depth and temperature were recorded at hourly intervals using automatic water level sensors, with atmospheric pressure compensation applied to obtain actual groundwater levels.

Meteorological data were collected from the standard meteorological observation field at the Linze Station of the Chinese Academy of Sciences (100°07 42.0 E, 39°20 59.0 N), with a temporal resolution of 1 hour. The site was leveled from fixed sand dunes, with surrounding vegetation dominated by *Haloxylon ammodendron*, *Tamarix*, and *Elaeagnus angustifolia.*

Water surface evaporation was measured using both Φ20 and E-601 evaporation pans at hourly resolution.

Soil water characteristic curves: Soil profiles were excavated at sample points, and standard ring samples (height 5 cm, volume 100 cm^3) were collected at 10 cm intervals. Soil water characteristic curves were measured in the laboratory using a high-speed refrigerated centrifuge (H-1400PF).

2.2 ETg Estimation Methods

White Method: The daily groundwater evapotranspiration is calculated as:

$$ET_g = S_y \cdot \frac{\Delta WT}{\Delta t} + r$$

where ETg is daily groundwater evapotranspiration ($\mathrm{mm \cdot d^{-1}}$); Sy is specific yield; r is groundwater recharge rate ($\mathrm{mm \cdot d^{-1}}$); and ΔWT is the daily change in groundwater depth (mm).

The method assumes: (1) During the period from midnight to predawn (T_1), ETg is very weak and can be neglected; (2) The groundwater recharge rate during this period can represent the recharge rate for the entire day [6].

Hays Method: This method divides the water level change process into falling and rising periods. The daily ETg is calculated as:

$$ET_g = S_y \cdot \left(\frac{H_1}{T_1} + \frac{H_2}{T_2} \right)$$

where H_1 is the peak-to-trough amplitude of the groundwater depth change curve between adjacent days; H_2 is the trough-to-peak amplitude; T_1 is the falling period; and T_2 is the rising period.

Loheide Method: This method involves three assumptions: (1) Groundwater depth fluctuations are caused by vegetation absorbing groundwater for transpiration and lateral groundwater flow; (2) ETg is very weak during the T_1 period; (3) The groundwater recharge rate during the T_1 period can represent the recharge rate for the entire day [10].

The detrended groundwater depth is calculated as:

$$WT_{DT} = a \cdot t + b$$

where WTDT is detrended groundwater depth; a is the slope of detrending; and b is the intercept.

The relationship between detrended groundwater depth and its change rate is established:

$$\frac{dWT_{DT}}{dt} = f(WT_{DT})$$

The recharge rate is then calculated, and ETg is obtained using:

$$ET_g = S_y \cdot \frac{dWT_{DT}}{dt} - r(t)$$

2.3 Specific Yield (Sy) Estimation

Specific yield reflects the water release capacity of aquifer media. Research has shown that when groundwater depth is <1.0 m, specific yield varies with depth (depth-dependent). When groundwater depth >1.0 m, specific yield approaches a constant value influenced only by medium particle size structure [16]. In this study, specific yield was calculated from soil water characteristic curves, which reflect regional soil properties and avoid complex uncertainties from pumping tests.

Since groundwater depth in the study area generally exceeds 1.0 m (except during irrigation periods when depth <1.0 m, which are not considered), specific yield is treated as constant. Based on soil water characteristic curves, soil water content at different potentials can be converted: soil water potential of -1/3 bar is considered field capacity (fc), and -15 bar is considered wilting coefficient (wp). Specific yield can be approximated as the difference between saturated water content and wilting coefficient (maximum available water). Following Meyboom [8], readily available specific yield (half of specific yield) was used in calculations.

2.4 Correlation Analysis

2.4.1 Potential Evapotranspiration (PET) PET represents evapotranspiration under conditions of uniform vegetation cover with sufficient water supply, equivalent to groundwater depth approaching zero. This study used the improved Penman-Monteith calculation method:

$$PET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_{hr}+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where Δ is the slope of the saturation vapor pressure-temperature curve (dimensionless); Rn is net surface radiation ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$); G is soil heat flux ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$); γ is the psychrometric constant ($\mathrm{kPa \cdot ℃^{-1}}$); Thr is hourly average temperature (℃); u_2 is average wind speed ($\mathrm{m \cdot s^{-1}}$); es is saturation vapor pressure (kPa); and ea is actual vapor pressure (kPa).

2.4.2 Pearson Correlation Analysis The Pearson correlation coefficient (R) was used to analyze correlations between different methods. The formula is:

$$R = \frac{\sum_{i=1}^{n}(a_i - \bar{a})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(a_i - \bar{a})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where ai and yi are daily values of two elements; $\bar{a}$ and $\bar{y}$ are multi-day averages; and n is sample size. Larger absolute R values indicate stronger correlation, with R>0 indicating positive correlation and R<0 indicating negative correlation.

In shallow groundwater areas, groundwater level changes are closely related to surface evapotranspiration, showing similar fluctuation trends. Therefore, correlation analysis between calculated ETg and PET (or $\mathrm{ET_0}$, $\mathrm{ET_1}$) with significance testing was used to validate calculation accuracy of the three methods [17].

3 Results

3.1 Groundwater Dynamics

Figure 4 shows precipitation and groundwater depth variation during the growing season at point L. After irrigation cessation, water levels began to decline slowly. Following irrigation events, groundwater levels rose rapidly. After a strong precipitation event (19.2 mm), groundwater showed no obvious response, indicating limited precipitation impact on groundwater fluctuations. Groundwater dynamics in the study area are primarily influenced by human factors such as irrigation, while small precipitation events have minimal impact.

