Hydrologic Evaluation of a Mediterranean Watershed Using the SWAT Model with Multiple PET Estimation Methods

F. Licciardello, C. G. Rossi, R. Srinivasan, S. M. Zimbone, S. Barbagallo

Abstract. *The Penman-Monteith (P-M) method suggested by the Food Agricultural Organization in irrigation and drainage paper 56 (FAO-56 P-M) was used in the Soil and Water Assessment Tool's (SWAT) water balance simulation at the outlet of an experimental watershed in Sicily, Italy. A sensitivity analysis determined that the model was more sensitive to this potential evapotranspiration (PET) parameter than to the other six parameters impacting surface runoff in this small Mediterranean watershed. The FAO-56 P-M method was compared to the three existing SWAT PET methods from 1997 to 2003. The watershed's water balance was more realistically simulated by the FAO-56 P-M method than by the other PET methods. The traditional P-M method incorporated into SWAT overestimated total (surface and base flow) runoff volumes observed during the entire period by approximately 50%; however, total runoff volumes were underestimated by only 17% when the FAO-56 P-M method was used. The surface runoff simulation results using the FAO-56 P-M PET equation for calculating daily values was sufficient at the monthly time interval (Nash-Sutcliffe efficiency >0.75) during the calibration and validation periods. The incorporation of the FAO-56 P-M method has broadened the SWAT model's applicability to watersheds that are in semi-arid environments with high-intensity, short-duration rainfall events.*

Keywords. *FAO-56 P-M, Potential evapotranspiration, Surface runoff, SWAT, Watershed modeling.*

Water availability and water quality issues have become increasingly important due to their impact on food supply, human health, ecosystems, and land uses (Nearing et al., 2004; Zhang and Nearing, 2005). In spite of several attempts to develop predictive hydrologic models as environmental tools, there is a lack of watershed models that can effectively simulate Mediterranean climates with short-duration, high-intensity rainfall events. For this study, a semi-arid Mediterranean environment, characterized by complex climatic, structural, and geomorphological factors, is simulated. Compared to humid climate regions, semi-arid environments have problems with predicting runoff, primarily due to the lack of data and research studies describing runoff generation mechanisms in catchments (Canton et al., 2001; Latron et al., 2003) that are more difficult to analyze due to high-intensity, short-duration, and highly variable rainfall events (Moussa et al., 2007). In Mediterranean watersheds, Agenda 21 (United Nations, 1992) and the EU Water Framework Directive (European Union, 2000) are interested in models that can adequately simulate water resources to assist in making environmental decisions.

Hydrologic models require the actual evapotranspiration (ET) since it is the primary mechanism by which water is transferred from the land surface to the atmosphere. ET includes evaporation from the plant canopy, transpiration, sublimation, and evaporation from the soil, which is difficult to measure at the watershed scale due to time constraints and costs. The ET computation is usually based on the potential evapotranspiration (PET), which is the amount of water that could evaporate and transpire from a vegetated landscape with no restrictions other than the atmospheric demand (Jensen et al., 1990). The available PET estimation methods (temperature-based, radiation-based, and temperature/radiation-based) often give inconsistent values due to the assumptions used in their determination, due to data requirements, or because they were developed for specific climate regions (Wang et al., 2006). Utilization of the optimum PET method for a region is crucial for obtaining realistic results in hydrological modeling (Kannan et al., 2007). There is a lack of information on how SWAT's simulation performance is affected by PET method (Wang et al., 2006).

Three of the commonly used methods, the temperature-based Hargreaves method (Hargreaves et al., 1985), the radiation-based Priestley-Taylor method (Priestley and Taylor, 1972), and the combination P-M method (Allen et al., 1989), were incorporated into the physically based Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998). The SWAT model has been applied in several countries with promising results in the assessment of runoff, mainly at annual and monthly scales (Tripathi et al., 2004; Chaplot, 2005; Di Luzio et al., 2005; Cau et al., 2005; Sulis et al., 2004).

Submitted for review in October 2010 as manuscript number SW 8842; approved for publication by the Soil & Water Division of ASABE in August 2011.

The authors are **Feliciana Licciardello,** Post-Doctoral Researcher, Department of Agri-food and Environmental Systems Management, University of Catania, Catania, Italy; **Colleen G. Rossi,** Soil Scientist, USDA-ARS Grassland Soil and Water Research Laboratory, Temple, Texas; **Raghavan Srinivasan, ASABE Member,** Professor, Department of Biological and Agricultural Engineering, and Director, Spatial Sciences Laboratory, Texas A&M University, College Station, Texas; **Santo M. Zimbone, ASABE Member,** Professor, Department of Agro-Forest and Environmental Sciences and Technology, Mediterranean University of Reggio Calabria, Reggio Calabria, Italy; and **Salvatore Barbagallo,** Professor, Department of Agri-food and Environmental Systems Management, University of Catania, Catania, Italy. **Corresponding author:** Feliciana Licciardello, Department of Agri-food and Environmental Systems Management, University of Catania, Via Santa Sofia 100, Catania, Italy 95123; phone: 0039-0957-147-551; fax: 0039-0957-147-600; e-mail: flicciar@unict.it.

These applications have occurred with a wide range of soil types, land uses, and climate conditions mainly at the large watershed scale; few applications have been carried out in small (about 1 km^2) watersheds (Arnold and Fohrer, 2005; Gassman et al., 2007). A proper calibration of model parameters is necessary when the model is applied at different spatial scales (Licciardello et al., 2008).

The choice of PET method is important for hot and dry areas, where the PET value differences can vary by 700 mm $year^{-1}$ (Federer et al., 1996) depending on the method selected, ultimately impacting the overall watershed hydrological budget. The FAO-56 P-M method performed better than other PET estimation equations (Hargreaves, FAO-24 Penman I and II) in predicting lysimetric measurements in the Spanish semiarid climate for both high and low evaporative demand periods (Lopez-Urrea et al., 2006). Only a few SWAT simulations pertaining to Mediterranean areas exist that demonstrate the relative importance of flow components (Sulis et al., 2004). Gikas et al. (2006) used the SWAT model in the prediction of hydrographs from a mountainous/agricultural watershed in northern Greece. The equation based on the Penman-Monteith (P-M) method reported by the Food and Agricultural Organization (FAO-56 P-M; Allen et al., 1998) is the recommended PET method for the region that includes the Cannata watershed.

Since obtaining a valid hydrologic simulation requires utilization of the correct PET method, which was previously unavailable with the SWAT model, the FAO-56 P-M method was incorporated to ascertain if the water balance within the Cannata watershed could be more realistically simulated. A successful water balance simulation would indicate applicability of the model in other watersheds with similar climatic characteristics for which data are unavailable.

The study's objective is to evaluate the hydrologic effectiveness of the SWAT model (Neitsch et al., 2002a) to accurately capture the water balance over an eight-year period for an area characterized by short-duration, high-intensity rainfall events. The choice of PET estimation method (between those included in SWAT and FAO-56 P-M) was included in a sensitivity analysis performed to define the model sensitivity to selected parameters for runoff volume at the outlet of a small experimental watershed in Sicily.

Model Background

The SWAT model is a physically based, semi-distributed parameter, watershed scale, continuous hydrologic model developed by the USDA-ARS to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soil, land use, and management conditions over long periods of time. The model can be run at multiple time steps including daily, monthly, and yearly (Neitsch et al., 2002a, 2002b).

In SWAT, a watershed is partitioned into a number of subwatersheds interconnected by a stream network. Each subwatershed can be further divided into a number of spatially unrelated hydrologic response units (HRUs) having unique land use and soil combinations. Daily precipitation and maximum and minimum air temperature data are required to more effectively simulate the water balance of the watershed. An imbedded weather generator can be used; however, the model outputs are only as good as the model inputs. The SWAT2000 version (Neitsch et al., 2002a) has options to use observed solar radiation, wind speed, relative humidity, and evaporation data. The model includes a number of storage databases (i.e., soils, land cover/plant growth, tillage, and fertilizer) that can be customized to reflect a particular watershed's characteristics.

