Evapotranspiration Partitioning and Control Mechanisms in the Nanxiaohegou Watershed Based on an Improved S-W Model (Postprint)

Authors: Yang Nan, Song Xiaoyu, Deng Jianwei, Li Lanjun, Zhao Xinkai, Meng Pengfei, Fu Chong, Wei Wanyin, Zhang Yubin, Ding Lin, Li Haolin

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Abstract

Accurately quantifying evapotranspiration (ET) and its components and identifying their controlling factors is conducive to the rational evaluation and planning management of regional water resources. Based on continuous long-term observation data and field experiments from 2016–2020 in the Nanxiaohegou watershed, a typical small watershed for soil and water conservation management in the Loess Plateau, the improved S-W (Shuttle worth-Wallace) model was employed to simulate the dynamic variations of ET and its components in typical artificial forest land, and Structural Equation Modeling (SEM) was utilized to analyze the coupling relationships between plant transpiration (T), soil evaporation (E), and controlling factors. The results indicate that: (1) The improved S-W model demonstrates good applicability in the Nanxiaohegou watershed, wherein the threshold value of soil surface resistance (r ss) ranges from 50~2500 s·m-1, the empirical function type with soil surface water content ( ) is exponential, and the linear slope increases with greater sand content in soil particles. (2) The ET range for typical artificial forest land is 276.76~402.86 mm, with multi-year averages of T and E accounting for 51.6% and 48.4% of ET, respectively. The temporal patterns of ET, T, and E exhibit no significant inter-monthly variation but show intense daily fluctuations; the fluctuation trends of T and E are basically consistent, aligning with annual rainfall variation while demonstrating hysteresis in response to individual rainfall events. (3) SEM analysis reveals that net radiation (Rn), air temperature (Ta), and exert the most significant influences on ET, with Rn having the greatest impact on T (total effect = 0.614) and Ta having the greatest impact on E (total effect = 0.426); T exhibits a positive correlation with E, with a contribution coefficient reaching 0.503. Evaluating ET and separating its components based on the improved S-W model provides a basis for profoundly revealing eco-hydrological processes in arid and semi-arid regions.

Research on the Distribution and Control Mechanism of Evapotranspiration in the Nanxiaohegou Watershed Based on an Improved S-W Model

YANG Nan[1], SONG Xiaoyu[2], DENG Jianwei[1], LI Lanjun[2], ZHAO Xinkai[2], MENG Pengfei[2], FU Chong[2], WEI Wanyin[2], ZHANG Yubin[1], DING Lin[1], LI Haolin[3]

[1]Gansu Academy for Water Conservancy, Lanzhou, Gansu 730000, China
[2]State Key Laboratory of Eco-Hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an, Shaanxi 710048, China
[3]Beijing University of Technology, Beijing 100124, China

Abstract: In this study, we aimed to accurately quantify evapotranspiration (ET) and its components while exploring the factors that control it, which will facilitate the practical evaluation, planning, and management of regional water resources. Utilizing continuous long-term observation data and field tests conducted from 2016 to 2020 in the Nanxiaohegou watershed—a typical small watershed for water and soil conservation on the Loess Plateau—this study simulated the dynamic changes of ET and its components in typical plantation land using the improved Shuttleworth-Wallace (S-W) model. Additionally, we analyzed the coupling relationships between plant transpiration (T), soil evaporation (E), and control factors using a structural equation model. The results revealed the following: (1) The modified S-W model was effective for evaluating ET and its components in Nanxiaohe Valley. The threshold value of soil surface resistance (r_{s_s}) was 50~2500 $s \cdot m^{-1}$, exhibiting an exponential relationship with the empirical function of soil surface water content ( ); moreover, higher sand content in the soil particles correlated with a steeper linear slope. (2) ET ranged from 276.76 mm to 402.86 mm in typical plantation land, with annual averages of T and E accounting for 51.6% and 48.4% of ET, respectively. While monthly ET, T, and E patterns were not pronounced, daily fluctuations were significant. The fluctuation trends of T and E largely reflected annual precipitation patterns but lagged behind rainfall. (3) Structural equation modeling analysis revealed that net radiation (Rn), temperature (Ta), and exerted the most significant effects on ET, with Rn having the largest impact on T (total impact of 0.614) and Ta having the most significant impact on E (total impact of 0.426). T was positively correlated with E, with a contribution coefficient of 0.503. Evaluating ET and its components using an improved S-W model establishes a foundation for a deeper understanding of ecological and hydrological processes in arid and semiarid regions.

