Regionalization in Hydrology (Proceedings of a conference held at Braunschweig, March 1997). IAHS Publ. no. 254, 1999.

The land surface parameterization scheme SWAP: description and validation

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Abstract A physically based land surface parameterization scheme SWAP (Soil Water-Atmosphere-Plants) for coupling with atmospheric models is presented. SWAP is a one-dimensional model based on a system of equations for the land surface energy balance, the water balance of a soil root zone, the heat and water transfer within the soil–vegetation/snow cover–atmosphere system. SWAP includes a two-dimensional kinematic wave equation to calculate the basin streamflow hydrograph. The model was validated at the local as well as catchment scale in the framework of PILPS (Project for Intercomparison of Land-surface Parameterization Schemes). Analysis of the results obtained shows that SWAP performs fairly well without any calibration at the local scale for mid-latitude homogeneous grassland under non-water-stressed condition. At the basin scale SWAP needs calibration of some soil parameters and land surface characteristics.

INTRODUCTION

The aim of this paper is to present a physically based model, namely SWAP (Soil Water-Atmosphere-Plants), describing the interaction between the land surface and the atmosphere throughout the year on a local scale and oriented towards coupling with atmospheric models. SWAP is a one-dimensional model based on a system of physical-mathematical equations for the surface energy balance, the water balance of the soil root-zone and for the heat and water transfer within the soil–vegetation/snow cover–atmosphere system (SVAS). It includes a description of the processes occurring (a) during the warm season: rainfall interception, surface runoff, infiltration, transpiration, soil evaporation, evaporation of intercepted precipitation, dynamics of soil water storage, drainage; and (b) during the cold season: soil freezing and soil thawing, formation of snow cover (snow accumulation, evaporation from snow and snowmelt), infiltration of melted snow and runoff after snowmelt. Besides that, SWAP can reproduce streamflow from a basin.

MODEL DESCRIPTION

The distinctive features of the model SWAP are that: (a) it is a physically based model especially with respect to a description of the processes of the winter-spring period which are usually described very schematically; (b) it attempts to solve the systems of equations by using analytical methods contrary to the usual practice of application of numerical ones; (c) it includes a relatively small set of parameters most of which can be obtained from literature and (d) when calculating the partition of non-intercepted rainfall into infiltration and surface runoff, the spatial variability of the hydraulic conductivity at saturation is taken into account. Relatively simple mathematical formalism and application of an analytical approach make the model compact and rational with respect to consuming computer resources. The limited length of this paper only allows a brief description of the model.

The water balance components of SVAS are calculated from the water balance equations for a canopy, snow and soil. The calculation of the soil water balance is based on the water balance equation for the soil root zone:

$$\rho_w h_r \frac{\partial W}{\partial \tau} = P - E - R_S - Q \tag{1}$$

where τ is the time, ρ_w is the water density, h_r is the root-zone depth, W is the volumetric soil moisture ($m^3\,m^{-3}$), P is the non-intercepted precipitation, E is the evapotranspiration flux which includes transpiration rate E_T, bare soil evaporation rate E_S, evaporation rate of intercepted precipitation E_C, and snow evaporation rate E_{SN}; R_S is the surface runoff, Q is the discharge at the bottom of the root-zone; P, E, R_S and Q are in kg $m^{-2}\,s^{-1}$. Hereafter SI units are used.

Simulation of E_T and E_S during the warm season is based on the semi-empirical theory by Budagovskiyi (1964, 1989). It should be noted that all empirical constants were obtained from numerous field experiments carried out in various agro- and natural ecosystems in the steppe and forest-steppe zones of the former Soviet Union. According to Budagovskiyi the transpiration rate E_T and soil evaporation rate E_S can be computed by the following equations:

$$E_T = \beta E_{PT}\left(1 - \psi(L)\right) \tag{2}$$

$$E_S = E_{PE}\psi(L)\left(1 - \left(1 - 2.5W_a\right)\exp\left(-\frac{P}{E_{PE}\psi(L)}\right)\right) \tag{3}$$