SWAT contains several hydrologic components (ET, surface runoff, recharge, streamflow, and subsurface flow) that have been developed and validated at smaller scales (Leonard et al., 1987; Arnold et al., 1990). Runoff is estimated separately for each subwatershed of the total watershed area and routed to obtain the total runoff for the watershed. Runoff volume is estimated from daily rainfall using the modified USDA-SCS curve number (CN) method. Interactions between surface flow and subsurface flow in SWAT are based on a linked surface-subsurface flow model developed by Arnold et al. (1993).

Characteristics of this flow model include non-empirical recharge estimates, accounting of percolation, and applicability to watershed-wide management assessments with a multi-component watershed water budget. The concentration time is calculated by summing overland flow and channel flow times. Overland flow and channel flow times are functions of overland flow and channel flow velocities, respectively. These velocities are estimated from Manning's equations as functions of Manning's roughness coefficient for overland and channel flow, respectively (Neitsch et al., 2002b). Lateral subsurface flow can occur in the soil profile from 0 to 2 m. Groundwater flow contribution to total streamflow is generated by simulating shallow aquifer storage (Arnold et al., 1993). Flow from the aquifer to the stream is lagged via a recession constant derived from daily streamflow records (Arnold and Allen, 1996).

A single growth model in SWAT is used for simulating crops and is based on the simplification of the Erosion Productivity Impact Calculator (EPIC; Williams et al., 1984) and Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC; Kiniry et al., 1992) models. The user can select whether to use the potential heat unit or date of operation for plant growth simulations. The model can simulate up to ten soil layers if sufficiently detailed information is available.

Materials and Methods

Input Data

AVSWAT-2000

The GIS ArcView interface AVSWAT-2000 (Di Luzio et al., 2002) was used in this study. Spatial data sets are required and include a digital elevation model (DEM), land cover, and soil type. Elevation, land use, and soil characteristics input data sets for the Cannata watershed were obtained from GIS data layers at different resolutions. The elevation layer was extracted from a 5 m resolution DEM purposely arranged by digitizing 2 m elevation contour lines. The soil and land use layers were obtained from maps at 25 m resolution of the five soil textures (clay, loam, loam-clay, loam-sand, and loam-sand-clay) and two management practices (pasture and winter wheat cultivation with rotation), determined during a survey conducted in the watershed in 1996.

Watershed Description

The monitored Cannata watershed is mountainous with an ephemeral tributary from the Flascio River in eastern Sicily (37° 53′ N, 14° 46′ E). The watershed covers about 1.3 km^2 between 903 m and 1270 m a.s.l. with an average slope of 21%. The longest pathway is about 2.4 km, with an average slope of approximately 12%. The concentration time, calculated with the Kirpich equation (Chow et al., 1988), is equal to 0.29 h. The monitoring equipment includes (fig. 1) a meteorological station (A in fig. 1) recording rainfall, air temperature, wind, solar radiation, and pan evaporation; two pluviometric stations (B and C); and a hydrometrograph (D) continually measuring the water flow level.

Topographic Data

The watershed is divided into 31 subwatersheds, ranging in size from 0.3 to 11.1 ha (fig. 1). This discretization gave the suitable representation of the observed drainage network geometry and density (Licciardello et al., 2006; Licciardello et al., 2007). The multiple HRUs option in AVSWAT-2000 was used to enable the creation of multiple HRUs for each subwatershed. Minimum thresholds of 5% for land use and 10% for soil texture were used. These thresholds resulted in 63 HRUs.

Hydrologic Discharge Data

Rainfall data are collected in three locations close to and within the Cannata watershed at 15 s intervals. Air temperature, wind, solar radiation, and pan evaporation data are recorded by a meteorological station located close to the watershed with a time resolution of 1 h. The flow levels are recorded above the confluence of the Flascio River using a floating hydrometrograph. Land use and ground cover modifications are monitored every six months for 24 sites within the watershed using a 1 m^2 grid with 0.4 m^2 subgrids. Surface runoff, evaluated by an automated digital filter (Arnold et al., 1995; Arnold and Allen, 1999) was the dominant component of flow for each year (table 1).

Soil and Land Use Data

Fifty-seven field soil samples were taken in the watershed following three main directions (northeast-southwest, north-south, and northwest-southeast) starting from the same point in a squared scheme with a side length of 200 m based on the observed variation in the texture samples. Soil samples were predominantly from the topsoil to represent the soil textures simulated by SWAT. The planting, harvest, and tillage operations and irrigation, nutrient, and pesticide applications are scheduled by date (table 2). The potential heat unit value (representing the number of heat units required to bring a plant to maturity for both pasture and winter wheat plants) was equal to 1800°C. This is the value set in the U.S. database for areas with climatic characteristics similar to those observed in the present study. A pasture was planted between two winter wheat cultivations to simulate the crop rotation.

Table 1. Yearly surface runoff and base flow volumes evaluated by an automated digital filter.

Runoff Component	Yearly Volumes (mm)						
	1997	1998	1999	2000	2001	2002	2003
Surface runoff	67.4	32.6	75.8	54.4	49.2	102.8	283
Base flow	12.3	5.6	37.8	9.0	0.0	15.5	117.6

Table 2. Management operations for the Cannata watershed.

Crop	Date	Management Operation
Winter wheat	July 1	Kill/end of growing season
	Aug. 31	Tillage
	Oct. 31	Plant/begin growing season for winter wheat
	Oct. 31	Auto-irrigation initialization
	Nov. 30[a]	Fertilizer application
Pasture	Jan. 1	Plant/begin growing season for pasture
	Apr. 1	Grazing operation
	Dec. 31	Kill/end of growing season

[a] A crop field is only cultivated on alternated years.

The curve number hydrologic group II (CN2) values were derived using the standard procedure set by the USDA-SCS (1972). Based on the available distributed samples of texture, structure, and field saturated conductivity, the watershed was represented by soil hydrological groups C and D, characterized with the highest surface runoff yield potential. The CN values for the initial condition (AMC-II) for pasture and winter wheat, taken from the SWAT database (USDA-SCS, 1986) for arid/semi-arid rangelands and for cultivated agricultural lands, were 81 and 89 for pasture and 81 and 84 for winter wheat, respectively. A single curve number was used throughout the year for both land uses. The three continuous precipitation recording gauges and the meteorological station (A in fig. 1) were used for daily precipitation and climate input data.

The 1996 survey identified the dominant (63%) soil texture in the watershed as clay-loam (USDA classification). The rest of the watershed is characterized as loam (21%), loam-sand (10.5%), clay (3.5%), and loam-sand-clay (2.0%). The soil saturated hydraulic conductivity, measured with a Guelph permeameter (model 2800, Eijkelkamp, Giesbeek, The Netherlands), was determined to be 0.2 to 17.6 mm h^{-1} in the collected soil samples. Land use monitoring highlighted the prevalence of pasture areas (ranging between 87% and 92% of the watershed area) with different vegetation (up to 15 species) and ground covers. The four dominant soil covers included: (1) a high-density herbaceous vegetation (eventually subjected to tillage operations) characterized by *Ranunculus bulbosus*, *Trifolium stellatum*, *Trifolium repens*, and *Festuca circummediterranea* with a ground cover value in the observation period between 17% and 86% (mean of 47%); (2) a medium-density herbaceous vegetation characterized by *Dactylis glomerata*, *Trifolium repens*, *Cynosorus cristatus*, and *Hedysarum coronarium* with a ground cover value between 14% and 67% (mean of 36%); (3) sparse shrubs characterized in the higher layer of vegetation by *Crataegus monogyna*, *Genista aetnensis*, *Calicotome infesta*, *Rubus ulmifolium*, and *Pyrus communis* and in the low layer by the same species as the high-density herbaceous vegetation with a ground cover value in the observation period between 30% and 70% (mean of 50%); and (4) cultivated winter wheat planted at the end of October and harvested at the end of July with a wheat-fallow rotation. Additional watershed characteristics and sampling information are reported by Licciardello and Zimbone (2002).

