Analysis of the soil water balance for large-scale reforestation with *Eucommia ulmoides* in the hilly red soil region of southern China

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Abstract Returning farmland to forests is important for the protection of ecological values. *Eucommia ulmoides* is considered to be a suitable species for reforestation in the hilly red soil region of southern China. The objective of this study was to investigate the relationship between the water supply and demand of an *E. ulmoides* plantation to provide insights into the feasibility of large-scale planting for ecological restoration and forest management activities in the hilly red soil region of southern China. With the measured precipitation, surface runoff and interflow and actual evapotranspiration (ET_c) estimated by the modified P–M model, soil water storage (SWS) was estimated based on the water balance equation. Monthly variations of SWS were then compared with in situ measured SWS. The results showed that the estimated mean monthly water losses (the sum of the surface runoff, interflow and ET_c) were 139.8 mm in a wet year and 120.0 mm in a dry year, while the measured mean monthly water input values (net precipitation) were 131.2 mm in a wet year and 70.8 mm in a dry year. Net soil water storage (ΔSWS) was negative in each month of the growing season in a dry year, but the soil water deficit was replenished during the following

season. The model performance showed that the modified P–M model can be adapted to estimate the soil water storage in other forest catchments where no adequate in situ data are available. As a result of estimating the water balance and observing soil water storage in two different hydrological years, *E. ulmoides* is recommended as a suitable forest rehabilitation species in the study area, and a suitable plant region has been defined by the GIS technique based on the water balance model.

Keywords Soil water content · Soil water balance · Modified P–M model · Effective precipitation · Actual evapotranspiration · Suitable plant region

Introduction

Rapid human population increases have placed heavy pressure on productive soil resources, with the increasing conversion of forest areas on sloping land being into cropland in the hilly red soil region of southern China. The destruction of natural broadleaf deciduous forests that has occurred since the 1950s has led to very serious soil and water erosion in southern China (Zhang et al. 2004), leading to an increase in the scale and severity of soil erosion and water loss over ten provinces in this region, covering 2.18×10^6 km², which is now known as the ‘red desert of southern China’ (Zhao 2002). Meanwhile, the distribution of rainfall and solar thermal resources is uneven in the subtropical hilly red soil region of southern China, which causes frequent seasonal droughts. Generally, seasonal drought in this area coupled with high temperatures and large evapotranspiration has significant impacts on agriculture, the fruit industry and product quality (Wang 1997; Chen and Zhang 2002; Xiao et al. 2008). There are

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two typical seasonal drought periods: One is the period from July to August, which is coupled with high temperature, and the other is the period from September to October, which is coupled with little rainfall. The probability of the occurrence of a drought is over 85 %, and the detrimental influence on agriculture and forestry is gradually aggravated (Huang et al. 2004).

The policies of ‘Returning Farmland to Forests’ in the middle and lower reaches of the Yangtze River have resulted in the replanting of sloping land with Chinese red pine (*Pinus massoniana* L.), Eucommia tree (*Eucommia ulmoides* L.), tung tree (*Vernicia fordii* L.), Chinese fir (*Metasequoia glyptostroboides* Hu and Cheng), tea oil (*Camellia oleifera* Abel) and other tree species. In a few areas, fallow farmlands have been left to undergo natural succession into secondary forest (Zheng et al. 2008). To mediate soil erosion and water loss in the hilly red soil region, great efforts have been made since the 1980s to stabilize the land surface and to retain precipitation in the soils by planting trees and crops. Furthermore, the ecological values in this typical subtropical monsoon climate area need to be restored and economic productivity maintained or improved to sustain the population. *E. ulmoides* has been considered for reforestation both for its hydrological effects and for its economic benefits. *E. ulmoides* is an important economic tree species, with important benefits to industry (Lin et al. 2007) and to curatorial trading (Hu and Wang 2001; Lee et al. 2005), and it has been used as a representative species in ‘the Yangtze River Protection Forest’ since 1989 (Li et al. 2003).

