Calibration of an evapotranspiration model using runoff records and regional evapotranspiration

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Abstract Modelling the time distribution of soil moisture is a key issue for biomass evaluation and is often adopted for deriving drought awareness indices. A vertically-averaged water budget over the root zone is implemented to estimate the evapotranspiration flux at daily time step for a lumped watershed. The water balance is computed including evapotranspiration, runoff, leakage and capillary rise components, as well as the concept of contributing area. Soil property-related parameters are derived according to pedotransfer functions, while parameters linked to the resistance of vegetation to evapotranspiration and to watershed area contributing to runoff are considered as data driven and are subject to calibration. The contributing area is assumed to be indexed by the soil moisture content. The model is calibrated using daily hydro-meteorological data (solar radiation, air temperature, air humidity, mean areal rainfall) as well as daily runoff records and also average annual evapotranspiration. The latter is referred to as regional evapotranspiration because it is estimated using an empirical sub-model based on annual rainfall and potential evapotranspiration data from at-site and surrounding stations. Acceptable solutions are identified according to a compromise between the Nash coefficient for monthly runoff and relative bias for average annual evapotranspiration. The case study is a watershed of 250 km^2 in an arid climate. Meteorological and hydrological data are available for a 10-year calibration period and a 4-year validation period. It is found that the parameter linked to the resistance of vegetation to evapotranspiration is the most subject to uncertainty.

Key words evapotranspiration; bucket model; soil moisture; contributing area

INTRODUCTION

Modelling the time distribution of soil moisture is a key issue for biomass evaluation and is often adopted for deriving drought awareness indices. Budyko (1974) proposed calculating annual evapotranspiration with data from meteorological stations using one single parameter, w_0, representing a critical soil water storage. An average annual water balance equation is also developed in Eagleson (1978) in terms of 23 variables, including soil, climate and vegetation parameters, with the assumption of a homogeneous soil–atmosphere column and using Richards equation. The daily bucket with bottom hole model (BBH) proposed by Kobayashi *et al*. (2001) is based on the Manabe model (1969) involving a one-layer bucket but including gravity drainage (leakage) as well as capillary rise. Vrugt *et al*. (2004) compared the daily bucket model to a 3-D model (MODHMS) based on the Richards equation, using drainage observations. They concluded that both models have similar results. Also, Kalma & Boulet (1998) compared simulation results of the VIC hydrological model, which assumes a bucket representation including spatial variability of soil parameters, to the 1-D physically-based model SiSPAT. Using soil moisture profile data for calibration, they concluded that the catchment-scale wetness index for very dry and very wet periods are misrepresented by SiSPAT while captured by VIC. Analysing the VIC parameter identifiability using streamflow data, DeMaria *et al*. (2007) concluded that parameter sensitivity was more strongly dictated by climatic gradients than by changes in soil properties. Kobayachi *et al*. (2001) adjusted soil humidity profile measurements for model calibration. Vrugt *et al*. (2004) suggested that effective soil hydraulic properties are poorly identifiable using drainage discharge data. Therefore, model structure as well as calibration data and period are very important in evapotranspiration assessment. The scope of this work is to examine the effect of using daily runoff and annual evapotranspiration to calibrate a model predicting daily evapotranspiration rates.

DATA

The case study is the Wadi Chaffar watershed (250 km^2) situated in the arid climate of southern Tunisia. The vegetation cover comprises mainly olives. The soil type is sandy. Meteorological data (solar radiation, air temperature and humidity, sky cloudiness, wind and Piche evaporation) are available from September 1989 to August 1999 for computing the daily reference evapotranspiration ET_0 according to Allen *et al.* (1998). The ET_0 is multiplied by the crop coefficient K_c of olive trees to obtain daily potential evapotranspiration (ETP) (Allen *et al.*, 1998). Daily average basin rainfall data are available from September 1985 to August 1999 using the Thiessen method based on a network of 10 raingauges. Stream discharge data are available for the basin outlet at the daily time step for the same period. Monthly rainfall and stream discharge from September 1985 to August 1999 are reported in Fig. 1. In the period September 1985 to August 1989, meteorological data are missing and the ETP values are represented by the daily long-term average computed for September 1989–August 1999. The Hsuen Chen model (1988) is used for estimating the mean annual evapotranspiration E_m, which is found to be 213 mm/year (Bargaoui & Houcine, 2010). It is a semi-empirical model computing E_m as a function of annual potential evapotranspiration and precipitation from at-site and surrounding stations. This model has been calibrated using 18 rainfall stations, 21 runoff stations and 8 meteorological stations in Tunisia (Bargaoui & Houcine, 2010).