PET Estimation Methods in SWAT and the P-M Equation Suggested by FAO-56

The three PET methods included in SWAT vary in the amount of required inputs. The P-M method requires solar

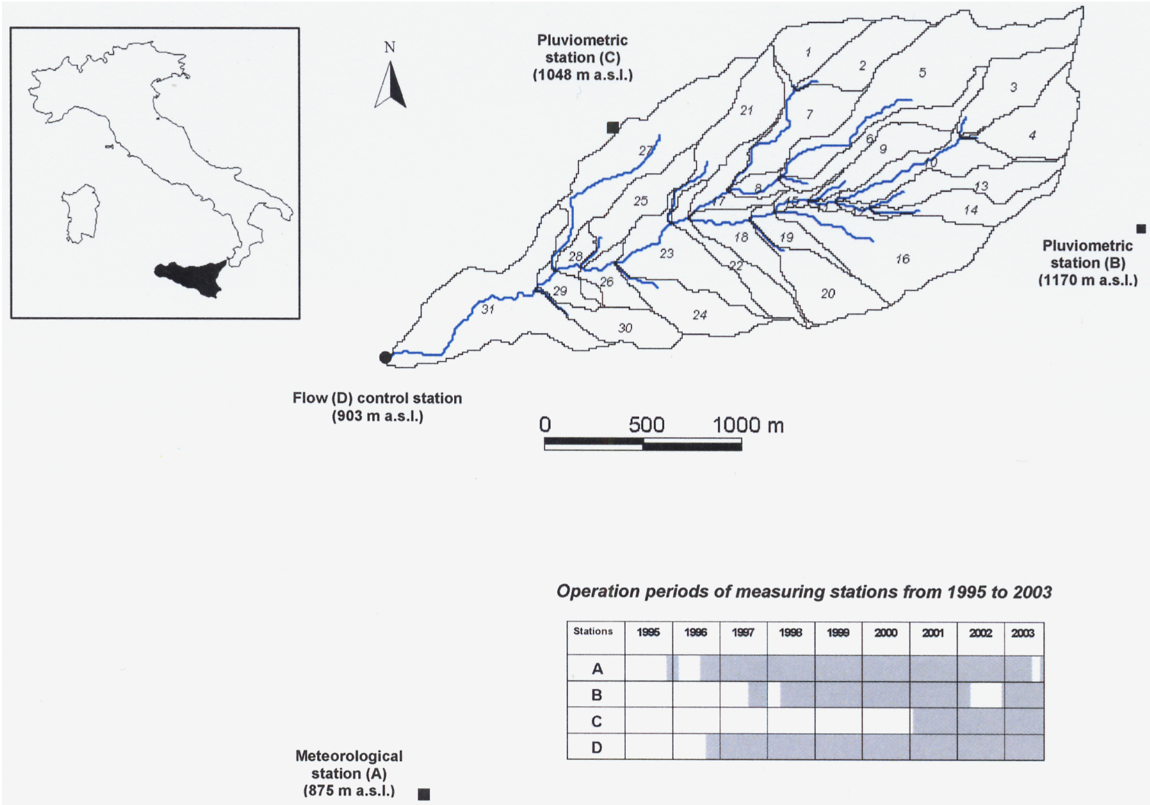

Figure 1. Layout of subwatersheds and hydrological network in the Cannata watershed, Sicily.

radiation, air temperature, relative humidity, and wind speed. The Priestley-Taylor method requires solar radiation, air temperature, and relative humidity. The Hargreaves method requires air temperature only. The P-M equation suggested by FAO-56 P-M (Allen et al., 1998) is a modified version of the P-M method incorporated in SWAT. The different PET estimation methods in SWAT are described by Neitsch et al. (2002b). Here, some differences identified between the P-M method and the FAO-56 P-M method are reported in order to help in understanding the differences in the PET estimations.

The original P-M equation combines components that account for the energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapor, and aerodynamic and surface resistance terms. The P-M equation is expressed as:

$$\lambda E = \frac{\Delta\left(H_{net} - G\right) + \rho_{air} c_p \dfrac{\left(e_z^0 - e_z\right)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_c}{r_a}\right)} \quad (1)$$

where λE is the latent heat flux density (MJ m^{-2} d^{-1}), E is the depth rate evaporation (mm d^{-1}), Δ is the slope of the saturation vapor pressure-temperature curve de/dT (kPa °C^{-1}), H_{net} is the net radiation (MJ m^{-2} d^{-1}), G is the heat flux density to the ground (MJ m^{-2} d^{-1}), ρ_{air} is the air density (kg m^{-3}), c_p is the specific heat at constant pressure (MJ kg^{-1} °C^{-1}), e_z^0 is the saturation vapor pressure of air at height z (kPa), e_z is the water vapor pressure of air at height z (kPa), γ is the psychrometric constant (kPa °C^{-1}), r_c is the plant canopy resistance (s m^{-1}), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1}).

One difference between the FAO-56 P-M equation and the SWAT P-M equation is in the calculation of the term H_{net}, which is equal to:

$$H_{net} = \left(1 - \alpha\right) H_{day} + H_b \quad (2)$$

where H_{day} is the shortwave solar radiation reaching the ground (MJ m^{-2} d^{-1}), and H_b is the net incoming longwave radiation (MJ m^{-2} d^{-1}). The first difference is related to the term α, which is the shortwave reflectance or albedo. In SWAT, α is calculated as a function of the soil type, plant cover, and snow cover. In the FAO-56 P-M method, α is the canopy reflection coefficient (equal to 0.23 for the hypothetical grass reference crop).

The second difference is in the H_b term calculation. In SWAT, H_b is calculated as follows (Jensen et al., 1990; Wright and Jensen, 1972; Brunt, 1932; Doorenbos and Pruitt, 1977):

$$H_b = -\left(0.9 \frac{H_{day}}{H_{MX}} + 0.1\right)\left(0.34 - 0.139\sqrt{e}\right)\sigma T_K^4 \quad (3)$$

where H_{MX} is the maximum possible solar radiation to reach the ground surface on a given day (MJ m^{-2} d^{-1}), e is the vapor pressure on a given day (kPa), T_K^4 is the Stefan-Boltzmann constant (4.903 × 10^{-9} MJ m^{-2} K^{-4} d^{-1}), and T_K is the mean air temperature in Kelvin (273.15 + °C).

In the FAO-56 P-M method, H_b is calculated by the following equation:

$$H_b = -\left(1.35\frac{H_{day}}{H_{MX}} - 0.35\right)\left(0.34 - 0.139\sqrt{e}\right)$$

$$\times \sigma\left(\frac{T_{\max,K}^4 + T_{\min,K}^4}{2}\right) \quad (4)$$

Another difference is in the calculation of the following term:

$$\frac{\rho_{air} c_p}{r_a} \quad (5)$$

In SWAT, considering well-watered plants under neutral atmospheric stability and assuming logarithmic wind profiles, the following equation is used (for wind speed in m s^{-1}) (Jensen et al., 1990) to calculate the term:

$$\frac{\rho_{air} c_p}{r_a} = \frac{\gamma K_1 \left(0.622\lambda \frac{\rho_{air}}{P}\right)}{r_a}$$

$$= \frac{\gamma\left(1710 - 6.85 T_{avg}\right)}{r_a} \quad (6)$$

where K_1 is a dimension coefficient needed to ensure that the two terms in the numerator of the P-M equation have the same units (for u_z in m s^{-1}, $K_1 = 8.64 \times 10^4$), P is the atmospheric pressure (kPa), and T_{avg} is the mean air temperature for the day (°C).