$$\psi(L) = \exp(-0.45L),\quad \beta = \min(W_a / W_{cr}, 1),\quad W_{cr} = \zeta_1 + \zeta_2 E_{PT} \tag{4}$$

where E_{PT} is the potential transpiration rate, i.e. transpiration by full plant cover under unlimited water supply and current meteorological conditions; E_{PE} is the potential soil evaporation rate; β is the soil moisture availability function; L is the leaf area index; W_a is the volumetric available soil moisture of the root zone (m m^{-3}) (calculated as the difference between the soil moisture of the root zone and plant wilting point W_{wp}); W_{cr} is the critical volumetric available soil moisture content; ζ_1 and ζ_2 are the empirical coefficients equal to 0.06 and 0.0042 day m^2 kg^{-1}, respectively (if E_{PE} is in kg m^{-2} day^{-1}).

It should be noted that equation (3) was obtained for time steps of 10 days and more, consequently, for smaller time steps it can be applied only as a first approximation.

Potential evaporation from the land surface (soil or snow) E_{PE} is calculated using atmospheric forcings from the lowest atmospheric layer of a general circulation model (GCM). Since the lowest layer can be situated at a height of an order 10^1–10^2 m from the land surface, the turbulent fluxes and surface temperature should be calculated taking into account the atmospheric stability. Here, for this purpose we use the main outcome of the Monin-Obukhov (MO) similarity theory (Zilitinkhevich, 1970). The system of equations for the calculation of potential evaporation includes: (a) equations for the heat and water turbulent fluxes at the land surface, defined in terms of MO scaling parameters; (b) equations for the vertical profiles of wind speed, air temperature and air specific humidity resulting from the MO theory; (c) an equation for net radiation; (d) Magnus' equation for surface air humidity at saturation; and (e) the equation for the heat balance at the land surface. The latter equation is written as:

$$R = \lambda E + H + G + \lambda_{Ic} M \tag{5}$$

where R_n is the net radiation flux, H is the sensible heat flux, G is the ground heat flux, and M is the snowmelt rate; $\lambda = \lambda_W + \lambda_{Ic}$, where λ_W is the latent heat of vaporization of water and λ_{Ic} is the latent heat of fusion of ice.

For the warm season G is calculated approximately from the empirical relations of Budyko (1956). For the cold season G can be calculated from Gusev (1993) (see equations (13) and (16)). The cold season is identified by the fulfilment of at least one of the following conditions: (a) daily surface temperature is below 0°C, (b) presence of snow cover, (c) presence of frozen soil zone.

Potential transpiration rate E_{PT} can be derived from potential soil evaporation rate as (Gusev & Nasonova, 1997):

$$E_{PT} = \omega E_{PE}\ ,\ \omega = 0.041/\sqrt{Lf} + 0.78 \tag{6}$$

where Lf is the mean size of the plant's leaves (m). The evaporation rate of intercepted precipitation E_C, and the snow evaporation rate E_{SN}, are assumed to be equal to the rate of potential evaporation E_{PE}.

The upward flux of water at the lower boundary of the root zone for the warm period is calculated empirically (Dzhogan, 1990); for the cold period the algorithm is not simplified. A downward flux of water occurs when the liquid water content in the root-zone exceeds field capacity.

The calculation of surface runoff R_S is based on the Hortonian surface runoff concept, i.e. R_S occurs when the non-intercepted precipitation rate P exceeds the soil infiltration rate I, when I is calculated from a modification of the Green-Ampt equation (Gusev, 1989). It should be noted that one of the specific features of the cold season is that I depends on the soil ice content Ic along with other factors and can be calculated as (Gusev, 1989, 1993):

$$I = \begin{cases} V & \text{if} \quad u < W_{sat} - Ic \\ k_0 \left(\dfrac{W_{sat} - Ic - u_s}{W_{sat} - u_s} \right)^4 \dfrac{1}{(1 + 8Ic)^2} & \text{if} \quad u = W_{sat} - Ic \end{cases} \tag{7}$$

where V is the rate of water yield of snow cover; W_{sat} is the soil moisture at saturation; u is volumetric content of liquid water in wetted soil during snowmelt; u_s is static soil water; k_0 is hydraulic conductivity at saturation.