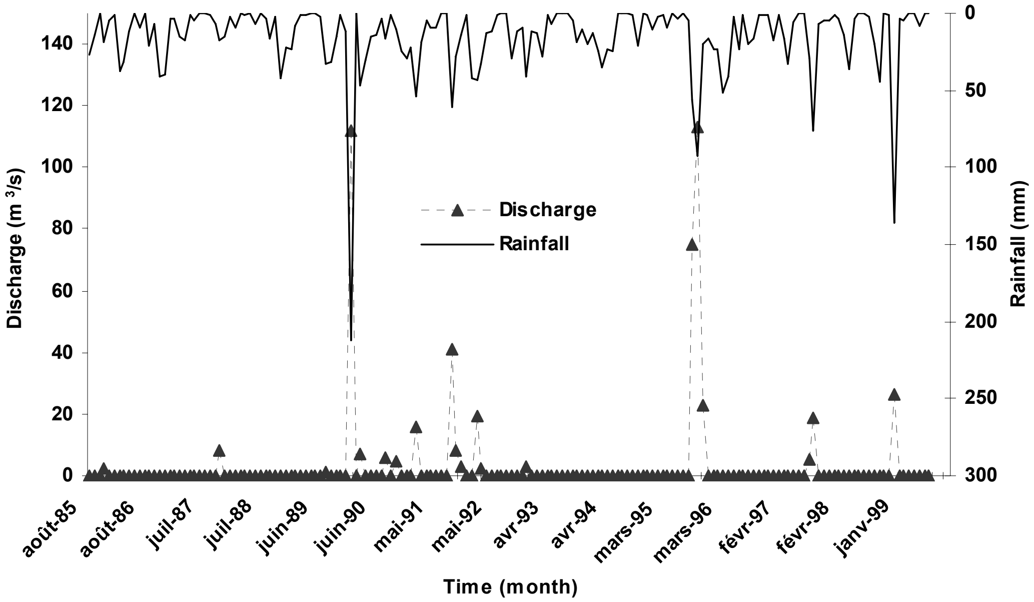

Fig. 1 Monthly rainfall and discharge data.

METHODOLOGY

The evapotranspiration flux is estimated at a daily time step using the water budget equations of the lumped BBH model (Table 1). The empirical parameter σ is assumed to reflect effects of canopy stomatal resistance. According to Kobayachi *et al.* (2001), a/W_{max} is "nearly equal to or somewhat smaller than the field capacity". After Teshima *et al.* (2006), parameter b is a measure of soil moisture recession that depends on hydraulic conductivity and active soil layer depth (D). In Iwanaga *et al.* (2005), a sensitivity analysis of the BBH model applied to an irrigated area in a semi-arid region suggested that soil moisture RMSE is most sensitive to the parameters σ, η and c.

Pedotransfer functions are introduced to reduce the number of parameters to be calibrated. The percolation function is represented as (Guswa *et al.*, 2002):

$$\mathrm{L}(s) = K_s \frac{\mathrm{e}^{B(s\text{-}S_{FC})} - 1}{\mathrm{e}^{B(1-S_{FC})} - 1} \quad (1)$$

where L(s) is the leakage, s is the ratio W/W_{max}, K_s is the saturated hydraulic conductivity, B is a

Table 1 Equations and parameters of the BBH model (Kobayashi *et al*., 2001).