In the FAO-56 P-M method, the term in equation 5 is approximated by the following equation:

$$\frac{\rho_{air} c_p}{r_a} = \gamma \frac{900\lambda}{T + 273} u_2 \quad (7)$$

where u_2 is the wind speed at 2 m (m s^{-1}).

Moreover, the reference crops are alfalfa at a height of 0.40 m with a minimum leaf resistance of 100 s m^{-1} and a crop at a height of 0.12 m, and a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, respectively, in SWAT P-M and FAO-56 P-M.

Model Performance Assessment

Model performance was evaluated by qualitative and quantitative approaches. The qualitative procedure consisted of visually comparing data-display graphics of the observed and simulated values. The hydrologic component of the model was quantitatively evaluated at different time scales by a combination of both summary and difference measures (table 3), as suggested by Willmott (1982), Legates and McCabe (1999), and Krause et al. (2005).

Statistical parameters included the means and standard deviations of both the observed and simulated values (Moriasi et al., 2007). The Nash and Sutcliffe (1970) coefficient of efficiency (E) and its modified form (E_1) were used to assess model efficiency because E results are more sensitive to extreme values, while E_1 better demonstrates significant over- or underprediction by reducing the effect of squared terms. The E and E_1 coefficients were integrated with the root mean square error (RMSE), which describes the difference between the observed values and the model predictions in the unit of the variable (Legates and McCabe, 1999; Krause et al., 2005). In addition, following Willmott (1982), the "systematic" and "unsystematic" portions of the RMSE were quantified. For a "good" model, the systematic error ($RMSE_s$) approaches zero, while the unsystematic error ($RMSE_u$) is close to the RMSE value. The coefficient of residual mass (CRM) was used to indicate model over- or underestimation of the observed values (Loague and Green, 1991; Chanasyk et al., 2003).

Table 3. Coefficients and difference measures for model evaluation and their range of variability.

Coefficient or Measure	Equation	Range of Variability
Coefficient of efficiency (Nash and Sutcliffe, 1970)	$E = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}$	$-\infty$ to 1
Modified coefficient of efficiency (Willmott, 1982)	$E_1 = 1 - \frac{\sum_{i=1}^{n}\left\|O_i - P_i\right\|}{\sum_{i=1}^{n}\left\|O_i - \overline{O}\right\|}$	$-\infty$ to 1
Root mean square error	$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}}$	0 to ∞
Systematic root mean square error (Willmott, 1982)	$\text{RMSE}_s = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{P}_i - O_i\right)^2}{n}}$	0 to ∞
Unsystematic root mean square error (Willmott, 1982)	$\text{RMSE}_u = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - \hat{P}_i\right)^2}{n}}$	0 to ∞
Coefficient of residual mass (Loague and Green, 1991; Chanasyk et al., 2003)	$\text{CRM} = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i}$	$-\infty$ to ∞

where
n = number of observations.
O_i, P_i = observed and predicted values at the time step i.
$\overline{O}$ = mean of observed values.
$\hat{P}_i$ = value predicted by the regression equation at the time step i.

The values considered to be optimal for these criteria were 1 for E and E_1, and 0 for RMSE and CRM (table 3). According to Van Liew and Garbrecht (2003), simulation results are considered good for annual values of E greater than or equal to 0.75, satisfactory for annual values of E between 0.75 and 0.36, and unsatisfactory for values below 0.36.

Model Evaluation Procedure

A model parameter sensitivity analysis was performed to elucidate the model's sensitivity to selected parameters for runoff at the outlet of the Cannata watershed. The Morris qualitative screening method (Morris, 1991) was used initially to determine model sensitivity to selected para–meters among those suggested by the SWAT documentation (Neitsch et al., 2002a) and previous analyses (van Griensven et al., 2006; Veith et al., 2010). The FAO-56 P-M variable was added to the list of parameters in the sensitivity analysis, resulting in a total of 24 parameters screened by the Morris method. This method uses a random one-factor-at-a-time (OAT) design in which only one input parameter (X_i) is modified between two successive runs of the model. The change induced in the model outcome $Y = Y(X_1, X_2, ..., X_m)$ can be unambiguously attributed to such a modification by means of an elementary effect (e_i) defined by:

$$e_i = \frac{Y_{i+1} - Y_i}{\Delta X_i} \tag{8}$$

where Y_{i+1} is the new outcome, Y_i is the previous outcome, and ΔX_i is the variation in the parameter.

Next, a global sensitivity analysis of the parameters that indicated a degree of sensitivity for runoff volume was carried out with the help of the software SimLab (2011), based on the Monte Carlo (MC) method. The MC-based uncertainty and sensitivity analyses are based on performing multiple model evaluations with probabilistically selected model input. The parameters were assumed to be in a uniform distribution. The Latin hypercube sampling (LHS) method was chosen because it can reduce sampling times and it has great computational efficiency (van Griensven et al., 2006; Shen et al., 2008).

Latin hypercube simulation (McKay et al., 1979; Iman and Conover, 1980; McKay, 1988) is based on MC simulation but uses a stratified sampling approach that allows efficient estimation of the output statistics. It subdivides the distribution of each parameter into n strata with a probability of occurrence equal to $1/n$. For uniform distributions, the parameter range is subdivided into n equal intervals. Random values of the parameter are generated such that for each of the m parameters, each interval is sampled only once. This approach results in n non-overlapping realizations. The choice of sample size (n) in LHS depends on the number of parameters (m). Satisfactory results can be obtained with $n > 4/3m$ (Shen et al., 2008). Hence, for the m parameters screened by the Morris method, the range of each parameter was divided into $n = 2m$ subintervals of equivalent probability. The number of the model execution was fixed equal to $10m$, as suggested by the SimLab documentation. Based on the sensitivity analysis results, a rank was assigned to order the parameters on the basis of model sensitivity from the highest (1) to the lowest (m). The parameter with the highest rank was adjusted first, followed by the other parameters. The input parameters that demonstrated negligible variation in the output maintained the SWAT default parameter values. The adjusted parameters and their values are presented in table 4.

The objective of the calibration process was to approach the means and standard deviations calculated for the observed and simulated runoff values, to maximize the summary measures (E, E_1), and to minimize the residuals (RMSE, CRM) at different time scale, following the approach to continuous simulation model evaluations proposed by Neitsch et al. (2002a).

Table 4. Parameters ranges and results of the sensitivity analysis at the outlet of the Cannata watershed.

Name	Min.	Max.	Definition	Process[a]	Rank of SA for Annual R	Calibrated Value or Method
ALPHA_BF	0	1	Base flow alpha factor (days)	GW	--	--
CH_COV	-0.001	1	Channel cover factor	E	--	--
CH_EROD	-0.05	0.6	Channel erodibility factor	E	--	--
CH_K2	-0.01	150	Effective hydraulic conductivity in main channel alluvium (mm h^{-1})	C	--	--
CH_K1	0	150	Effective hydraulic conductivity in tributary channel alluvium (mm h^{-1})	C	--	--
CH_N2	-0.01	0.3	Manning coefficient for channel	C	--	--
CH_N1	0.01	30	Manning coefficient for the tributary channels	C	--	--
CN2[b]	35	98	SCS runoff curve number for moisture condition II	R	2	81-89
EPCO	0	1	Plant evaporation compensation factor	Ev	--	--
ESCO	0	1	Soil evaporation compensation factor	Ev	--	--
GW_REVAP	0.02	0.2	Groundwater “revap” coefficient	GW	--	--
GWQMN	0	5000	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	S	--	--
PET[c]	0	7.2	Potential evapotranspiration in the Cannata watershed (mm d^{-1})	ET	1	FAO-56 P-M
RCHR_DP	0	1	Groundwater recharge to deep aquifer (fraction)	GW	--	--
REVAPMN	0	500	Threshold depth of water in the shallow aquifer required for “revap” to occur (mm)	GW	--	--
SLOPE	0.0001	0.6	Average slope steepness (m m^{-1})	GM	--	--
SLSUBBSN	10	150	Average slope length (m)[d]	GM	--	--
SOL_AWC	0	1	Available water capacity of the soil layer (mm mm^{-1} soil)	S	6	0.19-0.23
SOL_Z	0	3000	Soil depth (mm)	S	4	3000
SPCON	0.001	0.01	Linear parameter for calculating the channel sediment routing	C	--	--
SPEXP	1	1.5	Exponent parameter for calculating the channel sediment routing	C	3	1.5
SURLAG	0	10	Surface runoff lag coefficient	R	7	4
USLE_C[b]	0.001	0.5	USLE equation land cover/plant (C) factor	E	5	0.04/0.4[e]
USLE_P	0.1	1	USLE equation support practice (P) factor	E	--	--