Keywords: evapotranspiration components; improved S-W model; evaporation resistance; Nanxiaohegou watershed

Introduction

Evapotranspiration (ET) is an indispensable component of the hydrological cycle and a critical part of water and energy balance in ecosystems, particularly in the Loess Plateau region where ET accounts for the majority of water loss from the system. ET serves as a key indicator for both plant water requirements and water resource assessment, as well as drought monitoring. Its two components—plant transpiration (T) and soil evaporation (E)—are governed by distinct biological and physical processes with different dominant factors. Therefore, accurately simulating ET and its components and investigating the control mechanisms of ET partitioning are essential for efficient planning, management, and utilization of water resources in the Loess gully region.

Currently, mathematical modeling represents the primary method for ET assessment. The Penman-Monteith model is widely applied due to its simple structure, strong adaptability, and cost-effectiveness, especially in areas with complex topography. However, this model cannot separate ET components. The Shuttleworth-Wallace (S-W) model has emerged as a superior alternative because it captures the physical processes with relatively few parameters that have clear physical meaning and high simulation accuracy. The improved S-W model can address the calculation of soil surface resistance for different soil textures and has proven effective for ET partitioning in arid and semi-arid regions.

Regarding the control mechanisms of ET partitioning and the relationships among influencing factors, scholars have primarily employed traditional statistical methods such as comparing pairwise correlation coefficients or using multiple regression analysis. These approaches only examine relationships between one or multiple independent variables and a single dependent variable, cannot analyze multiple independent variables against multiple dependent variables simultaneously, and often overlook autocorrelation between independent and dependent variables, leading to inconsistent or even contradictory results. In recent years, Structural Equation Modeling (SEM) has emerged as an effective solution to these limitations. SEM can fully consider correlations among independent variables while distinguishing their effects on dependent variables, and has been widely applied in economics and ecology. However, its application in hydrological process analysis remains limited.

The Nanxiaohegou watershed serves as a typical prototype observation watershed in the Loess gully region. Based on continuous long-term observation data and field experiments from typical plantation land within the watershed, this study quantified and dynamically evaluated ET and its components using an improved S-W model, and analyzed their control mechanisms using SEM. This approach clarifies the response processes between ET components and control factors, providing a reference for reasonably estimating plant water requirements, improving water use potential, and conducting drought monitoring and assessment in the Loess Plateau gully region.

1. Materials and Methods

1.1 Study Area

The study area is located in the Nanxiaohegou watershed within Xifeng District, Qingyang City, Gansu Province (35°40 43 ~35°44 58 N, 107°30 8 ~107°37 52 E), covering an area of 38.7 km^2. Established in 1954 by the Xifeng Soil and Water Conservation Experimental Station of the Yellow River Conservancy Commission, this watershed serves as a typical prototype observation site in the Loess gully region [Figure 38: see original paper]. The area features typical Loess Plateau gully geomorphology, primarily comprising three types: tableland surfaces, ridge slopes, and valley bottoms. The watershed has a simple geological structure with sandy loam soil that is highly erodible and prone to water and soil loss. In recent years, extensive soil and water conservation efforts on the Loess Plateau have significantly increased vegetation coverage in the watershed. Dominant vegetation types include artificial forests of locust (*Robinia pseudoacacia*), oriental arborvitae (*Platycladus orientalis*), Chinese pine (*Pinus tabuliformis*), Siberian apricot (*Armeniaca sibirica*), and alfalfa (*Medicago sativa*).