However, the hydrological effects of *E. ulmoides* are still unclear, including how it influences the spatial and temporal dynamics of soil moisture, how it adapts to the

drought stress and how it influences the processes of runoff and soil erosion. Therefore, it is necessary to analyze the ecological suitability of *E. ulmoides* as a representative afforestation species in the hilly red soil region of southern China. Some studies analyzed agricultural land use suitability based on soil properties by using the GIS technique (Kalogirou 2002; Bandyopadhyay et al. 2009; Akinc et al. 2013). Walke et al. (2012) analyzed the suitable black soil region for cotton based on a soil suitability evaluation by using the GIS-based multi-criteria overlay technique. However, we believe that water supply and demand are the prerequisite key factor for ecological restoration. In this study, we considered water supply and demand as the main factor for defining a suitable planting region for *E. ulmoides*. Through our research work, we attempted to (1) investigate the hydrological effects of *E. ulmoides* plantations and (2) provide insights into the feasibility of the large-scale planting of this species for ecological restoration and water management.

Materials and methods

Study area

The experiments were conducted at the Ecological Benefit Monitoring Station of the Yangtze River Protection Forest, which is located in the Nü'er'zhai catchment in Cili county (29°26' N, 111°13' E), Hunan Province, China (Fig. 1). The station covers approximately 2.81 km² of rugged hilly terrain ranging from 210 to 917 m above sea level. The climate is subtropical humid monsoonal. The annual mean precipitation is 1353.9 ± 307.0 mm (1970–2009), and

Fig. 1 Map A marks the distribution region of the red soil in China, and map B shows the distribution of meteorological station and the location of study site in Hunan Province

over 57.5 % of the gross precipitation falls between April and July. The average monthly air temperature ranges from -1.0 to 38.1 °C, with a mean annual temperature of 16.7 °C. The predominant arenaceous red soil, which developed on shale and sandstone parent material with silt texture, was classified as a fine loamy, hyperthermic, acidic, Udic Cambisol in the Chinese Soil Taxonomy (Gong 1999; a Haplic Alisol in the FAO Taxonomy).

Experimental design and sampling

Three rectangular experimental sites (parallel to the contour line at 20 m and vertical to the contour at line 50 m) were selected to measure runoff. These sites were situated on an uphill mesoslope and downhill of an *E. ulmoides* plantation on a 26.7 % east-facing slope. The *E. ulmoides* plantation was established in 1989 at a planting rate of 2422 trees per hectare. The mean tree height and mean diameter at breast height were 9.7 m and 7.5 cm, respectively, in 2009. There was a (10 ± 2) % coverage of shrubs and a (25 ± 6) % coverage of some grass species, including *Camellia oleifera*, *Dicranopteris pedata*, *Artemisia annua*, *Flos lonicerae* and *Lonicera japonica*. The LAI was measured by a plant canopy analyzer (LAI-2000). The growing season of *E. ulmoides* is from mid-March to early November. *E. ulmoides* begins to sprout in mid-March, and the leaf area index (LAI) is assumed to be zero at this time.

A weather station was located approximately 50 m from the experimental plots. Meteorological observations included atmospheric pressure, precipitation, evaporation (measured by a pan of the E-601 type), wind speed and direction, sunshine hours, air temperature and dew point temperature, relative humidity and soil surface temperature (0–25 cm). Dew point temperature was monitored by a dew thermometer (type: DM-70, made in China). Measurements were taken from January 2009 to December 2010, and the rainfall amount was 1616 mm in 2009 and 1232 mm in 2010. In this study, we adopt meteorological data measured at three meteorological stations near the study region to analyze the precipitation regime using serious precipitation statistical analysis. The results showed that precipitation ranged from 941.5 to 2282.5 mm, with a mean value of 1378.0 ± 274.5 mm, during years from 1960 to 2009. The precipitation anomaly rate in 2009 and 2010 was 17.3 and -10.6 %, respectively. The precipitation accumulated frequency of annual precipitation over 1600 and 1150 mm was 20 and 76 %, respectively, during the recent 50 years. In general, when the precipitation anomaly rate falls into the interval of -10 to 10 %, the precipitation is regarded as normal in humid regions. In addition, according to the local forestry managerial experience, when the annual precipitation was less than

1200 mm, there were different levels of drought. In terms of the experience, we regarded 2009 as a wet year and 2010 as a dry year.