[a] GW = groundwater; E = erosion; C = channel; R = runoff; Ev = evaporation; GM = geomorphology; S = soil.
[b] The temporal variation of both CN2 and USLE_C factor was not calibrated.
[c] PET was calibrated by using the different estimation methods in SWAT and the FAO-56 P-M equation.
[d] On the basis of the DEM.
[e] For pasture and winter wheat, respectively.

The split-sample technique (Klemes, 1986) was used to evaluate the hydrologic component of the model. In particular, the observed surface runoff volumes from October 1996 to December 2000 at the watershed outlet were used for model calibration at annual, monthly, and event scales. It was necessary to use the surface runoff measured from October to December 1996 in the calibration process because the following years were dryer than the years used for validation. The performance of the calibrated model was evaluated for the period of January 2001 to December 2003. The surface runoff calibration and validation time periods were selected because they each have representative wet and dry events (Green et al., 2006).

Results

Surface Runoff Volumes

The Morris screening method identified seven parameters to which the model indicated sensitivity related to annual surface runoff at the outlet of the Cannata watershed. Table 4 presents the parameter ranking (based on model sensitivity) and calibrated values that gave the best performance of the SWAT model regarding surface runoff volumes. To determine the PET method to which the SWAT model demonstrated the greatest sensitivity impacting surface runoff, calibration simulations used the following PET estimation methods: SWAT P-M (simulation series I), Hargreaves (II), Priestley-Taylor (III), and the FAO-56 P-M equation.

The results of the statistics of the calibration and validation process for surface runoff volumes at annual, monthly, and daily scales are presented in table 5. The cumulative simulated surface runoff volume from October 1996 to December 2000 (356.5 mm) was only slightly higher than the observed value (343.5 mm). The simulation of surface runoff was good (E > 0.75) at annual, monthly, and event scales. The goodness of fit between the observed and simulated surface runoff volumes was also confirmed by the satisfactory values of E_1 and the low values of RMSE and CRM. As expected, the coefficient E_1 was less sensitive to peaks (Krause et al., 2005) and was generally lower than E. The $RMSE_u$ was higher than $RMSE_s$ at each time scale, confirming the good model performance (Willmott, 1982).

A logarithmic scale was used to facilitate a better visual comparison of the observed and simulated daily surface runoff flows (fig. 2). The four observed surface flows higher than 30 mm that occurred in the calibration period were underestimated by the model.

Table 5. Coefficients, summary, and difference measures applied to surface runoff at different time scales for calibration and validation tests at the Cannata watershed, Sicily.

	Surface Runoff	Mean (mm)	SD (mm)	E	E_1	RMSE (mm)	$RMSE_s$ (mm)	$RMSE_u$ (mm)	CRM
Calibration (Oct. 1996 to Dec. 2000)									
Annual scale	Observed	68.7	39.1	0.8	0.6	22.4	14.6	17.1	-0.04
	Simulated	71.3	58.5						
Monthly scale	Observed	6.7	15.0	0.8	0.6	6.9	4.0	5.0	-0.04
	Simulated	7.0	11.3						
Event scale	Observed	0.2	2.3	0.8	0.6	1.1	0.6	0.9	-0.04
	Simulated	0.2	1.8						
Validation (Jan. 2001 to Dec. 2003)									
Annual scale	Observed	141.0	121.8	0.9	0.7	32.4	32.1	13.7	0.2
	Simulated	117.5	95.1						
Monthly scale	Observed	11.8	29.5	0.9	0.6	9.0	8.0	5.0	0.2
	Simulated	9.79	22.8						
Event scale	Observed	0.4	4.9	0.9	0.6	1.7	1.3	1.2	0.2
	Simulated	0.3	3.9						

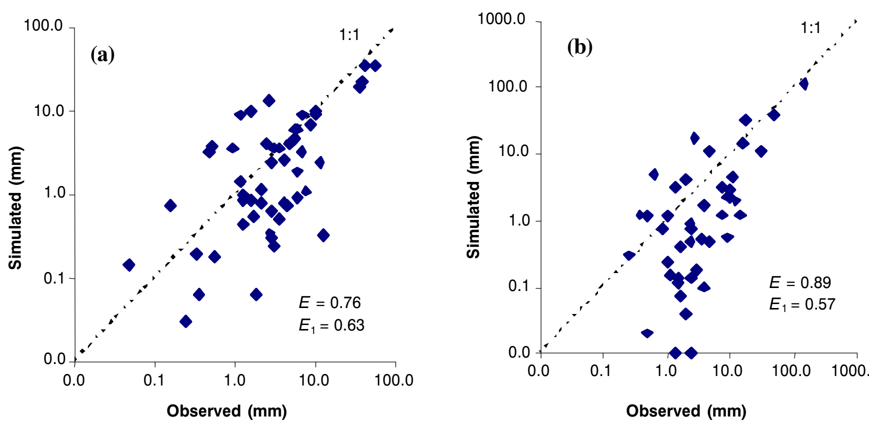

Figure 2. Portion of observed and simulated daily surface flows for (a) calibration and (b) validation periods at the Cannata watershed, Sicily.

Table 6. Predicted hydrologic budget for the Cannata watershed from October 1996 through December 2003.

Hydrologic Component	Calibration (Oct. 1996 to Dec. 2000) Obs. (mm)	Calibration Sim. (mm)	Validation (Jan. 2001 to Dec. 2003) Obs. (mm)	Validation Sim. (mm)
Precipitation[a]	591.2	591.2	809.2	809.2
Surface runoff	52.2	68.3	141.0	113.8
Lateral flow	16.2	10.8	44.4	12.5
Groundwater flow		3.3		0.0
ET	--	598.6	--	619.4
PET[b]	--	925.4	--	1134.8

[a] Determined by interpolation.
[b] Using the FAO-56 P-M equation.

The simulation for the validation period had good and satisfactory values of E and E_1, respectively, at each time scale. However, an underestimation was highlighted by the differences in summary measures between observed and simulated values. The underestimation was confirmed by the high values of RMSE (especially its systematic part) and by the positive value of CRM. The three events higher than 30 mm were underestimated by up to 64% (fig. 2). In table 6, the complete water balance at the Cannata watershed is shown for the calibration and validation periods.

Discussion

Hydrological Component

The sensitivity analysis results obtained from this study are very similar to those of other studies except for the inclusion of the FAO-56 P-M PET parameter. The PET method-related runoff simulations that represented the changing of additional parameters to which the model was sensitive were not statistically significant (α = 0.05) compared with the improvements obtained by using the FAO-56 P-M equation. The reason that the surface runoff is more sensitive to PET as compared with other input parameters can be due to location and cover type (Federer et al., 2006).

An evaluation of the entire period of simulation (1996-2003) indicated that the average PET simulated by the FAO-56 P-M equation resulted in 28% greater values compared to using the traditional SWAT P-M method and 20% and 3% smaller values than the values calculated by using the Hargreaves and Priestley-Taylor equations, respectively (table 7). In terms of ET, the differences were smaller (17%, 3% and 1%, respectively; table 7). On a monthly scale, considering the FAO-56 P-M equation as a baseline, the SWAT P-M and Priestly-Taylor equations underestimated the ET for 76% and 53% of the months, respectively, and the Hargreaves equation overestimated the ET for 80% of the months. The differences in both cases were higher during the peak season of evaporative demand (April-August) (fig. 3).