The quantity V is obtained easily from the water balance equation for snow. The soil ice content Ic is determined by the solution of the heat balance equation of frozen soil. The liquid water content u can be calculated as (Gusev 1989, 1993):

$$u = \min\left[u_s + (W_{sat} - u_s)\left(\frac{V(1+8Ic)^2}{k_0}\right)^{1/4},\ W_{sat} - Ic \right] \tag{8}$$

The quantities u and Ic are connected with the root-zone soil moisture W:

$$W = u + Ic \cdot \rho_w / \rho_{Ic} \tag{9}$$

where ρ_{Ic} is the ice density.

To calculate Ic it is necessary to know the depths of soil freezing ξ and soil thawing ξ_{th}. The value of ξ is calculated when the surface temperature $t_S < 0$. Equations for these variables were derived by Gusev (1988, 1993). The equation for ξ was obtained by solving the equation for the rate of movement of the freezing front, which, in its turn, is based on the heat balance equation for frozen soil:

$$\lambda^* \frac{d\xi}{d\tau} = q_f - q_{un} \tag{10}$$

$$\lambda^* = \lambda_{Ic}\rho_w(W - u_{\min}) + \frac{C_2|t_g|}{2} \tag{11}$$

$$t_g = \frac{t_S\xi}{\xi + hk_2/k_1} \tag{12}$$

$$q_f = -G = -\frac{t_S}{\xi/k_2 + h/k_1} \tag{13}$$

$$q_{un} = \frac{2k_3t^*}{\sqrt{2.25\xi^2 + 12a_3(\tau+\tau_0)} - 1.5\xi} \tag{14}$$

Here, q_{un} is the heat flux from the unfrozen zone to the freezing front; t_g is the temperature at the soil surface; t^* is constant soil temperature at the depth where annual amplitude of soil temperature is damped out; t_S , t_g and t^* are in °C; h is the snow height; u_{min} is the minimum amount of unfrozen water in frozen soil; k_1, k_2 and k_3 are the thermal conductivities of snow, frozen soil and unfrozen soil, respectively; C_2 is the volumetric heat capacity of frozen soil; a_3 is the thermal diffusivity of unfrozen soil; the parameter τ_0 is characterizing the influence of a period prior to freezing taken to be 10 days (Gusev, 1993).

The soil thawing depth ξ_{th} can be obtained from the heat balance equation for thawing of the frozen soil when $t_S > 0$ (Gusev *et al.*, 1993):

$$\lambda^* \frac{d\xi_{th}}{d\tau} = q_{ts} \tag{15}$$

$$q_{ts} = G = \frac{t_S}{\xi_{th}/k_3} \tag{16}$$

$$\lambda^* = \lambda_{Ic}\rho_w(W - u_{\min}) \tag{17}$$

The intensity of surface runoff $R_S = P - I$ for the warm period and $R_S = V - I$ for the cold season. At the basin scale the model SWAP calculates the streamflow hydrograph $q(\tau)$, which is obtained from the two-dimensional kinematic wave equation:

$$\frac{\partial h_w}{\partial \tau} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = (R_S + Q)/\rho_w \tag{18}$$

$$q = q_x + q_y \quad , \quad q_x = \frac{1}{n}\frac{i_x}{\sqrt{|\mathrm{grad}\,\eta|}} h_w^{5/3} \quad , \quad q_y = \frac{1}{n}\frac{i_y}{\sqrt{|\mathrm{grad}\,\eta|}} h_w^{5/3} \tag{19}$$

$$\mathrm{grad}\eta = \sqrt{i_x^2 + i_y^2} \tag{20}$$

where h_w is the effective depth of flow along basin slopes; x and y are spatial coordinates; q_x and q_y are the discharges of water per unit width of flow along the x and y axes; n is the effective Manning roughness coefficient and i_x and i_y are the average slopes of the basin surface along the x and y axes.

