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Water balance estimation via SESOIL: Pinios River Basin, Greece

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Abstract The mathematical modelling of a river basin water balance is a complex process which requires extensive calibration and the use of data that are frequently not available. The seasonal soil compartment model, SESOIL, of the USEPA, is an international tool well suited for this purpose. Knowledge of the water balance on an annual or a monthly basis is particularly important in regions with increased water demand and limited resources. SESOIL has been applied to the Pinios River Basin in Central Greece. Observed input and simulated output are discussed. The model behaved well. The study extends the use of SESOIL which can be run with limited calibration compared to other models in the literature and with data readily available in Europe such as the Corine land cover. Simulations can be used for water allocation practices, water related impacts due to climatic changes and other human activities indicated in the new EC Water Framework Directive EC/2000/60.

Keywords Hydrology · Mathematical modelling · Pinios River · Water balance · Water resources · SESOIL · EC Directive 2000/60

Résumé La modélisation numérique du bilan hydrologique d'un bassin versant est une opération complexe qui demande d'importantes calibrations et des données qui ne sont pas toujours disponibles. Le modèle SESOIL d'USEPA est un outil international bien adapté. La connaissance des bilans hydrologiques, sur une base mensuelle ou annuelle, est particulièrement importante pour des régions où la demande en eau augmente et où les ressources sont limitées. SESOIL a été utilisé pour le bassin versant de Pinios en Grèce centrale. Les données d'entrée du modèle, mesurées, et les résultats de sortie du modèle, calculés, sont discutés. Le modèle se comporte correctement. L'étude ètend le domaine d'application de SESOIL qui peut être mis enœuvre avec peu de calibrations, comparé aux autres modèles du commerce, et avec des données facilement disponibles en Europe telles que le modèle de terrain Corine. Des simulations peuvent être réalisées pour des projets de distribution d'eau, pour étudier les conséquences hydrologiques de changements climatiques et d'activités anthropiques décrites dans la nouvelle Directive européenne EC/2000/60.

Mots clés Hydrologie · Modélisation numérique · Rivière Pinios · Bilan hydrologique · Ressources en eau · SESOIL · Directive européenne

Introduction

The European Commission/Eurostat supported research for the implementation of the USEPA seasonal soil compartment model SESOIL (Bonazountas and Wagner 1984) to estimate river basin water balances on a European scale, including the Pinios River Basin in Greece. The aim has been to test SESOIL in Europe using limited data input and calibration procedures.

SESOIL is a one-dimensional vertical transport software code for the "unsaturated soil zone". It is a unique model, both in its structure and mathematics. It is an integrated screening level soil compartment model and is designed to simultaneously model water transport, sediment transport and pollutant fate as originating from natural and man's activities.

The EPA Office of Toxic Substances (OTS) uses the model to predict the behaviour of pollutants in soil compartments for analysing and prioritising new chemical exposures. Numerous studies have been conducted with SESOIL since 1984, including sensitivity analysis, comparison with other models and comparisons with field data (Bonazountas and Fiksel 1982; Hetrick 1984; Kincaid et al. 1984; Watson and Brown 1985; Melancon et al. 1986; Hetrick and Travis 1988; Hetrick et al. 1989). SESOIL has also been applied in risk assessments of coal liquefaction (Walsh et al. 1984), incineration of hazardous waste (Holton et al. 1985; Travis et al. 1986; Ladwig et al. 1993), the transport of benzene to groundwater (Tucker et al. 1986), remediating soils in California (Odencrantz et al. 1992), site sensitivity ranking of Wisconsin soils (Ladwig et al. 1992) and for many other applications (see Vighi and Funari 1995).

The SESOIL model predictions of watershed hydrological components have been compared to those of more data-intensive terrestrial ecosystem models (Hetrick et al. 1982) and empirical measurements at watershed levels (Hetrick et al. 1986). Although there were some differences in monthly results between the two models, good agreement was obtained between model predictions for annual values of infiltration, evapotranspiration, surface runoff and groundwater runoff (recharge). SESOIL model predictions compared well with the empirical measurements at the forest stand and the grassland watersheds.

The hydrological cycle of the model has been adapted from the water balance dynamics theory of Eagleson (1978), with the annual balance:

$$P - E - \mathrm{MR} = S + G = Y \quad (1)$$

$$I = P - S \quad (2)$$

where P is precipitation, E evapotranspiration, MR moisture retention, S surface runoff, G groundwater runoff, Y yield, I infiltration. A list of the SESOIL hydrological equations is provided in Table 1.