Water balance equation	$\Delta W = W(t+1) - W(t) = P(t) - ETR(t) - Rs(t) - Gd(t)$ t: time (day) W(t): soil moisture content (mm) P: daily precipitation (mm) ETR: daily actual evapotranspiration (mm) Rs: daily surface runoff (mm) Gd: daily percolation (if Gd > 0) or capillary rise (if Gd < 0) (mm)
Daily actual evapotranspiration	$ETR(t) = M(t)\,ETP(t)$ ETP: daily potential evapotranspiration (mm) $M(t) = Min(1, W(t)/(\sigma \times W_{max}))$ σ: parameter representing the resistance of vegetation to evapotranspiration $W_{max} = pD$ W_{max}: total water-holding capacity (mm) *D*: thickness of active soil layer (mm) *p*: effective soil porosity
Daily percolation and capillary rise	$Gd(t) = \exp((W(t)-a)/b)-c$ *a*: parameter related to the field capacity (mm) *b*: parameter representing the decay of soil moisture (mm) *c*: parameter representing the daily maximal capillary rise (mm)
Daily surface runoff	$Rs(t) = \max\left[P(t) - (W_{BC} - W(t)) - ETR(t) - Gd(t), 0\right]$ $W_{BC} = \eta W_{max}$ η: parameter representing the moisture retaining capacity (0< η < 1)

soil water retention curve shape parameter, and S_{FC} is the field capacity. Parameters *a*, *b* and *c* are given by Bargaoui & Houcine (2010):

$$a = W_{max}\left[S_{FC} - \frac{1}{B}\mathrm{Ln}\left(K_S \frac{1}{e^{B(1-S_{FC})}-1}\right)\right] \tag{2}$$

$$b = W_{max}\frac{1}{B} \tag{3}$$

$$c = \left(\frac{1}{e^{B(1-S_{FC})}-1}\right)K_S \tag{4}$$

Sub-models (a) and (b)

The pedotransfer model by Rawls *et al.* (1982) is adopted for K_s while S_{FC} is derived according to the Cosby and Saxton model recently adopted by Zhan *et al.* (2008). Finally $B = 9$ is adopted in agreement with Rodriguez-Iturbe *et al.* (1999). We assume that lumped parameters can be derived from the soil properties of the dominant soil class. Two different model structures are investigated assuming that: (a) the total basin area contributes to runoff at the basin outlet, and (b) the entire basin might not contribute to the runoff at the outlet, and the contributing area A_j is related to the soil humidity index IH_j (Dickinson & Whiteley, 1969) according to a logistic distribution with parameters a_c and b_c (equation (5)). The humidity index is the sum of the soil water content of the previous day and a weighted rainfall index. The latter is the sum of the cumulative rainfall during the *k* previous days and the current day *j* (equation (6)):

$$A_j = \frac{e^{((IH_j - a_c)/b_c)}}{(1+e^{((IH_j - a_c)/b_c)})} \tag{5}$$

$$IH_j = W_{j-1} + \omega\sum_{l=0}^{k} P_{j-l} \tag{6}$$

where ω is a fixed weight.

Calibration process

The model is run for cases (a) and (b) using a daily time step, while monthly and annual time steps are used for evaluating the averaged runoff and evapotranspiration simulations. The calibration using only runoff information (calibration method 1) takes account of the absolute value of the annual relative volume runoff bias $C_y(\sigma, \eta)$ which is first computed for each pair of generated parameters. Then, for each pair with $C_y(\sigma, \eta) < \alpha$ (equation (7)), the Nash coefficient R_N is evaluated at the monthly scale. Moreover, assuming a threshold value R_{N0}, pairs for which $R_N > R_{N0}$ are selected. When E_m is included for model calibration (calibration method 2), the absolute value $C_E(\sigma, \eta)$ of the relative error between mean annual simulated evapotranspiration and E_m, is used as an additional selection criterion (equation (8)). Pairs which satisfy both $C_y(\sigma, \eta) < \alpha$; $R_N > R_{N0}$ and $C_E(\sigma, \eta) < \alpha'$ are selected. Hence, this second method merges runoff and evapotranspiration information:

$$C_y(\sigma,\eta) = \frac{1}{N}\sum_{i=1}^{N}\left|(y_{si} - y_{oi})/y_{oi}\right| \tag{7}$$

$$C_E(\sigma,\eta) = \frac{1}{N}\sum_{i=1}^{N}\left|(E_{si} - E_m)/E_m\right| \tag{8}$$

In equation (7), y_{oi} and y_{si} are respectively annual observed and simulated volume runoff, and N is the number of simulated years. In equation (8), E_{si} is simulated annual evapotranspiration.