1.2 Data Sources and Processing

Three sample plots of mixed artificial forests with relatively uniform tree age and good growth conditions were selected, including locust, oriental arborvitae, and Chinese pine. Field experiments and observations were conducted in these plots from 2016 to 2020. Observation parameters primarily included meteorological elements, soil water content, soil evaporation, vegetation leaf area index, etc. Plant parameters were represented by mean values, with specific tree species details provided in Table 1 .

1.2.1 Meteorological Data Meteorological data were collected using three small field meteorological stations (Watchdog Series 2000, China) powered by solar energy. Observed parameters included wind speed, wind direction, air temperature, humidity, total radiation, and precipitation. The stations were installed in open areas near the three sample plots with a 30-minute observation interval, with results converted to daily scale data for subsequent analysis and calculation. To prevent data loss and distortion, the meteorological stations were inspected and maintained approximately every week. Missing data points were replaced using data from the nearest meteorological station.

1.2.2 Soil Moisture Soil water content was measured using Trime TDR (Time Domain Reflectometry) tubes. In each of the three sample plots, three measurement points were established at locations representing 1-3 times the average canopy radius, totaling nine tubes. During installation, disturbance to the original forest soil was minimized. Soil moisture was measured at depths of 0-2 m, with 20 cm intervals in the 0-1 m layer and 10 cm intervals in the 1-2 m layer. To reduce error, observations were conducted between 8:00-11:00 AM each day, with three measurements taken at each depth and averaged. Additional measurements were taken after each rainfall event.

1.2.3 Soil Evaporation Soil evaporation was measured using micro-lysimeters in the three sample plots, with three measurement points per plot totaling nine tubes. During installation, a soil hammer was used to drive a 25 cm long, 16 cm diameter cylinder into the ground. The intact soil core was then carefully extracted, wrapped with gauze at the bottom, and placed back in position, ensuring the soil surface inside the micro-lysimeter remained level with the tube opening. Vegetation on the soil surface was removed. A wire handle was attached to the top for convenient observation. Measurements were taken daily between 1-3 PM using a precision electronic balance (0.01 g accuracy). The difference between two consecutive weighings represented soil evaporation over the measurement period. To ensure measurement accuracy, soil was replaced every 7-10 days, maintaining the same mass as the previous observation.

1.2.4 Leaf Area Index Leaf Area Index (LAI) was measured using a plant canopy observation system (Winscanopy 2006, Canada). In each of the three sample plots, three fixed observation points were established. After leveling the tripod, a fisheye camera was used to capture representative canopy images, which were processed using Winscanopy software to obtain LAI values. Observations were conducted every 4-7 days, with mean values calculated.

1.3 Research Methods

1.3.1 Shuttleworth-Wallace Model The Shuttleworth-Wallace model incorporates canopy resistance and soil resistance parameters, treating evapotranspiration as originating from two "sources": soil evaporation and plant transpiration. The total water vapor source can be expressed as latent heat flux λE, calculated as:

$$\lambda E = C_s PM_s + C_c PM_c$$

where:

$$PM_s = \frac{\rho C_p D}{...}$$

$$PM_c = \frac{\rho C_p D}{...}$$

In these equations: - ET is the simulated evapotranspiration $(\mathrm{MJ \cdot kg^{-1}})$ - λ is the latent heat of vaporization of water $(\mathrm{MJ \cdot kg^{-1}})$ - PM_s is the simulated soil evaporation - PM_c is the simulated plant transpiration - C_s and C_c are proportion coefficients for soil evaporation and plant transpiration - r_{s_s} is soil surface resistance ($\mathrm{s \cdot m^{-1}}$) - r_{c_s} is canopy stomatal resistance ($\mathrm{s \cdot m^{-1}}$) - r_{s_a} is aerodynamic resistance from leaf surface to canopy height ($\mathrm{s \cdot m^{-1}}$) - r_{c_a} is aerodynamic resistance from canopy height to reference height ($\mathrm{s \cdot m^{-1}}$) - r_{a_a} is aerodynamic resistance for latent heat from canopy height to reference height ($\mathrm{s \cdot m^{-1}}$) - Δ is the slope of the saturation vapor pressure curve ($\mathrm{kPa \cdot °C^{-1}}$) - is air density ($\mathrm{kg \cdot m^{-3}}$) - C_p is specific heat capacity of air - γ is the psychrometric constant ($0.67\ \mathrm{hPa \cdot k^{-1}}$) - R_n is net radiation ($\mathrm{W \cdot m^{-2}}$) - R_s is radiation absorbed by soil ($\mathrm{W \cdot m^{-2}}$) - G is soil heat flux ($\mathrm{W \cdot m^{-2}}$) - D is vapor pressure deficit (kPa)

The radiation components are calculated as:

$$R_s = R_n \exp(-C \cdot LAI)$$

$$R_c = R_n - R_s$$

where C is the extinction coefficient (value 0.46).

1.3.2 Structural Equation Model Structural Equation Modeling (SEM) is a statistical method based on covariance matrix analysis that simultaneously examines causal relationships among multiple variables. It integrates factor analysis and path analysis to establish, estimate, and test causal models, while analyzing the total, direct, and indirect effects of independent variables on dependent variables. SEM is suitable for studying complex interrelationships among multiple variables. Parameters are typically estimated using maximum likelihood estimation, whose fitting function follows a ^{2} distribution; thus, ^{2} tests are commonly used to evaluate model performance in SEM. In this study, we used Amos 24 software to analyze the control mechanisms of plant transpiration (T) and soil evaporation (E), adjusting and refining the model based on test results.

1.4 Improved Parameter Calculation

The core of the improved S-W model lies in the calculation and validation of five resistance parameters: r_{s_s}, r_{c_s}, r_{s_a}, r_{c_a}, and r_{a_a}. Based on previous research and the actual conditions of the study area, methods for calculating r_{s_a}, r_{c_a}, and r_{a_a} are well-established. This study continued to use the original model formulas from reference [10] for these three parameters. The r_{c_s} and r_{s_s} parameters were calculated using methods recommended by other scholars, as detailed below.

1.4.1 Canopy Stomatal Resistance Canopy stomatal resistance (r_{c_s}) can be expressed as a function of solar radiation, vapor pressure deficit, air temperature, and soil water content:

$$r_{c_s} = r_{c_{min}} \cdot f_1(R_s) \cdot f_2(D) \cdot f_3(T_a) \cdot f_4(\theta)$$

where: - r_c_{min} is minimum canopy stomatal resistance - R_s is shortwave radiation absorbed by plants - D is vapor pressure deficit - T_a is air temperature - is soil water content

1.4.2 Soil Surface Resistance Soil surface resistance (r_{s_s}) regulates water vapor movement from within the soil to the surface and shows strong dependence on upper soil moisture. Research indicates that r_{s_s} and soil surface water content have functional relationships, including linear [25], exponential [23], and power function [26] forms.

1.5 Model Evaluation

The purpose of model evaluation is to determine whether the model meets research requirements. This study used Root Mean Square Error (RMSE), coefficient of determination (R^2), and Nash-Sutcliffe Efficiency coefficient (NSE) to evaluate model simulation accuracy. Calculation formulas and evaluation criteria are detailed in reference [21].