Table 7. Yearly potential and actual evapotranspiration simulated by the SWAT model at the Cannata watershed, Sicily using the SWAT P-M equation (series I), the Hargreaves equation (II), the Priestley-Taylor equation (III), and the FAO-56 P-M equation (IV).

Complete Year	Precipitation[a] (mm)	PET (mm) I	PET II	PET III	PET IV	ET (mm) I	ET II	ET III	ET IV
1997	725.2	663.0	1154.7	961.3	927.5	482.6	686.0	658.2	642.0
1998	534.4	633.1	1110.0	917.0	916.9	459.5	641.5	624.2	620.0
1999	527.4	617.4	1196.6	889.2	936.5	438.0	529.3	519.9	543.3
2000	577.9	599.1	1169.5	863.9	967.8	430.9	519.9	504.9	526.8
2001	606.4	793.5	1206.0	1149.8	1053.7	516.9	563.4	586.8	558.9
2002	803.9	792.6	1202.2	1144.7	1024.4	520.6	557.7	555.8	547.6
2003	1017.3	774.6	1171.2	1109.9	984.2	557.7	722.2	715.8	670.3
Average	684.6	696.2	1172.9	1005.1	973.0	486.6	602.8	595.1	587.0

PET = Potential Evapotranspiration (PET, mm) by Series; ET = Actual Evapotranspiration (ET, mm) by Series.

[a] Determined by interpolation.

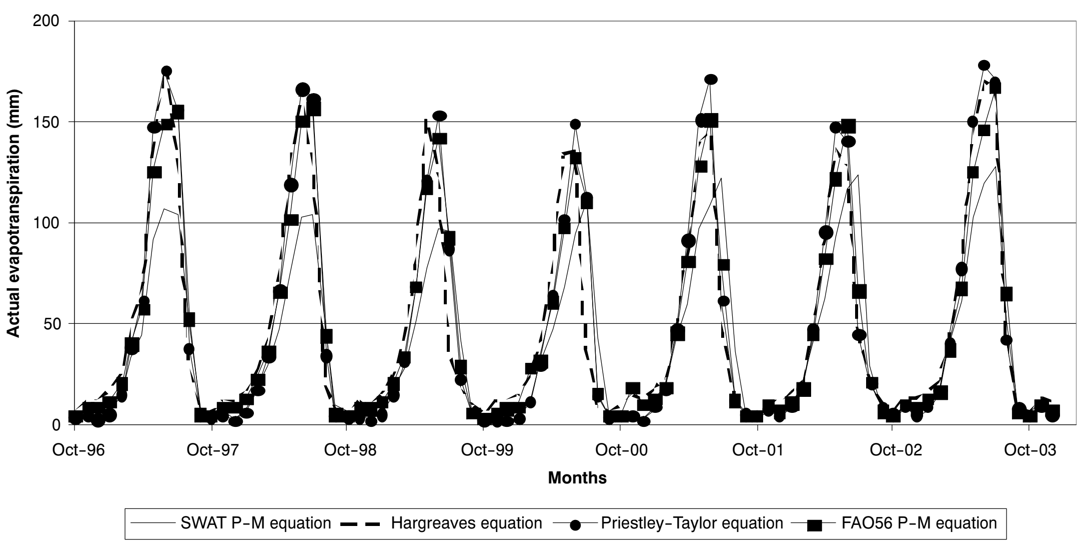

Figure 3. Monthly values of ET calculated by the SWAT P-M, Hargreaves, Priestley-Taylor, and FAO-56 P-M equations in the period October 1996 through December 2003 for the Cannata watershed, Sicily.

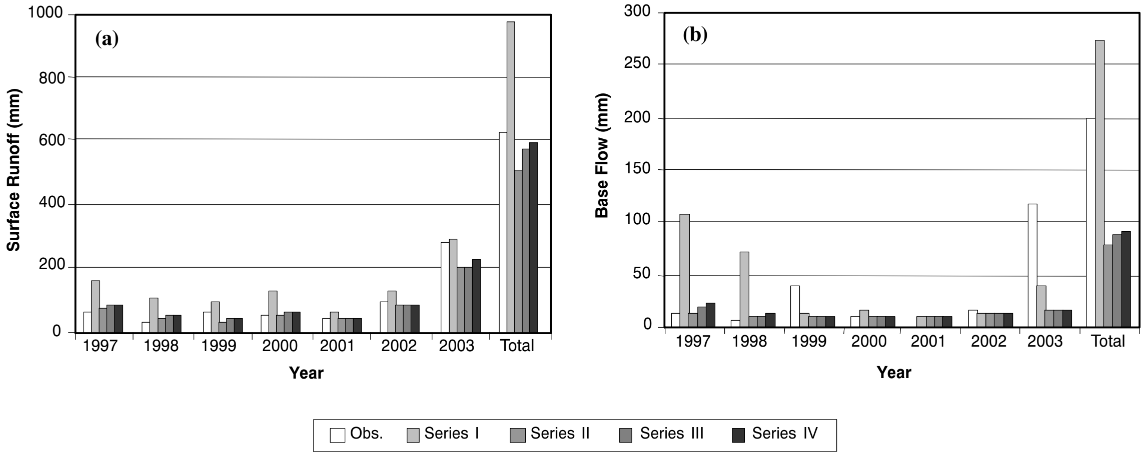

Figure 4. Yearly observed and simulated (a) surface runoff and (b) base flow at the Cannata watershed, Sicily, obtained using the SWAT P-M equation (series I), the Hargreaves equation (II), the Priestley-Taylor equation (III), and the FAO-56 P-M equation (IV).

The differences in PET estimations by different methods can be due to several reasons (e.g., different assumption or data requirements; Wang et al., 2006). It can be useful for the user to know the sources of the differences in the PET estimations by the two P-M methods used here. In particular, while it was not easy to quantify the difference due to the term α, the H_b value calculated by SWAT resulted in an underestimation compared to the H_b value calculated by FAO-56 P-M. Moreover, the bigger the difference between H_{day} and H_{MX} (the cloudiness increases), the bigger the difference was between the H_b estimations by the two methods. Considering the calculation of the $(\rho_{air}\, c_p)/r_a$ term, it was found that the higher the wind speed and the bigger the saturation vapor pressure deficit ($e_z^0 - e_z$), the bigger the difference was between the two methods in the second addendum of the P-M equation. The difference in the reference crops gave small differences in the determination of the plant canopy resistance and the diffusion resistance of the air layer (aerodynamic resistance). In particular, in SWAT P-M, r_c and r_a for the reference crop are equal to:

$$r_c = \frac{49}{\left(1.4 - 0.4\dfrac{CO_2}{330}\right)} \tag{9}$$

where the default value for CO_2 equal to 330 ppmv is r_c = 49.

$$r_a = \frac{114}{u_z} \tag{10}$$

where u_z is the wind speed at z m (m s^{-1}).

In FAO-56 P-M, r_c and r_a are calculated by:

$$r_c = 70 \text{ s m}^{-1} \tag{11}$$

$$r_a = \frac{208}{u_2} \tag{12}$$

To obtain Hargreaves PET value estimations closer to the FAO-56 P-M method results, the conversion factor and the exponent for the change in humidity need to be changed. The EPIC model (Sharpley and Williams, 1990) uses a default value of 0.0032 and an exponent value of 0.6, rather than 0.0023 and 0.5, respectively, to increase simulation accuracy for humidity in the southern region of the U.S., which is similar to the humidity in Sicily.