A 20 (parallel to the contour line) $\times$ 5 m (vertical to the contour line) runoff plot, fenced by a 30-cm-high dike, was established at each experimental site, and a pond of $1 \text{ m}^2 \times 1 \text{ m}$ volume collected surface runoff at the downstream end of each plot. To collect interflow, we installed an iron sheet (thickness of 0.2 cm, width of 5 m and height of 160 cm) vertical with the surface to cut off the interflow from the upslope upstream of each plot. Meanwhile, we installed another iron sheet 30 cm under the surface at the downstream end of each plot to conflux interflow of the runoff plot into a pond of $1 \text{ m}^2 \times 1 \text{ m}$ volume. The surface runoff depth was measured after each rainfall event, while the interflow depth was measured after each rainfall event and the following 3 days. In this study, we used the sum of the surface runoff and interflow generated during each rainfall event as the output (R) in the water balance equation.

The volumetric soil moisture was measured in situ using a calibrated delta-T3 theta probe (made in Germany) based on time domain reflectometry (TDR) at approximately weekly intervals during January in 2009 to December in 2010, providing a spectrum of soil water moisture conditions ranging from the dry season to the wet season. At each experimental site, we installed four wave guides at 10-m intervals along the slope aspect to measure the soil water content at seven layers ranging from 0 to 140 cm soil depth at 20-cm intervals. The mean soil moisture content for the 12 wave guides was computed as the soil water content at each depth at the sample site. Soil chemical and physical characteristics are shown in Table 1.

Description of the modified P–M model

The reference evapotranspiration (ET_0) of the plant canopy, litter and soil layers can be approximately simulated with the modified Penman–Monteith model recommended by ‘FAO Irrigation and drainage paper 56’ (Allen et al. 1998; Zhao et al. 2004). The model is described in Eq. (1–4):

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

$$R_n = (1 - \alpha) \left(0.25 + 0.5 \frac{n}{N} \right) R_s - \left(0.9 \frac{n}{N} + 0.1 \right) (0.34 - 0.14\sqrt{e_a}) \sigma (T + 273)^4 \quad (2)$$

$$R_s = \frac{24 \times 60}{\pi} \times 0.0820 \times d_r \cdot (\omega_s \cdot \sin(\varphi) \sin(\delta) + \cos(\omega) \cos(\delta) \sin(\omega_s)) \quad (3)$$

Table 1 Average soil properties in the *E. ulmoides* plantation in 2009

Soil property	Mean value
Soil texture of 0–40 cm soil layer	
Clay, % weight (<0.002 mm)	22.5
Silt, % weight (0.05–0.002 mm)	48.1
Sand, % weight (0.05–2 mm)	29.4
Bulk density of 0–40 cm soil layer (g/cm ³)	1.56
Field water-holding capacity (%)	
Soil depth 0–20 cm	22.7
Soil depth 20–40 cm	15.9
Soil depth 40–60 cm	14.8
Soil depth 60–80 cm	15.2
Soil depth 80–100 cm	14.9
Soil depth 100–120 cm	14.6
Soil depth 120–140 cm	14.0
Wilting point of 0–100 cm soil layer (gravimetric; %)	8.8
Total porosity of 0–100 cm soil layer (%)	42.7
Infiltration rate (mm/min)	1.14
Organic matter (g/kg of dry soil)	10.8

Data source ecological benefit monitoring station of the Yangtze River protection forest, Hunan Province

$$G = C_s d_s \frac{T_2 - T_1}{\Delta t} \quad (4)$$

where ET_0 is the reference evapotranspiration (mm/day), R_n is the net radiation at the crop surface [$\text{MJ}/(\text{m}^2 \cdot \text{day})$], G is the soil heat flux density [$\text{MJ}/(\text{m}^2 \cdot \text{day})$], T is the mean daily air temperature at 2 m height ($^{\circ}\text{C}$), u_2 is the wind speed at 2 m height (m/s), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve (kPa/ $^{\circ}\text{C}$), γ is the psychrometric constant (kPa/ $^{\circ}\text{C}$), n is the bright sunshine hours (h) per day, N is the total day length (h), R_s is the extraterrestrial radiation [$\text{MJ}/(\text{m}^2 \cdot \text{day})$], σ is the Stefan–Boltzmann constant [$4.903 \times 10^{-9} \text{ MJ}/(\text{m}^2 \cdot \text{K}^4 \cdot \text{day})$] and α is the reflection coefficient. In this study, the value of α was defined as 0.19 for the *E. ulmoides* plantation. The parameter d_r is the inverse relative distance Earth–Sun, ω_s is sunset hour angle (rad), φ is latitude (rad) and δ is solar declination (rad). T_2 is the temperature at the end of the period considered ($^{\circ}\text{C}$), T_1 is the temperature at the beginning of the period considered ($^{\circ}\text{C}$), Δt is the length of the period (days), c_s is the soil heat capacity [$1.224 \text{ MJ}/(\text{m}^3 \cdot ^{\circ}\text{C})$] for arenaceous yellow soils in southern China and d_s is the estimated effective soil depth. The effective soil depth was typically 25 cm in the study area. This equation has been widely used to analyze the relationship between transpiration and canopy properties and meteorological conditions (Shuttleworth 1993).