Table 1 SESOIL hydrologic equations

Infiltration	$fi(t,s_o) = (1-s_o)\left[\frac{5nK(1)\Psi(1)\phi_i(d,s_o)}{3\pi mt}\right]^{1/2} + \frac{1}{2}K(1)\left[1+s_o^c\right] - w$ Where $\phi i = 10^{\left(0.66+\frac{0.55}{m}+\frac{0.14}{m^2}\right)}$
Precipitation distribution	$\mathrm{Pr}\,ob\left[\frac{P_A}{m_{PA}}<z\right] = \mathrm{e}^{-\omega m\tau}\left\{1+\sum_{\nu=1}^{\infty}\frac{(\omega m_\tau)^\nu}{\nu!}P[\nu\kappa, \omega m_\tau \kappa z]\right\}$
Capillary rise	$w = \left[\frac{mc+0.5}{mc-1}\right]K(1)\left[\frac{\Psi(1)}{\mathrm{Z}}\right]^{mc}; \quad w/e_p \leqslant 1$ Where $\psi(1) = \frac{\sigma_w}{\gamma_w}\left[\frac{n}{k(1)\phi(c)}\right]^{1/2}$
Ex-filtration	$fe(t,s_o) = s_o^{1+d/2}\left[\frac{nK(1)\Psi(1)\phi e(d)}{\pi mt}\right]^{1/2} + w$
Percolation	$v(s_o) = K(1)s_o^c - w$
Annual average surface runoff $E[R_{\mathrm{SA}}]$	$\frac{E[R_{SA}]}{m_{PA}} = \mathrm{e}^{-G-2\sigma}\Gamma(\sigma+1)/\sigma^\sigma$
Net Infiltration	$\frac{E[I_A]}{E[P_A]} = 1 - \mathrm{e}^{-G-2\sigma}\Gamma(\sigma+1)/\sigma^\sigma = 1 - \xi$
Potential evapotranspiration	$\bar{e}_p = \frac{\bar{q}_i(1-A)-\bar{q}_b+H}{\rho_e L_e(1+\gamma/\Delta)}$
Annual evapotranspiration	$\frac{\mathrm{E[E_{TA}]}}{\mathrm{E}[\mathrm{E}_{PA}]} = J(E) = 1 - [1+2^{1/2}E]\mathrm{e}^{-E} + (2E)^{1/2}\Gamma\left[\frac{3}{2},\mathrm{E}\right]$ Where $\mathrm{E} = \frac{2\beta nK(1)\Psi(1)\phi_e(d)}{\pi m(\bar{e}_p-w)^2}s_o^{d+2}$
Groundwater runoff	$\frac{E[R_{gA}]}{m_{PA}} = \frac{m_\tau \mathrm{K}(1)}{m_{PA}}s_o^c - \frac{Tw}{m_{PA}}$
Seasonal spatial average soil moisture	$\Delta S_{u\,\Delta t} = nZ_r\int_{t_o}^{t_o+\Delta t}\frac{\partial s(t)}{\partial t}dt = \int_{t_o}^{t_o+\Delta t}\{fi(t) - e_T(t) + v_{ss}(t) - p_N(t)\}dt$ Where $p_N(T) \equiv K(1)s^c(t) - w$ $\Delta Su_A = nZ_r(\bar{s}_j - \bar{s}_{j-1}) = V_{su\,j} - V_{su\,j-1}$
Interflow	$E[I_A] - v(s_o) - \bar{s}$ $\Delta Su_A = nZ_r(\bar{s} - s_o)$

Pinios River Basin application

General

This paper discusses the application of the SESOIL model to the Pinios River Basin, Thessalia, Central Greece (Fig. 1) where the water requirements are for the municipal water supply, industrial use, irrigation and the maintenance of the ecological balance.

The total length of the Pinios River is 206 km and the mean annual flow 81 m^3/s. However, during the summer the river is unable to supply sufficient clean water in view of both the reduced flow and the pollution by agrochemical, municipal and industrial effluents.

Input

For this research hydrology/climate observations available from public services organisations have been used. Rainfall and climatic data (1950–today) were obtained from the monitoring stations of the Ministry of Environment, Planning and Public Works (YPEXODE), the Ministry of Agriculture and the National Meteorological Agency (EMY). Soil data were obtained from the data files of two geophysical projects conducted for a petrol survey and for hydrogeological purposes (after Zerva 1985).