2. Results

2.1 Model Performance

2.1.1 Model Validation Monthly meteorological and observation data from 2016-2018 were used for parameter calibration, while 2019-2020 data were used for model validation. Based on the original model formulas for r_{s_a}, r_{c_a}, and r_{a_a} parameters and the revised calculations for r_{c_s} and r_{s_s} parameters, soil evaporation simulations were conducted. The results are shown in Figure 2 [Figure 2: see original paper]. The improved S-W model demonstrated good performance in simulating soil evaporation, with small differences between measured and simulated values. Model accuracy evaluation metrics were RMSE = 0.16 $\mathrm{mm \cdot d^{-1}}$, R^2 = 0.83, and NSE = 0.81. All evaluation indices fell within reasonable ranges, indicating that parameter calculations were appropriate and that the improved S-W model is suitable for simulating typical plantation land in the Nanxiaohegou watershed.

2.1.2 ET and Component Dynamics Daily-scale simulations of ET and its components were conducted for typical plantation land in the Nanxiaohegou watershed (Figure 3 [Figure 3: see original paper]). Results showed that during the experimental period, ET, plant transpiration, and soil evaporation exhibited minimal monthly variation but significant daily fluctuations, with T and E showing largely consistent fluctuation patterns. Simulated ET ranged from 276.76 to 402.86 mm, with soil evaporation of 134.26-167.08 mm (daily average 0.34-2.10 $\mathrm{mm \cdot d^{-1}}$) and plant transpiration of 142.26-239.12 mm (daily average 0.14-3.40 $\mathrm{mm \cdot d^{-1}}$). Maximum values of ET, T, and E generally occurred in mid-year, with noticeable declines after mid-August when plant transpiration approached or even fell below soil evaporation. Statistics showed that during the growing season, the daily T/ET ratio ranged from 40.2% to 58.5%, while the E/ET ratio ranged from 41.5% to 59.8%. The response of ET, T, and E to rainfall showed consistent interannual trends with precipitation but exhibited temporal lag at the event scale. ET, T, and E amounts followed the pattern: wet year (2018) > normal year (2019) > dry year (2020). Influenced by heavy rainfall events (>20 mm), phase peaks of ET, T, and E showed temporal lag relative to individual rainfall events.

2.2 Control Factors of Plant Transpiration and Soil Evaporation

Previous studies have identified leaf area index, soil surface water content, and vapor pressure deficit as primary factors influencing plant transpiration and soil evaporation. Combining these with parameters calculated from the S-W model, we conducted a control factor analysis for T and E. Six indicators were selected as independent variables: leaf area index, soil surface water content, vapor pressure deficit, air temperature, wind speed at reference height, and net radiation. Plant transpiration and soil evaporation served as dependent variables. Using Amos 24 software, we analyzed the control mechanisms based on Structural Equation Modeling (SEM). The initial hypothetical model is shown in Figure 4 [Figure 4: see original paper].

2.2.1 Model Fit Assessment After initial model runs, paths that did not achieve significance or had small coefficients were removed to obtain the revised model (Figure 4 [Figure 4: see original paper]). Standardized coefficients and significance levels for initial and revised models are shown in Table 2 . The revised model demonstrated excellent fit, with both absolute and incremental fit indices meeting established criteria (Table 3).

2.2.2 Control Factor Effects The model explained 79.1% of variance in plant transpiration and 61.3% of variance in soil evaporation. Plant transpiration showed a positive correlation with soil evaporation (path coefficient = 0.503), with E increasing as T increased. Among all control factors, net radiation had the greatest total impact on plant transpiration (0.614), followed by air temperature, soil surface water content, leaf area index, and wind speed at reference height. All control factors exerted direct effects on plant transpiration. Air temperature had the largest total impact on soil evaporation (0.426), while factors other than vapor pressure deficit and air temperature showed indirect effects on soil evaporation.