In this study, we adopted the single crop coefficient approach recommended by ‘FAO Irrigation and drainage paper 56’ (FAO 56) to calculate ET_c for the *E. ulmoides* plantation (Allen, et al. 1998). We chose a walnut orchard as the reference object, considering the distribution area, canopy type, leaf shape, stem and branch structure and growth stage. The total growth stage of *E. ulmoides* was divided into four periods (initial, developmental, middle and end stages), and the lengths of the four development stages were 20, 10, 130 and 30 days, respectively. The crop coefficients for the initial stage (K_{cini}), middle stage (K_{cmid}) and end stage (K_{cend}) were 0.60, 1.20 and 0.75, respectively. The crop coefficient should be revised based on local meteorological data according to Eqs. (5–6). Thus, the actual evapotranspiration (ET_c) can be estimated by Eq. (7):

$$K_{ci} = K_{cprew} + \left[\frac{i - \sum (L_{prew})}{L_{stage}} \right] (K_{cnext} - K_{cprew}) \quad (5)$$

$$K_{cm} = K_c + 0.04 \times (U_2 - 2) - 0.004 \times (RH_{min} - 45) \times (h/3)^{0.3} \quad (6)$$

$$ET_c = K_c \cdot ET_0 \quad (7)$$

Water balance model

Precipitation (P) was considered to be the only water input in the Nü'er'zhai catchment. The input was balanced through surface runoff and interflow (R), net change in soil water storage (ΔSWS), actual evapotranspiration (ET_c) and deep percolation. We dug three profiles to analyze root vertical distribution in 2009. The result showed that root biomass was mainly concentrated at 0–100 cm, which accounted for 96.3 % of the total root biomass. According to the results of the national soil survey taken in the 2000s, the soil depth ranged from 0 to 150 cm in the hilly red soil region of southern China. The soil depth ranged from 100 to 140 cm in the study area, as determined by the soil profiles. Therefore, we chose the 0- to 140-cm soil layer as the soil water transfer layer to install TDR wave guides close to the soil parent material layer to control the deep percolation that was ignored in the water balance equation in this study. The soil water storage (SWS) can be calculated using Eq. (8):

$$SWS = P - R - ET_c + \Delta SWS \quad (8)$$

where $\Delta SWS = SWS_{t+i} - SWS_i$, SWS_{t+i} is the soil water content at a given time interval and SWS_i is the antecedent soil water storage. For the growth season of the *E. ulmoides* plantation, the measured soil water storage in late March was assumed to be the antecedent soil water content. Daily precipitation (P), surface runoff and interflow (R) and soil

water storage (SWS) were measured in situ. Daily evapotranspiration could thus be estimated by Eq. (8).

Effective precipitation was estimated according to an empirical model suggested by the US Department of Agriculture (USDA) and expressed as Eq. (9) (Patwardhan et al. 1990):

$$\begin{aligned} P_{\text{eff}} &= P_{\text{month}} \times (125 - 0.2 \times P_{\text{month}}) / 125, \dots P_{\text{month}} \leq 250 \text{ mm} \\ P_{\text{eff}} &= 125 + 0.1 \times P_{\text{month}}, \dots P_{\text{month}} > 250 \text{ mm} \end{aligned} \quad (9)$$

where P_{eff} and P_{month} are the monthly effective precipitation and total precipitation, respectively, (mm/month).