Groundwater depth variation showed significant diurnal fluctuations (Figure 5). Daily maximum values typically occurred between 6:00–9:00, while minimum values occurred between 15:00–18:00. The overall trend was downward. No abrupt changes occurred (no irrigation or pumping events). Only one small precipitation event (3.6 mm) occurred on day 19, after day 15. As small precipitation events rarely generate surface runoff, their impact on ETg calculations was neglected.

3.2 Daily ETg

Due to method limitations, daily ETg was calculated for the period. To ensure representativeness, the normality of sample data was tested using the Kolmogorov-Smirnov test, confirming normal distribution ($P<0.05$). Pearson correlation analysis between daily ETg from different methods and PET showed that the Hays method performed best ($R=0.785$, $P<0.01$), followed by White ($R=0.463$, $P<0.05$), with Loheide performing worst. Therefore, for daily ETg calculation, Hays method is recommended, with ET_0 as validation data.

During the study period, ETg ranged 6-9 $mm \cdot d^{-1}$. Some days showed abnormal values, with Loheide method even producing negative ETg. This may result from noise in pressure sensors affecting detrended water level change rates, leading to mismatched signals [10].

3.3 Hourly ETg

To analyze the reasons for poor Loheide method performance, hourly ETg was calculated and correlated with hourly PET. Results showed weak but significant correlation ($R=0.463$, $P<0.01$). After time-lag processing, correlation improved significantly. When lag time was set to 2–4 hours, correlation was better ($R=0.75$, $P<0.01$), with optimal correlation at 3-hour lag ($R=0.821$, $P<0.01$) (Table 2).

Comparison across sample points revealed varying degrees of time lag under different vegetation cover conditions. Old oasis ecosystems with surface *Haloxylon* cover showed 3-hour lag, shelterbelts showed 2-hour lag, and desert edges showed 4-hour lag (Table 3). Detrended groundwater depth (WTDT) and ETg showed clear extrema, but WTDT peaks were more rounded. Signal peaks and troughs did not completely overlap temporally, with WTDT extrema lagging PET extrema by approximately 3 hours, confirming the time lag phenomenon.

4 Analysis of Calculation Results

4.1 Validation Data Selection

For validating the three methods' accuracy, ET_0 data (daily ETg) is optimal. This may relate to instrument structure—the E-601 pan has larger diameter and more scientific installation, making measured evaporation more representative. The Φ20 pan (20 cm diameter) cannot well represent regional evaporation capacity. PET is simulated data based on the Penman formula, which is semi-empirical with insufficient theoretical basis, thus having limitations as validation data.

4.2 Time Lag Relationship Between ETg and PET

The Loheide method can calculate higher-resolution ETg (hourly), but exhibits obvious time lag. After time-lag processing, calculation accuracy improves significantly and R values increase markedly. If Loheide-calculated ETg is directly correlated with PET without time-lag consideration, correlation is weak, possibly due to the method' s own limitations—detrending weakens original groundwater depth signals and masks some useful information. For similar regions, time-lag effects must be considered. Lag duration may relate to local hydrology, meteorology, soil texture, and vegetation type. In this study, different ecosystem types showed varying lag times: old oasis with *Haloxylon* cover lagged 3 hours, shelterbelts 2 hours, and desert edges 4 hours.

Time lag may result from plant water transport mechanisms: due to physiological water absorption and consumption processes, surface evapotranspiration and groundwater depth response cannot occur simultaneously. The lag time may represent the duration required for vegetation to absorb water from groundwater, transport it to the canopy for storage, and then transpire. The canopy can store substantial water, and this water storage reflects the time lag between vegetation transpiration and root water absorption [18]. Additionally, soil water movement (upward) in the unsaturated zone also exhibits time lag [19].

4.3 Uncertainty Analysis

Methodological uncertainty: The Hays method selects recharge and consumption periods based on natural characteristics of groundwater depth change curves, avoiding human selection of ETg periods and being closer to reality, thus achieving higher accuracy. The White method involves manual selection of periods, introducing some limitations. The Loheide method can calculate higher-resolution ETg, but detrending weakens some original groundwater depth signals, masking useful information.

Data uncertainty: Instrument and sensor installation and automatic monitoring affect data collection (noise). Both simulated (PET) and measured data contain noise, impacting results [10]. Groundwater depth magnitude and change rate directly affect soil specific yield, which varies constantly with obvious diurnal fluctuations. When water level rise/fall rates are high, Sy is not constant, but is treated as constant in calculations, introducing transient errors.

Study period selection: Typical study periods must exclude large precipitation events, groundwater pumping, and irrigation events, which constrain period selection and reduce available sample data, affecting results.

5 Conclusions

Based on the above analysis, the following conclusions are drawn:

1. All three methods are applicable in the middle reaches of the Hexi Corridor. The Hays method, which naturally selects recharge and consumption periods based on groundwater depth change curve characteristics, performs best and is closest to reality. The White method involves manual period selection with certain limitations. The Loheide method can calculate higher-resolution ETg but requires consideration of time-lag effects.
2. When applying the Loheide method to similar regions, time-lag effects must be considered. In this study area, ETg lags PET by approximately 3 hours.
3. Using well-structured and scientifically installed ET_0 measured data to validate the three methods' daily ETg calculations yields reliable results.
4. Specific yield values directly affect calculation results, making appropriate Sy selection crucial. For this study area, specific yield is considered constant and can be calculated from soil water characteristic curves.

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