RESULTS

Subsequent to many trials, it was concluded that the value D = 0.5 m is more adequate than the usual value D = 1 m. Owing to the sandy dominant soil type, p = 0.34 is set. It is found that K_s = 3634 mm/d and S_{FC} = 0.166. The search for parameter settings of σ and η is then performed in the feasible space $0 < \sigma < 1$; $0 < \eta < 1$. Parameter sets are generated following a grid considering the steps $\Delta\sigma = \Delta\eta = 0.01$; $0 < \sigma < 1$; $0 < \eta < 1$. Model evaluation is performed using the 10-year period from September 1989 to August 1999. In addition, this 10-year period is subdivided into seven sub-periods of 4 years each (Table 2). The period September 1985–August 1989 is used as the validation period. This period was selected for validation because it represents the first part of the

Table 2 Number of acceptable solutions according to calibration methods 1 and 2 for case (a) and case (b) and for different periods.

Periods	Mean annual:			Number of solutions		Number of solutions:	
	Precipitation over the period (mm/year)	Potential evapo-transpiration over the period (mm/year)	Volume of runoff over the period (hm^3/year)	without contributing area (case a), method 1	with contributing area (case b), method 1	without contributing area (case a), method 2	with contributing area (case b), method 2
Calibration	207	1006	4.185	119 (0.53–0.62)*	99 (0.50–0.59)	6 (0.53–0.54)	7 (0.50–0.51)
Validation	133	975	0.261	0	0	0	0
P1	246	966	4.813	43 (0.50–0.88)	47 (0.55–0.80)	43 (0.50–0.88)	47 (0.55–0.80)
P2	200	1015	2.113	0	0	0	0
P3	158	1024	1.663	155 (0.60–0.94)	56 (0.51–0.73)	22 (0.85–0.93)**	0
P4	188	1008	4.619	230 (0.62–0.75)	295 (0.58–0.72)	102 (0.63–0.75)	158 (0.58–0.72)
P5	181	1028	4.675	259 (0.60–0.75)	325 (0.54–0.71)	94 (0.62–0.75)	120 (0.60–0.71)
P6	176	1014	5.081	283 (0.50–0.65)	237 (0.50–0.60)	37 (0.51-0.61)	17 (0.56–0.60)
P7	216	1000	5.650	183 (0.50–0.67)	138 (0.50–0.63)	45 (0.50-0.63)	16 (0.52–0.55)

Calibration period: Sept. 1989–Aug. 1999.

Validation period: Sept. 1985–Aug. 1989; P1: Sept. 1989–Aug. 1993; P2: Sept. 1990–Aug. 1994; P3: Sept. 1991–Aug. 1995; P4: Sept. 1992–Aug. 1996; P5: Sept. 1993–Aug. 1997; P6: Sept. 1994–Aug. 1998; P7: Sept. 1995–Aug. 1999.

*numbers between brackets are minimum and maximum value of Nash coefficients for selected solutions.

** this period displays the four highest Nash coefficients.

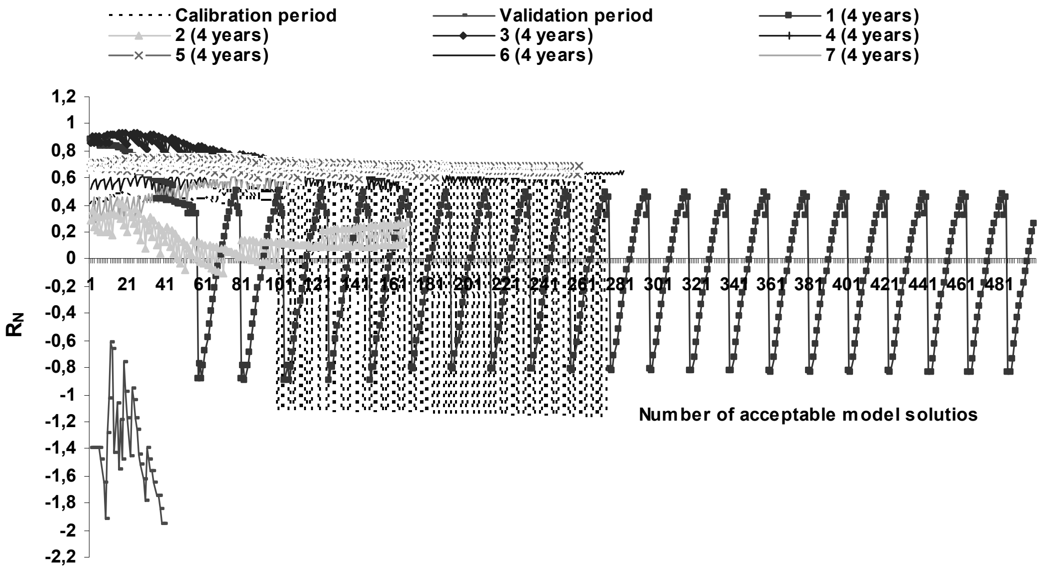

Fig. 2 Nash coefficient (R_N) using submodel (a) and calibration method 1.