Method to define a suitable plant region

To define an *E. ulmoides* suitable plant region based on the water supply and demand, 31 years (1980–2010) of measured meteorological data from 165 meteorological stations belonging to the National Meteorological Center, which is subordinate to the China Meteorological Administration, were collected. The water deficit ratio (WDR) was used to quantify the degree of water deficit, which is described as follows. The annual ET_c and effective precipitation (P_{eff}) for each meteorological station were calculated by Eq. (10).

$$WDR (\%) = 100 \times (P_{\text{eff}} - ET_c) / ET_c \quad (10)$$

Subsequently, the WDR data were processed by an interpolation calculation, and the WDR contour line was extracted by the ArcGIS 10.2 software. We used the WDR value in 2010 (dry year) as the water deficit lower threshold to distinguish whether a region was suitable for *E. ulmoides* planting.

Model evaluation criteria

In this study, three statistical parameters of different goodness-of-fit measures, including the index of agreement (d), root-mean-square error (RMSE) and relative bias (RB), were used to evaluate the performance of the modified P–M model (Alexandris et al. 2006; Cai et al. 2007; Ali et al. 2008). The value of d , RMSE and RB were expressed in Eqs. (11–13), respectively,

$$d = 1 - \frac{\sum_{j=1}^n (SWS_e - SWS_o)^2}{\sum_{j=1}^n [(|SWS_e - SWS_m|) + (|SWS_o - SWS_m|)]^2} \quad (11)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{j=1}^n (SWS_e - SWS_o)^2} \quad (12)$$

$$RB = \frac{1}{n} \sum_{j=1}^n (SWS_e - SWS_o) \quad (13)$$

where SWS_e is the simulated soil water storage by using the P–M equation and crop coefficient model (mm), SWS_o is the observed soil water storage (mm), SWS_m is the mean value of SWS_o (mm) and n is the case numbers of the observation.

Results

Temporal variation of the observed soil water storage

As indicated in Fig. 2, the observed monthly soil water storage (SWS) ranged from 139.2 to 333.7 mm at the 0–140 cm soil depth during the two hydrological years; the peak value occurred in the wet year (June 2009), and the minimum value occurred in the dry year (July 2010). The maximal field water-holding capacity (SWS_f), 60 % of the maximal field water-holding capacity (60 % of SWS_f) and wilting point soil water storage (SWS_w) were 224.1, 134.5 and 123.3 mm, respectively, according to Table 1. In this study, the rainfall in the wet year had a more positive effect than the rainfall in the dry year. Apparently, the observed monthly soil water storage was higher than 60 % of SWS_f and SWS_w during the whole growing stage. That is, the soil water storage in a dry year could meet the water consumption by the *E. ulmoides* plantation as well as in a wet year.

Spatial variation of the observed soil volumetric water content

Profile changes of the soil volumetric water content had similar trends in the wet year and dry year during the growing and non-growing season stages (Fig. 3), and the dynamics of the soil volumetric water could be divided into several phases characterized by increase, reduction and a greater increase and reduction. In the study period, the mean soil volumetric water content in the non-growing stage was higher than in the growing stage in the dry year by -4.6 to 44.3 %, but was lower than in the growing stage in the wet year by 4.2 – 20.9 %. The wet year was higher than in the dry year by 5.0 – 68.3 % for each equal soil depth. The soil volumetric water content under the two growing stages was significantly higher than the wilting point soil water content by 64.4 – 164.3 % in the wet year and 31.3 – 91.9 % in the dry year. During the non-growing stage, the mean soil volumetric water content was significantly higher than the wilting point soil water content by 57.7 – 124.1 % at equal soil depths. Obviously, the soil

Fig. 2 Monthly variation of different soil water storage composition under *E. ulmoides* plantation from April 2009 to October 2010; SWS indicates soil water storage; SWS_f indicates the maximal field water-holding capacity; and SWS_w indicates the wilting point soil water storage

Fig. 3 Profile changes of the soil volumetric water content under the *E. ulmoides* plantation during growing and non-growing seasons

water content could meet the water consumption of an *E. ulmoides* plantation with 0- to 140-cm-deep soil whether in a wet year or dry year.