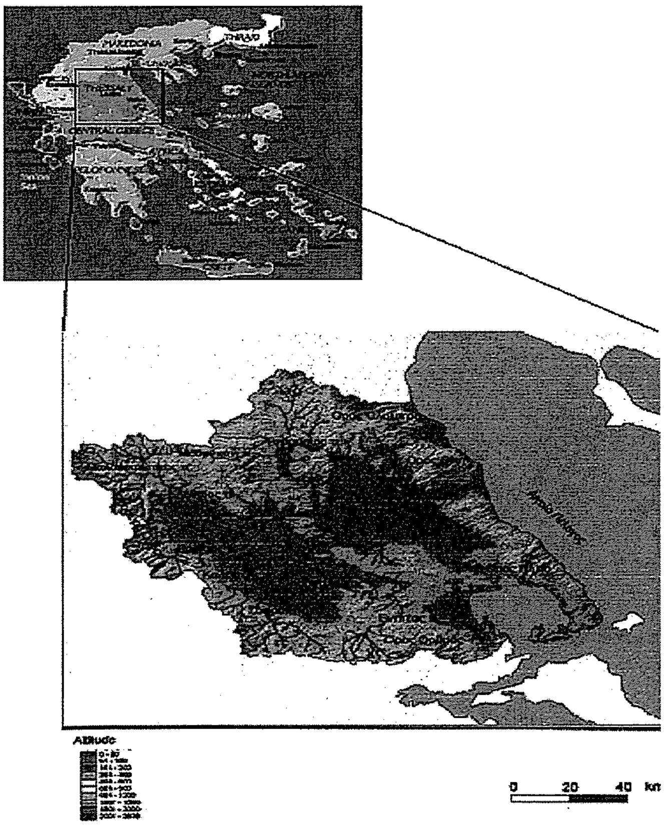

Fig. 1 Location of the Pinios River Basin, Thessalia, Central Greece

The mean annual rainfall in the area is 696 mm, varying from 500–900 mm in the lowlands to 1,800 mm in the mountains. Rain falls mostly in the winter when the soils store a quantity of water which allows the growth of vegetation during the early months, although irrigation is necessary during the summer months (from May to September).

The mean annual temperature is 12.4°C, varying from 5°C in January to 24°C in July and August. Summers can be warm and dry and temperatures may rise to 40°C.

The rate of annual flow in the river is 81.25 m^3/s ($2,562\times10^6$ m^3/year) and the mean annual surface runoff from the basin is $3,253\times10^6$ m^3/year. The total annual water consumption is 700×10^6 m^3.

The data for the simulation of the water balance of the basin with the SESOIL model are divided into five major categories: climate, rainfall, soil, geography, and river flow.

The study used a latitude of 39.5°N for the entire area and an albedo (for areas covered with vegetation) of 0.25. Rainfall data has been recorded at 29 gauge stations. Average monthly precipitation values were calculated via the Thiessen polygon methodology and were taken from the Sogreah study.

Figures 2 and 3 depict the monthly mean air temperature, monthly mean relative humidity, and monthly mean cloud cover fraction, while Figs. 4, 5 and 6 depict the precipitation, the mean duration of individual storm events and the number of storm events.

The hydrological cycle submodel assumes the calibrated soil parameters given in Table 2. The square