observation series and because it contains missing ETP data, unlike the other periods where all data were available at the daily time scale. Thus, the availability of the complete data series was adopted as justification for choosing the calibration period as September 1989 to August 1999. We assume that α = 20%; α' = 30% and R_{N0} = 0.5. After many trials, the value ω = 0.1 was assumed as well as k = 90, a_c = 20 and b_c = 10 for the contributing area sub-model, reflecting the fact that the mean area of contribution for this basin is 20%.

Figure 2 reports the Nash coefficients of runoff volumes obtained for each time period and the number of accepted solutions in case (a). Minimum and maximum values of R_N are reported in Table 2. The results show that there is no clear evidence of performance enhancement when introducing the contributing area. As evident from Fig. 2 and Table 2, no solution is acceptable for the (drier) validation period 1985–1989, neither in case (a) nor (b), and calibration methods 1 and 2. The model might fail to represent the hydrological cycle for very dry periods. Alternatively, it may be suggested that the adopted synthetic ETP for the period 1985–1989 data might not be adequate to represent a dry period. The reduction of the number of acceptable solutions is found rather important for the calibration method 2 in comparison to calibration method 1 (Table 2). This causes rejection of solutions having the lowest R_N. However, for the period P3, the two criteria do not converge and no solution is found. In order to assess the uncertainty about the parameters σ and η, Table 3 reports the interval values for both parameters when using only runoff volume for

Table 3 Acceptable σ and η parameters according to different periods.

Periods	Sigma (σ) without contributing area:		Sigma (σ) with contributing area:		Neta (η) without contributing area:		Neta (η) with contributing area:	
	(case a), method 1	(case a), method 2	(case b), method 1	(case b), method 2	(case a), met2od 1	(case a), method 2	(case b), method 1	(case b), method 2
P1	0.01 – 0.40	0.01 – 0.40	0.01 – 0.28	0.01 - 0.28	0.19 – 0.77	0.19 – 0.77	0.17 – 0.20	0.17 – 0.20
P2	-	-	-	-	-	-	-	-
P3	0.01 – 1.00	0.01 – 0.13	0.01 – 0.38	-	0.18 – 0.26	0.18 – 0.21	0.13 – 0.23	-
P4	0.01 – 1.00	0.01 – 0.35	0.01 – 1.00	0.01 – 0.35	0.15 – 0.24	0.15 – 0.22	0.09 – 0.24	0.09 – 0.22
P5	0.01 – 1.00	0.01 – 0.28	0.01 – 1.00	0.01 – 0.27	0.15 – 0.24	0.15 – 0.22	0.09 – 0.24	0.11 – 0.21
P6	0.01 – 1.00	0.01 – 0.12	0.01 – 1.00	0.01 – 0.10	0.17 – 0.25	0.17 – 0.22	0.10 – 0.24	0.16 – 0.20
P7	0.14 – 1.00	0.14 – 0.35	0.19 – 1.00	0.19 – 0.34	0.23 – 0.25	0.23 – 0.25	0.23 – 0.25	0.24
Calibration	0.30 – 1.00	0.30 – 0.35	0.07 – 1.00	0.07 – 0.13	0.24 – 0.25	0.24	0.20 – 0.25	0.20
Validation	-	-	-	-	-	-	-	-

calibration (method 1) and when also incorporating actual evapotranspiration information (method 2). It is worth noting that the adoption of the contributing area sub-model is not reflected by a reduction of the acceptable interval for any parameters. The results suggest that the effect of the choice of the calibration criteria (method 1 or method 2) is more significant. Besides, this effect is more important to constrain the setting for σ which is far more uncertain than η.