Temporal variation of estimated ET_c

The LAI initially increased slowly (in mid-March) and then increased more rapidly in mid-April (Fig. 4). The LAI reached a maximum value (3.5) in mid-July and then decreased due to decreasing physiological activity and leaf abscission. There were no significant differences in LAI between the wet year and dry year during the growing stage.

The dynamic variation in the ET_c and ET_{601} values is expressed by Fig. 4. The estimated mean daily ET_c values were 3.51 mm in 2009 and 3.43 mm in 2010, with a fluctuation range of 0.77 to 6.89 mm in 2009 and 0.73 to 8.90 mm in 2010 (Fig. 4). The mean daily ET_{601} values were 5.16 mm in 2009 and 5.15 mm in 2010, with a fluctuation range of 0.50 to 11.40 mm in 2009 and 0.40 to 12.20 mm in 2010 (Fig. 4).

The ET_c varied with the day series and was controlled mainly by the net radiation and LAI; the net radiation is a key factor forth potential evapotranspiration rate (ET_0 and ET_{601}), and the LAI is the main factor for the transpiration rate. During the growing stage, a good exponential

Fig. 4 Daily variation of the estimated ET_c and ET_{601} and LAI under the *E. ulmoides* plantation during the growing stage; the x -coordinate represents the day series of the year beginning April 1, 2009, so the

relationship existed between the ET_c and LAI [$Y_{ET_c} = 0.573 \times \text{EXP}(0.58 \times \text{LAI})$, $R^2 = 0.675$], and a good linear correlation also existed between the ET_c and ET_{601} ($Y_{ET_c} = 0.463 \times ET_{601} + 1.084$, $R^2 = 0.588$). Therefore, we could estimate the ET_c by using the ET_{601} or LAI when some other data were absent.

Water balance of the *E. ulmoides* plantation

The monthly soil water balance components under the *E. ulmoides* plantation during the growing stage are presented in Table 2. We used the calculated net rainfall based on the findings by Cao et al. (2008) as the water input parameter. During the growing stage, the mean rainfall intercept rate in the dry year was 39.9 %, which was higher than the mean rainfall intercept rate in the wet year by 16.0 %. The mean surface runoff coefficient in the dry year was 3.27 %, which was higher than the mean surface runoff coefficient in the wet year by 0.26 %, but the mean interflow coefficient in the wet year (22.95 %) was higher than the mean interflow coefficient in the dry year by 4.09 %. The estimated mean monthly ET_c values were 105.1 mm in the wet year and 102.3 mm in the dry year, with a range of 49.4 to 138.3 mm in the wet year and 44.6 to 162.1 mm in the dry year.

The monthly water loss (the sum of the surface runoff, interflow and ET_c) ranged from 75.6 to 244.7 mm in the wet year (2009) and 45.8 to 166.2 mm in the dry year (2010), while the water input (net rainfall) ranged from 34.1 to 263.4 mm in the wet year and 8.4 to 216 mm in the dry year.

In this subtropical humid monsoonal climatic region, the net soil water storage (ΔSWS) was negative when the net

corresponding series number is 91 in 2009; ET_c indicates actual evapotranspiration; ET_{601} indicates evaporation measured by pan of E-601 type; and LAI indicates leaf area index, the same for below

rainfall was less than 200 mm during the growth seasons, indicating that the soil water loss exceeded the replenishment. The soil water storage decreased continuously during the growth season and nearly reached the wilting point (140.8 mm) by the end of October because of little rainfall in September and October. Usually, the replenishment of the soil water occurs from November to March in the study area (Fig. 5).

Evaluation of the model performance

The plot of the measured and simulated soil water storage obtained from the modified P–M model is in good agreement with the 1:1 line. Whether in the wet year or dry year, the values of the estimated soil water storage were underestimated and the slope in the wet year (0.812) was slightly higher than the slope of the dry year (0.731). The coefficients of determination (R^2) for the two hydrological years were very high (0.795 in the wet year and 0.807 in the dry year), so we recommend the linear regulation model to estimate the actual soil water storage when observed data are absent.