Surface runoff volumes varied depending on the method of PET and ET estimation. In particular, the SWAT model overestimated by approximately 50% the total (surface and base) runoff observed at an annual scale during the entire period (October 1996 to December 2003) using the traditional default P-M method. Total annual runoff volumes were underestimated by approximately 29%, 20%, and 17% when the Hargreaves, Priestley-Taylor, and FAO-56 P-M methods were used, respectively (fig. 4).

When the traditional SWAT P-M method was used, the total annual runoff was larger than the observed volumes in six of the seven years. The simulated annual total runoff was underestimated for four of the seven years, with the higher observed surface runoff when the FAO-56 P-M equation was used. The Hargreaves and Priestley-Taylor methods resulted in underestimation of total runoff for five and four of the seven years, respectively. The use of the traditional P-M method resulted in the smallest difference with the base flow estimation (38%) but the greatest difference in the surface runoff estimation (54%) (fig. 4). The FAO-56 P-M, Priestley-Taylor, and Hargreaves equations resulted in daily surface runoff underestimated values of 32%, 37% and 38%, respectively (considering 71 observed daily surface flow values higher than 1 mm). Use of the FAO-56 P-M equation minimized the daily surface flow overestimation obtained with the traditional SWAT P-M equation (from 1082% to 660%, respectively), allowing the water balance to be more representative of the Cannata watershed. This result is probably due to the peculiarity of the hydrologic processes in Mediterranean regions. Runoff depends on catchment characteristics, antecedent hydrologic conditions, and rainfall event variability, including low runoff coefficients reflecting short-duration, high-intensity convective storms over dry soils (Licciardello et al., 2007; Latron et al., 2003).

The underestimated disparity present between the daily observed and SWAT-simulated surface runoff volumes, especially for the most significant events (higher than 30 mm), was also determined by Govender and Everson (2005). These authors had E = 0.68 for a small natural uld be due, at least in part, to the fact that both empirical and physically based models are deterministic in nature, and observed data have a significant random component for which models cannot account within the deterministic framework (Nearing, 1998). Additionally, the model output is only as good as the input data. The daily-scale runoff volumes are the most difficult to represent because of the short-duration, high-intensity rainfall that occurs in this region.

It should be noted that the values of E and E_1 were generally higher in the validation period than in the calibration period, most likely due to the presence of more rainfall events generating significant runoff volumes from 2001 to 2003. Gómez et al. (2001) found that large rainfall events resulted in higher E values (table 5).

Conclusions

Results for the SWAT model hydrologic simulation of a Cannata, Sicily, watershed were promising after the traditional SWAT P-M equation was replaced with the FAO-56 P-M equation, which is more representative of a Mediterranean climate. Overall, the statistics for the daily timescale were best when the FAO-56 P-M method was employed. The model was more sensitive to this PET method, as evidenced by a model sensitivity analysis, than to the other six parameters that impact surface runoff volume. Observed surface flows higher than 30 mm were underestimated in both the calibration and validation periods. The incorporation of the FAO-56 P-M PET method has broadened the model's applicability to watersheds in semi-arid environments with high-intensity, short-duration rainfall events.

Acknowledgement

The authors wish to thank Jeff Arnold for his helpful comments.

References

Allen, R. G., M. E. Jensen, J. L. Wright, and R. D. Barman. 1989. Operational estimates of reference evapotranspiration. *Agron. J.* 81(4): 650-662.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy: United Nations FAO.

Arnold, J. G., and P. M. Allen. 1996. Estimating hydrologic budgets for three Illinois watersheds. *J. Hydrol.* 176(1-4): 57-77.

Arnold, J. G., and P. M. Allen. 1999. Automated methods for estimating baseflow and groundwater recharge from streamflow records. *J. American Water Res. Assoc.* 35(2): 411-424.

Arnold, J. G., and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modelling. *Hydrol. Proc.* 19(3): 563-572.

Arnold, J. G., J. R. Williams, A. D. Nicks, and N. B. Sammons. 1990. *SWRRB: A Basin-Scale Simulation Model for Soil and Water Resources Management.* College Station, Tex.: Texas A&M University Press.

Arnold, J. G., P. M. Allen, and G. Bernhardt. 1993. A comprehensive surface-groundwater flow model. *J. Hydrol.* 142(1-4): 47-69.

Arnold, J. G., P. M. Allen, R. Muttiah, and G. Bernhardt. 1995. Automated base flow separation and recession analysis techniques, *Ground Water* 33(6): 1010-1018.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Res. Assoc.* 34(1): 73-89.

Brunt, D. 1932. Notes on radiation in the atmosphere. *Qtly. J. Roy. Meteorol. Soc.* 58(247): 389-418.

Canton, Y., A. Sole-Benet, I. Queralt, and R. Pini. 2001. Weathering of a gypsum-calcareous mudstone under semi-arid environment at Tabernas, SE Spain: Laboratory and field-based experimental approaches. *Catena* 44(2): 111-132.

Cau, P., A. Cadeddu, G. Lecca, C. Gallo, and M. Marrocu. 2005. Calcolo del bilancio idrico della regione Sardegna con il modello idrologico SWAT. *L'Acqua* 5: 29-38.

Chanasyk, D. S., E. Mapfumo, and W. Willms. 2003. Quantification and simulation of surface runoff from fescue grassland watersheds. *Agric. Waste Mgmt.* 59(2): 137-153.

Chaplot, V. 2005. Impact of DEM mesh size and soil map scale on SWAT runoff, sediment, and NO_3-N loads predictions. *J. Hydrol.* 312(1-4): 207-222.

Chow, V. T., D. R. Maidment, and L. W. Mays. 1988. *Applied Hydrology.* New York, N.Y.: McGraw-Hill.

Di Luzio, M., J. G. Arnold, R. Srinivasan, and S. L. Neitch. 2002. ArcView interface for SWAT2000: User's guide. TWRI Report TR-193. College Station, Tex.: Texas Water Resources Institute.

Di Luzio, M., J. G. Arnold, and R. Srinivasan. 2005. Effect of GIS data quality on small watershed streamflow and sediment simulations. *Hydrol. Proc.* 19(3): 629-650.

Doorenbos, J., and W. O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drain. Paper 24. 2nd ed. Rome, Italy: United Nations FAO.

European Union. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Brussels, Belgium: European Commission.

Federer C. A., C. Vorosmarty, and B. Fekete. 1996. Intercomparison of methods for calculating potential evapotranspiration in regional and global water balance models. *Water Resour. Res.* 32(7): 2315-2321.

Gassman, P. W., M. Reyes, C. H. Green, and J. G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Trans. ASABE* 50(4): 1211-1250.

Gikas, G. D., T. Yiannakopoulou, and V. A. Tsihrintzis. 2006. Modeling of non-point source pollution in a Mediterranean drainage basin. *Environ. Model. Assess.* 11(2): 219-233.

Gómez, J. A, M. A. Nearing, J. V. Giráldez, and E. E. Alberts. 2001. Analysis of sources of variability of runoff volume in a 40-plot experiment using a numerical model. *J. Hydrol.* 248(1-4): 183-197.

Govender, M., and C. S. Everson. 2005. Modelling streamflow from two small South African experimental catchments using the SWAT model. *Hydrol. Proc.* 19(3): 683-692.

Green, C. H., M. D. Tomer, M. Di Luzio, and J. G. Arnold. 2006. Hydrologic evaluation of the soil and water assessment tool for a large tile-drained watershed in Iowa. *Trans. ASABE* 49(2): 413-422.

Hargreaves, G. L., G. H. Hargreaves, and J. P. Riley. 1985. Agricultural benefits for Senegal River watershed. *J. Irrig. Drain. Eng.* 111(2): 113-124.

Iman, R. L., and W. J. Conover. 1980. Small sample sensitivity analysis techniques for computer models, with an application to risk assessment. *Comm. in Statistics: Theory and Methods* A9(17): 1749-1842.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. *Evapotranspiration and Irrigation Water Requirements.* ASCE Manuals and Reports on Engineering Practice No. 70. Reston, Va.: ASCE.