3. Discussion

3.1 Parameterization of Soil Surface Resistance

Due to regional differences in soil type and texture, numerous factors affect r_{s_s}, making it difficult to determine through unified methods and necessitating empirical formula estimation. Previous studies have shown that empirical relationships between r_{s_s} and   include linear [25], exponential [23], and power function [26] forms. Through fitting the functional relationship between r_{s_s} and , this study determined that an exponential function best represents the Nanxiaohegou watershed (Figure 5 [Figure 5: see original paper]), where r_{s_s} increases as   decreases. This occurs because reduced   decreases the water vapor pressure gradient between soil interior and surface, slowing vapor transfer and increasing r_{s_s}. Comparative analysis revealed that higher sand content in soil particles leads to more pronounced exponential relationships between r_{s_s} and , with larger sand content yielding larger exponential coefficients. This finding provides a reference for empirical r_{s_s} estimation in other regions.

3.2 ET Component Ratios

Evapotranspiration is a crucial process in ecosystem water balance and energy exchange, closely related to ecosystem productivity. Previous studies have shown that the T/ET ratio during the growing season typically ranges from 60% to 80%. However, the T/ET ratio in this study area was relatively low (average 51.6%), likely resulting from combined effects of local soil moisture, topography, climate conditions, and vegetation type. Located in an arid to semi-arid climate zone with complex topography including tablelands, slopes, and gullies, the study area features coniferous artificial forests. Compared to regions with diverse, high-coverage broadleaf forests or grasslands, soil evaporation consumption is greater and plant transpiration proportion is relatively lower, indicating substantial potential for improving plant water use efficiency in the Nanxiaohegou watershed.

3.3 SEM Model Insights

Traditional studies on control factors of plant transpiration and soil evaporation have focused solely on direct effects, often neglecting interactions between T and E as well as among control factors themselves. Using SEM, this study examined the effects and path contributions of six control factors on T and E, while analyzing interrelationships among these factors. Results showed that net radiation, air temperature, and soil surface water content were the most important ET control factors, with net radiation having the greatest impact on plant transpiration. The six selected factors explained 61.3% of variance in soil evaporation, leaving a relatively large unexplained proportion, suggesting that soil evaporation may involve more complex processes and influencing factors than plant transpiration. Plant transpiration showed a positive correlation with soil evaporation (contribution coefficient = 0.503), indicating that vegetation effects on soil evaporation exceed meteorological effects. Air temperature had the largest total impact on soil evaporation (0.426), while soil surface water content had a total impact of 0.162. This suggests that appropriate soil surface water content may be a prerequisite for temperature to become the dominant control factor of soil evaporation under vegetation interference. The SEM model also revealed correlations among the six control factors, with soil surface water content showing the highest correlations (all negative) with the other five factors, particularly with net radiation (correlation coefficient = -0.52).

4. Conclusion

Based on multi-year field experimental data from the Nanxiaohegou watershed, this study applied the improved S-W model to quantify and dynamically simulate ET, T, and E in typical plantation land. The improved S-W model demonstrated good applicability in this region, with average annual ET of 320.24 mm. T and E accounted for 51.6% and 48.4% of ET, respectively, indicating relatively high soil evaporation and low plant water use efficiency, suggesting substantial potential for improving plant water uptake in the study area. Additionally, SEM analysis revealed the controlling effects of multiple meteorological factors on T and E and their interactions. Net radiation had the greatest impact on T, while air temperature most significantly affected E. Vegetation effects on ET exceeded meteorological factor effects. Plant transpiration positively correlated with soil evaporation, while soil evaporation involved more complex processes and influencing factors than transpiration. Due to variations in soil type and texture, r_{s_s} parameters cannot be determined through unified methods. For this study area, soil surface resistance followed the relationship r_{s_s} = 1.197 + 306exp(- / _{sat}). Comparative analysis showed that higher sand content in soil particles leads to more pronounced exponential relationships with larger exponential coefficients, providing a reference for empirical r_{s_s} estimation in other regions.

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Additional references from the Chinese text have been omitted for brevity while preserving the core citation structure.

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