CONCLUSIONS

Both runoff volume information as well as the average annual evapotranspiration have been adopted in order to calibrate the water budget model. This model is constituted by the BBH model which was completed using a contributing area sub-model. The introduction of three new parameters attached to this sub-model has no significant effect on the spreading of model outputs and parameters. However, the introduction of evapotranspiration information has greatly reduced the interval of acceptable solutions for vegetation stomatal resistance parameter. Also, it seems that the model fails to represent very dry periods when using only the information about runoff and evapotranspiration.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *FAO Irrigation and Drainage Paper no. 56*. FAO, Rome.

Bargaoui, Z. & Houcine, A. (2010) Sensitivity to calibration data of simulated soil moisture related drought indices. *Revue Sécheresse* **21**(4), 294–300.

Budyko, M. I. (1974) *Climate and Life*. Academic Press, New York. 508p.

Demaria, E. M., Nijssen, B. & Wagener, T. (2007) Monte Carlo sensitivity analysis of land surface parameters using the Variable Infiltration Capacity model. *J. Geophys. Res.* **112**, D11113, doi:10.1029/2006JD007534.

Dickinson, W. T. & Whiteley, H. (1970) Watershed areas contributing to runoff. *Results of Research on Representative and Experimental Basins*, 12–26. IAHS Publ. 96. Available at www.iahs.info/redbooks/096.htm.

Eagleson, P. S. (1978) Climate, soil, and vegetation. dynamics of the annual water balance. *Water Resour. Res.* **14**(5), 749–764.

Guswa, A. J., Celia, M. & Rodriguez-Iturbe, I. (2002) Models of soil moisture dynamics in ecohydrology: A comparative study. *Water Resour. Res*. **38**(9), 1166–1180.

Hsuen-Chun, Y. (1988) A composite method for estimating annual actual evapotranspiration. *Hydrol. Sci. J*. **33**(4), 345–356.

Iwanaga, R., Kobayashi, T., Wang, W., He, W., Teshima, J. & Cho, H. (2005) Evaluating the irrigation requirement at a cornfield in the Yellow River Basin based on the "dynamic field capacity". *J. Japan Soc. Hydrol. & Water Resour*. **18**, 664–674.

Kalma, J. D. & Boulet, G. (1998) Measurement and prediction of soil moisture in a medium-sized catchment. *Hydrol. Sci. J.* **43**(4), Special issue: *Monitoring and Modelling of Soil Moisture: Integration over Time and Space,* 597–610.

Kobayashi, T., Matsuda, S., Nagai, H. & Teshima, J. (2001) A bucket with a bottom hole (BBH) model of soil hydrology. In: *Soil–Vegetation–Atmosphere Transfer Schemes and Large-Scale Hydrological Models* (ed. by H. Dolman *et al.*), 41–45. IAHS Publ. 270. IAHS Press, Wallingford, UK.

Manabe, S. (1969) Climate and the ocean circulation, 1. The atmospheric circulation and the hydrology of the Earth's surface. *Mon. Weath. Rev.* **97**(11), 739–774.

Rawls, W., Brakensiek, D. & Saxton, K. (1982) Estimation of soil water properties. *Trans. Am. Soc. Agric. Engrs* **25**, 51–66.

Rodriguez-Iturbe, I., Porporato, A., Ridolfi, L., Isham, V. & Cox, D. (1999) Probabilistic modelling of water balance at a point: the role of climate, soil and vegetation. *Proc. Royal Soc. London Ser. A* **455**, 3789–3805.

Teshima, J., Hirayama, Y., Kobayashi, T. & Cho, H. (2006) Estimating evapotranspiration from a small area on a grass-covered slope using the BBH model of soil hydrology. *J. Agric. Met*. **62**(2), 65–74.

Vrugt, J. A., Schoups, G., Hopmans, J. W., Young, C., Wallender, W. W., Harter, T. & Bouten, W. (2004) Inverse modeling of large-scale spatially distributed vadose zone properties using global optimization. *Water Resour. Res.* **40**, W06503, doi:10.1029/2003WR002706.

Zhan, Ch.-S., Xia, J., Chen, Z. & Zuo, Q.-T. (2008) An integrated hydrological and meteorological approach for the simulation of terrestrial evapotranspiration. *Hydrol. Sci. J.* **53**(6), 1151–1164, doi:10.1623/hysj.53.6.1151.