Kannan, N., S. M. White, F. Worral, and M. J. Whelan. 2007. Sensitivity analysis and identification of the best evapotranspiration and runoff options for hydrological modelling in SWAT-2000. *J. Hydrol.* 322(3-4): 456-466.

Kiniry, J. R., J. R. Williams, P. W. Gassman, and P. Debaeke. 1992. A general, process-oriented model for two competing plant species. *Trans. ASAE* 35(3): 801-810.

Klemes, V. 1986. Operation testing of hydrological simulation models. *Hydrol. Sci. J.* 31(1-3): 13-24.

Krause, P., D. P. Boyle, and F. Base. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Adv. Geosci.* 5: 89-97

Latron, J., S. Anderton, S. White, P. Llorens, and F. Gallart. 2003. Seasonal characteristics of the hydrological response in a Mediterranean mountain research catchment (Vallcebre, Catalan Pyrenees): Field investigations and modelling. In *Proc. Intl. Symp. Hydrology of the Mediterranean and Semiarid Regions*, 106-110. IAHS Publ. No. 278. International Association of Hydrological Sciences.

Legates, D. R., and G. J. McCabe. 1999. Evaluating the use of “goodness of fit” measures in hydrologic and hydroclimatic model validation. *Water Resour. Res.* 35(1): 233-241.

Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: Groundwater Loading Effects on Agricultural Management Systems. *Trans. ASAE* 30(5): 1403-1428.

Licciardello, F., and S. M. Zimbone. 2002. Runoff and erosion modeling by AGNPS in an experimental Mediterranean watershed. In *Proc. ASAE Annual Intl. Meeting and CIGR XVth World Congress.* St. Joseph, Mich.: ASAE.

Licciardello, F., E. Amore, M. A. Nearing, and S. M. Zimbone. 2006. Runoff and erosion modelling by WEPP in an experimental Mediterranean watershed. In *Soil Erosion and Sediment Redistribution in River Catchments: Measurement, Modelling and Management*, 186-194. P. N. Owens and A. J. Collins, eds. Wallingford, U.K.: CABI.

Licciardello, F., D. A. Zema, S. M. Zimbone, and R. L. Bingner. 2007. Runoff and soil erosion evaluation by the AnnAGNPS model in a small Mediterranean watershed. *Tran. ASABE* 50(5): 1585-1593.

Licciardello, F., G. Govers, O. Cerdan, M. J. Kirkby, A. Vacca and F. J. P. M. Kwaad. 2008. Evaluation of PESERA model in two contrasting environments. *Earth Surf. Proc. Land.* 34(5): 629-640.

Loague, K., and R. E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. *J. Contam. Hydrol.* 7(1-2): 51-73.

Lopez-Urrea R., F. Martin de Santa Olalla, C. Fabeiro, and A. Moratalla. 2006. Testing evapotranspiration equations using lysimeter observation in a semiarid climate. *Agric. Water Mgmt.* 85(1-2): 15-26.

McKay, M. D. 1988. Uncertainty analysis. In *Sensitivity and Uncertainty Analysis Using a Statistical Sample of Input Values*, 145-186. Y. Ronoen, ed. Boca Raton, Fla.: CRC Press.

McKay, M. D., R. J. Beckman, and W. J. Conover. 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics* 21(2): 239-245.

Moussa, R., N. Chahinian, and C. Bocquillon. 2007. Distributed hydrological modelling of a Mediterranean mountainous catchment: Model construction and multi-site validation. *J. Hydrol.* 337(1-2): 35-51.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulation. *Trans. ASABE* 50(3): 885-900.

Morris, M. D. 1991. Factorial sampling plans for preliminary computational experiments. *Technometrics* 33(2): 161-174.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: 1. A discussion of principles. *J. Hydrol.* 10(3): 282-290.

Nearing, M. A. 1998. Why soil erosion model overpredict small soil losses and underpredict large soil losses. *Catena* 32(1): 15-22.

Nearing, M. A., F. F. Pruski, and M. R. O’Neal. 2004. Expected climate change impacts on soil erosion rates: A review. *J. Soil Water Cons.* 59(1): 43-50.

Neitsch, J. G., J. G. Arnold, J. R. Kiniry, R. Srinivasan, and K. W. Williams. 2002a. *SWAT: Soil and Water Assessment Tool. User’s Manual, Version 2000*. TWRI Report TR-193. College Station, Tex.: Texas Water Resources Institute.

Neitsch, J. G., J. G. Arnold, J. R. Kiniry, J. R. Williams, and K. W. King. 2002b. *Soil and Water Assessment Tool: Theoretical Documentation. Version 2000*. TWRI Report TR-191. College Station, Tex.: Texas Water Resources Institute.

Priestley, C. H. B., and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* 100(2): 81-92.

Sharpley, A. N., and J. R. Williams. 1990. EPIC —Erosion/ productivity impact calculator: 1. Model documentation. Tech. Bulletin No. 1768. Washington, D.C.: USDA.

Shen Z., Q. Hong, H. Yu, and R. Liu. 2008. Parameter uncertainty analysis of the non-point source pollution in the Daning River watershed of the Three Gorges Reservoir region, China. *Sci. Total Environ.* 405(1-3): 195-205.

SimLab. 2011. Software package for uncertainty and sensitivity analysis. Version 2.2. Joint Research Centre of the European Commission. Downloadable for free at: http://simlab.jrc.ec.europa.eu.

Sulis, M., M. G. Badas, R. Deidda, E. Piga, M. Marrocu, and C. Paniconi. 2004. Applicazione del modello SWAT al bacino dell’Araxisi. In *Proc. XXIX Convegno Nazionale di Idraulica e Costruzioni Idrauliche*, 677-683. Trento, Italy: Editorial BIOS.

Tripathi, M. P., R. K. Panda, N. S. Raghuwanshi, and R. Singh. 2004. Hydrological modelling of a small watershed using generated rainfall in the soil and water assessment tool model. *Hydrol. Proc.* 18(10): 1811-1821.

United Nations. 1992. *Agenda 21: The United Nations Program of Action from Rio*. New York, N.Y.: United Nations Division for Sustainable Development.

USDA-SCS. 1972. Section 4: Hydrology. In *National Engineering Handbook*. Washington, D.C.: USDA Soil Conservation Service.

USDA-SCS. 1986. Urban hydrology for small watersheds. Tech. Release 55. Washington, D.C.: USDA Soil Conservation Service.

Van Griensven A., T. Maixner, S. Grunwanld, T. Bishop, M. Diluzio, and R. Srinivasan. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. *J. Hydrol.* 324(1-4): 10-23.

Van Liew, M. W., and J. Garbrecht. 2003. Hydrologic simulation of the Little Washita River experimental watershed using SWAT. *J. American Water Resour. Assoc.* 39(2): 413-426.

Veith, T. L., M. W. Van Liew, D. D. Bosch, and J. G. Arnold. 2010. Parameter sensitivity and uncertainty in SWAT: A comparison across five USDA-ARS watersheds. *Tran. ASABE* 53(5): 1477-1485.

Wang X., A. M. Melesse, and W. Yang. 2006. Influences of potential evapotranspiration estimation methods on SWAT’s hydrologic simulation in a northwestern Minnesota watershed. *Trans. ASABE* 49(6): 1755-1771.

Williams, J. R., C. A. Jones, and P. T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129-144.

Willmott, C. J. 1982. Some comments on the evaluation of model performance. *Bull. American Meteorol. Soc.* 63(11): 1309-1313.

Wright, J. L., and M. E. Jensen. 1972. Peak water requirements of crops in southern Idaho. *J. Irrig. Drain. Div. ASCE* 96(IRI): 193-201.

Zhang, X. C., and M. A. Nearing. 2005. Impact of climate change on soil erosion, runoff, and wheat productivity in central Oklahoma. *Catena* 61(2-3): 185-195.