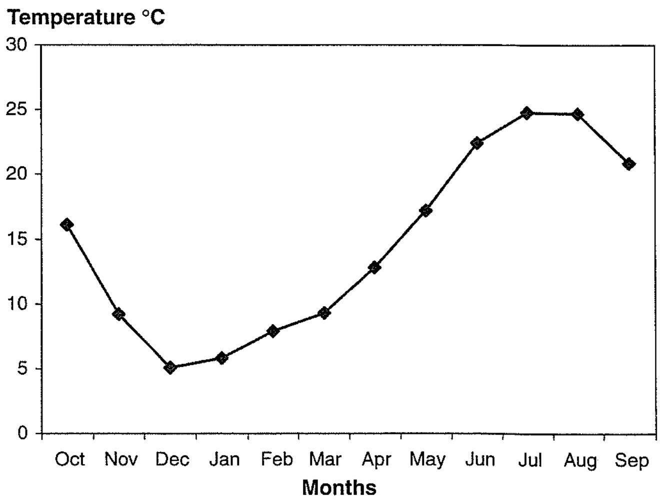

Fig. 2 Monthly mean air temperature

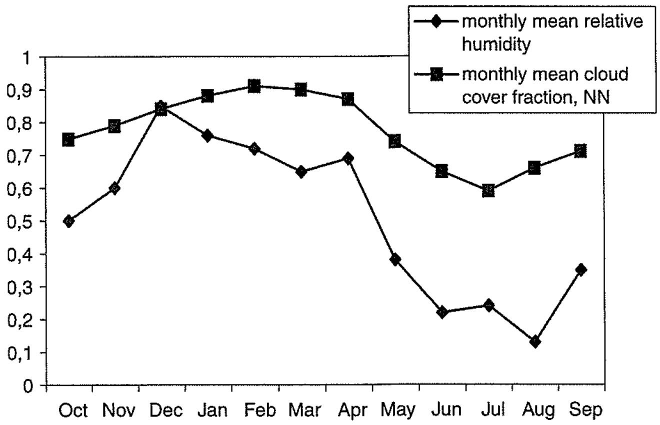

Fig. 3 Monthly mean relative humidity and cloud cover fraction

error criterion was used to verify the deviation between the observed and simulated values. The $\sum (Q_{obs} - Q_{simul})^2$ has to be minimized. Both the calibration and the simulation periods were one year.

Evaluation of SESOIL output

Table 3 shows the simulated values for the Pinios annual hydrological cycle, which equate the basic components of the Eagleson theory as modified to account for monthly simulations. Figure 7 shows the comparison between observed and simulated monthly surface runoff. The extended hydrological balance could not be tested with the SESOIL results because some of the components (e.g. interflow) are internal to the program and an insight was not possible at this stage.

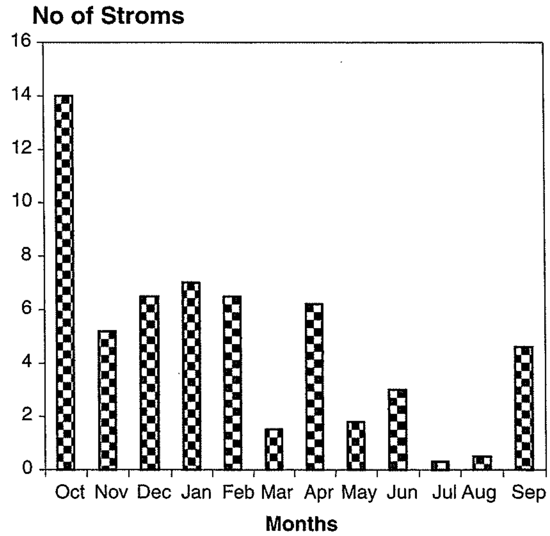

Fig. 5 Number of storm events

The simulation was based on the monthly values of the river discharge, because of a lack of measurements. The rest of the components of the water balance, (e.g. evapotranspiration, soil moisture, groundwater runoff) are calculated by the model and are difficult to verify. However, the ability of the model to reflect the surface runoff, which is an important output factor of the water balance, is encouraging for the satisfactory prediction of the rest of the components.

In Greece, there is no fully developed database of hydrological information which could be used as input (evaporation, moisture etc). Furthermore, where such data exist, they may be unreliable (fallibility of the observer, broken gauges etc.) or incomplete. Problems also arise with the use of old and probably unreliable data, while data obtained over only a short length of time