The performance of the modified P–M model was evaluated by comparing the statistical properties (Table 3). The statistical performance of the two methods in the wet year was 0.892 (R^2), 84.8 % (d), 5.63 (RMSE) and 31.68 (RB). The statistical performance of the two methods in the dry year was 0.899 (R^2), 86.5 % (d), 4.86 (RMSE) and 23.61 (RB). The statistical analyses revealed a close agreement between the data series generated by the modified P–M model and the observed values in the two

Table 2 Monthly estimated and observed water balance components under the *E. ulmoides* plantation during study period (Unit:mm)

Hydrological year	Month	Gross rainfall	Net rainfall	Surface Runoff	Interflow	ET _c	ΔSWS	SWS _e	SWS _o
2009	Jan.	41.3	37.4	0.2	0.4	32.5	4.3	265.7	232.4
	Feb.	86.9	78.5	0.1	0.3	52.4	25.7	270.3	226.3
	Mar.	63.2	45.1	0.1	0.5	74.7	−30.2	266.1	238.7
	Apr.	55.7	37.9	2.4	0.9	72.3	−37.7	252.7	241.3
	May.	206.4	163.8	3.5	10.9	120.5	28.9	270.7	255.4
	Jun.	328.1	263.4	11.1	52	123.7	76.6	303.4	294.3
	Jul.	358.1	249.9	10.8	95.6	138.3	5.2	349.3	308.2
	Aug.	162.9	123.5	1.6	45.0	126	−49.1	318.2	265.3
	Sep.	45.9	34.1	0.4	2.0	107.6	−75.9	249.2	214.7
	Oct.	50.9	46.1	0.4	4.4	49.4	−8.1	187.9	158.9
	Nov.	71	62.1	0.4	3.1	43.6	15.0	230.4	219.9
	Dec.	35.4	30.3	0	1.4	31.9	−3.0	254.2	244.9
2010	Jan.	26.8	22.4	0	0	32.1	−9.7	262.1	221.0
	Feb.	128.8	105.3	1.2	31.2	34.3	38.6	276.9	231.6
	Mar.	56.8	48.4	0.3	2.2	56	−10.1	265.2	228.2
	Apr.	62.3	44.5	0.3	6.4	68.4	−30.6	247.3	228.9
	May.	199.5	136	3.8	38	95.9	−1.7	275.1	249.5
	Jun.	146.5	115.5	1.3	40	119.3	−45.1	289.1	229.7
	Jul.	95.4	47.7	0.7	3.4	162.1	−118.5	188.2	170.5
	Agu.	246.7	103.6	14.1	14.6	114.7	−39.8	201.4	223.9
	Sep.	14.8	8.4	0	0	110.9	−102.5	213.7	194.2
	Oct.	59.3	40.1	0.2	1	44.6	−5.7	161	163.0
	Nov.	47.2	40.1	0.2	0.8	47.2	−8.1	196.2	182.3
	Dec.	36.6	32.1	0.1	0.5	34.7	−3.2	223.7	218.9

ΔSWS indicates the increment soil water storage during a time interval; SWS_e indicates the estimated soil water storage; and SWS_o indicates the observed soil water storage

Fig. 5 Daily distribution of estimated and observed soil water storage (140 cm soil depth, mm) under *E. ulmoides* plantation during growing seasons

Table 3 Performance of statistical parameters between estimated and observed soil water storage

	Model evaluation criteria of the estimated and observed SWS			
	R^2	d (%)	RMSE (mm)	RB (mm)
2009	0.892	84.8	5.63	31.68
2010	0.899	86.5	4.86	23.61

hydrological years, and the performance in the dry year was slightly better than in the wet year.

Definition of a suitable plant region

The effective precipitation calculated by Eq. (9) was 1049.5 mm in 2009 (the wet year) and 860.0 mm in 2010 (the dry year), respectively. The annual water deficit ratio, which was 7.9 % in 2009 (wet year) and -6.5 % in 2010 (dry year), was calculated during the study period. In this study, we used the WDR value in the dry year as the water deficit lower threshold (-6.5 %) to distinguish whether a region was suitable for *E. ulmoides* planting. The spatial distribution of the water deficit ratio contour line and suitable plant region for *E. ulmoides* was identified (Fig. 6). The total area suitable for *E. ulmoides* planting in

southern China was $44.3 \times 10^4 \text{ km}^2$, which accounted for 70.4 % of the total area. Simultaneously, the suitable plant region for *E. ulmoides* was distributed in the area where the effective precipitation was greater than 900 mm. The provinces suitable for *E. ulmoides* planting include all of Jiangxi, Zhejiang and Hunan Provinces, as well as portions of Guangxi, Guangdong, Fujian, Anhui and Hubei Provinces.