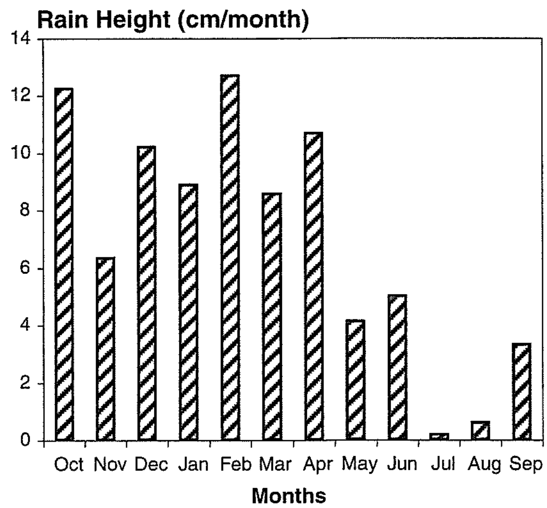

Fig. 4 Total precipitation

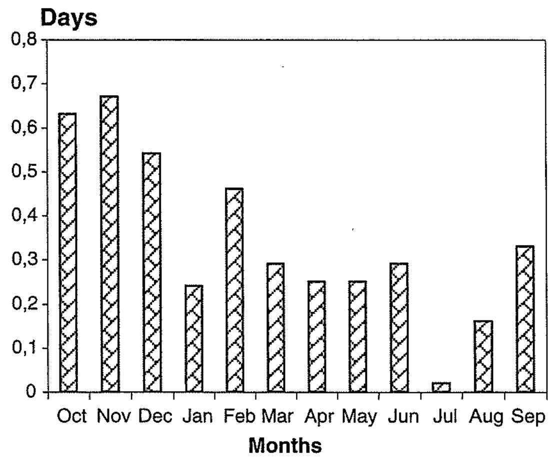

Fig. 6 Mean duration of storm events

Table 2 Calibration parameters

Parameter	Units	Description	Range	Final values
$K(1)$	cm^2	Average soil intrinsic permeability for the entire soil profile	2×10^{-10}–6×10^{-10}	3.5×10^{-10}
n	unitless	Effective porosity	0.25–0.4	0.4
c	unitless	Soil pore disconnectedness index	7–11	9
z	cm	Depth of the groundwater table	100–2,000	100

Table 3 Annual balance

Parameter	Pinios River simulation (cm)	Parameter	Pinios River simulation (cm)
Precipitation	83.172	Moisture retention	−0.003
Surface runoff	33.168	Interflow	–
Infiltration	50.004	Capillarity	–
Evapotranspiration	38.028	Percolation	–
Ex-filtration	–	Groundwater flow	11.979

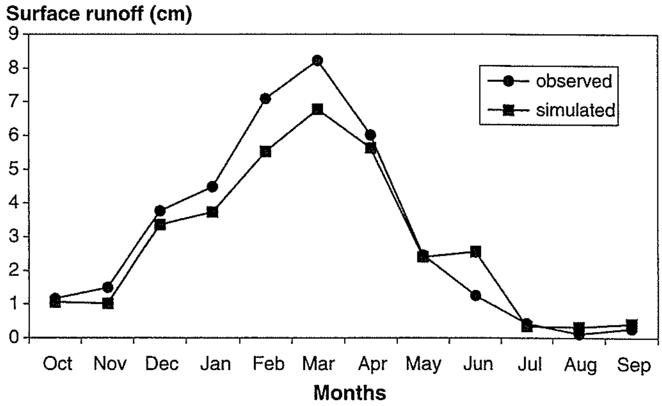

Fig. 7 Observed and simulated surface run-off

preclude the identification of persistence, such as the difference between dry and wet periods. In general, the larger the data sample, the better the simulation. SESOIL is structured in a way that avoids the use of data that are hard to find, thus it can be applied in regions without extensive data. In parallel, by using the model for annual simulations and time-series, there is a significant reduction of input data in comparison with other models that use daily time-series.

SESOIL does not differentiate between moisture obtained from rainfall and the snow events. This is not an issue for regions with limited snowfall, but could affect the results in mountainous catchments with a hysteresis in water yield of snow as surface runoff. In such cases, there is increased surface runoff during the spring, even with low precipitation, due to snow melting at higher elevations.

The comparison between the observed and the simulated values indicate that the SESOIL model delivered adequate predictions of surface runoff and thus a degree of confidence in the estimated groundwater runoff and evapotranspiration. From Fig. 7, it appears that the simulated monthly values are very close to those observed in two-thirds of the cases. However, the model did not manage to reach the value at the peak of the graph. At least three reasons must be considered:

- A comparison was made between the surface runoff and the river discharge. In general, the discharge also contains the contribution of the underground aquifer, which was not taken into consideration. (If the river-flow gauge stations were situated at higher elevations, the contribution of the underground aquifer would not cause any significant difference in the results).
- There has been a manual calibration of the soil parameters (because of lack of soil testing).
- The possible snow effect was not taken into consideration and hence melting could account for an increase in flow.

Conclusions

The SESOIL model as maintained and improved by several organizations has been applied to the Pinios River Basin in Greece. Simulations were compared with observed river flows and basin runoff values. The simulated monthly values were close to those observed in two-thirds of the cases. The reasons for the disparities may be found in the fractions of river runoff used, the manual calibration of the soil parameters and the snowmelt factor which was not taken into account.

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