Discussion

In this study, the estimated soil water content was higher than the observed values (shown in Fig. 5) mainly as a result of three factors. One factor was the overestimated diurnal amplitude of the soil surface temperature. In general, the air temperature in the forest plantation was always lower during the daytime and higher at night compared to outside the forest, and the diurnal amplitude of the air and soil temperature was always lower within the forest than outside due to the influence of the forest microclimate (Paul et al. 2004). The second factor was that the temperature used in calculating the soil heat flux (G) was not the soil surface temperature under the *E. ulmoides* plantation

Fig. 6 Spatial distribution of suitable plant region for *E. ulmoides* in hilly red soil region of southern China; P_{eff} indicates effective precipitation

but was from the weather station. The estimated soil heat flux (G) was therefore higher than it should be, leading to a higher estimated soil water content than observed. Finally, we ignored deep percolation. The study area belongs to the humid region mentioned above. The soil infiltration rate (189.6 mm/h from Table 1) was far higher than the rainfall intensity (not presented). The main cause of the runoff yield was the saturation overland flow, which is based on Horton's runoff mechanism. Subsequently, percolation would form in a deep soil layer (Sloan and Moore 1984). Percolation fluxes in a soil corresponding to the flow of water through the unsaturated zone are an important factor in groundwater recharge (Cattan et al. 2007). Over-estimated soil water contents in this study are therefore partially due to the ignored deep percolation.

The replenishment of the soil water in the non-growing season would improve the sprout of *E. ulmoides* and decrease the percentage of dead sprouts, thus encouraging a flourishing leaf system (Liu et al. 2008). A sufficient soil water supply from rainfall (because 71.1 % of the total rainfall focuses on April to July) could activate cambium growth leading to increased bark growth because cambium growth occurs from May to June (Liu et al. 2006). In this study, the soil water storage either in the wet year or the dry year was higher than 60 % of the maximal field water-holding capacity (60 % of SWS_f) under the *E. ulmoides* plantation (Fig. 2), so the soil water storage could provide the water demand for *E. ulmoides* growth. To some extent, we conclude that the water supply is not a limiting factor for *E. ulmoides* to be a reforestation species in the study area. However, the influence of climate change should be brought to the forefront in the later research. The impact of climate change based on observed precipitation data during the period from 1971 to 2000 and estimated precipitation data through the RCP8.5 emission scenario indicates that meteorological, hydrological and agricultural droughts will become more severe, prolonged and frequent for 2020–2049 relative to 1971–2000 in south China (Jiang et al. 2007; Qiu 2010; Wang et al. 2014; Leng et al. 2015; Huang et al. 2015). The frequency of long-term agricultural droughts (with duration larger than 4 months) will increase more than the short-term droughts (with duration <4 months; Leng et al. 2015). Therefore, we should pay more attention to the influence of climate change on precipitation in the suitable plant region for *E. ulmoides*.

This study provided estimates of the temporal and spatial variations in soil water storage in a forested catchment by integrating the measured parameters with modeled parameters as model input variables. The selected four statistical parameters (i.e., R^2 , d , RMSE and RB) to evaluate the performance of the modified P–M model indicated that the calculated temporal variations were in good agreement with the temporal variations measured in situ

(Fig. 5), showing that this approach could be adopted to estimate the soil water storage in other forested catchments where there is inadequate in situ data for assessing either the hydrological effects of planted vegetation or the potential for ecological restoration.

Conclusions

Water supply and demand were not the limiting factors for *E. ulmoides* planting based on measured data in situ and estimated data using the modified P–M model. Though soil water content deficits could occur at any time during the growth season in this subtropical humid monsoonal climate area, the deficit had no influence on sprout and cortical growth. Observations of the soil water storage in 2010 indicated that the soil water deficit at the 140 cm soil depth in 2009 was replenished during the non-growing stage. A suitable plant region was defined based on the water balance model by the GIS technique, and *E. ulmoides* is a suitable forest rehabilitation species in the hilly red soil region of southern China. The modified P–M model is recommended to estimate the variation tendency of soil water storage.

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