MODEL VALIDATION

The model was validated at both the local and basin scale within the framework of PILPS (Project for Intercomparison of Land-surface Parameterization Schemes) phase 2a (Chen *et al.*, 1997) and phase 2c (Wood *et al.*, 1997) experiments, respectively. The time step used in calculation was one day. All atmospheric and hydrological data, as well as most of the required parameters for model validation were provided by the PILPS 2a and 2c organizers. Some of the missing parameters, mainly concerning the winter-spring period, were taken from the literature (Kalyuzhnyi & Pavlova, 1981; Gusev, 1993).

Stand-alone land surface "point" simulations

The stand-alone land surface "point" simulations were carried out (without any calibration) using observed point data for the year 1987 from Cabauw (the Netherlands, grassland, PILPS 2a) as the atmospheric forcing. Full descriptions of the site, data and parameter values used for the model simulations are given in Chen *et al.* (1997). Simulated annually, monthly and daily averaged surface turbulent fluxes, net radiation and surface radiative temperature were compared with observations. Some results are given in Fig. 1 and summarized in Table 1.

Table 1 Statistical characteristics of the results of model validation for Cabauw (1987).

Variable	Root-mean-square errors for:		Annual means:	
	monthly values	daily values	modelled	observed
Sensible heat flux (W m^{-2})	4.5	9.8	−3.6	−1.3
Latent heat flux (W m^{-2})	4.7	14.9	39.8	38.8
Net radiation (W m^{-2})	4.2	13.9	37.1	36.8
Surface temperature (K)	1.4	1.9	281.7	280.8

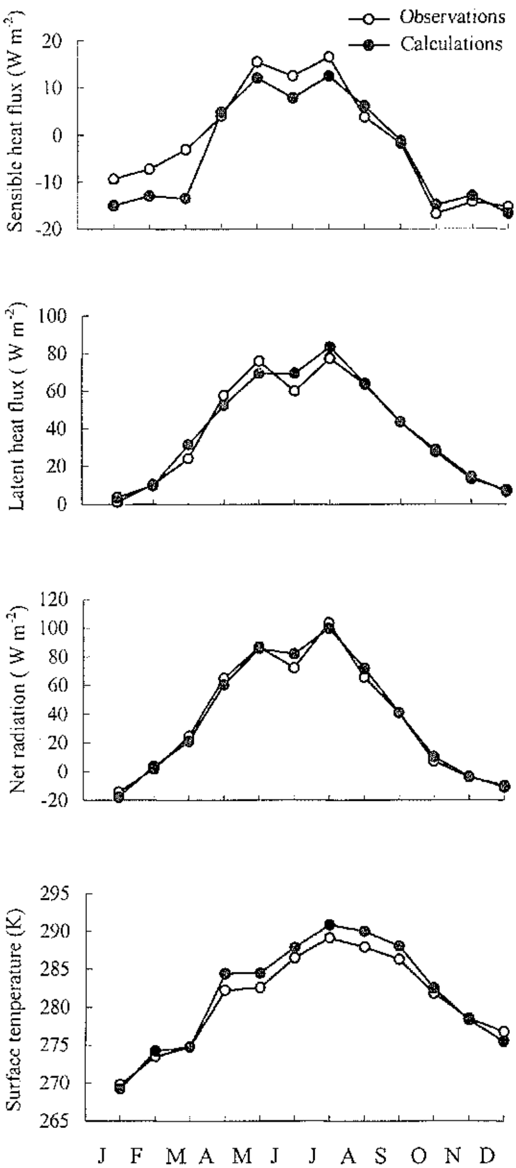

Fig. 1 Observed and simulated monthly mean turbulent heat fluxes, net radiation and surface radiative temperature.

As seen from Table 1 root-mean-square errors (RMSEs) of the calculated monthly values are equal to 4.5 W m^{-2} for H, 4.7 W m^{-2} for λE, and 4.2 W m^{-2} for R_n, whereas the range of observation errors for the monthly averages was estimated to be ±5 W m^{-2} for sensible heat flux and ±10 W m^{-2} for both latent heat flux and net radiation (Chen *et al.*, 1997). Evidently, RMSEs of the calculated daily values are greater than those of the monthly values.

It should be noted that most of our results are within the range of the other schemes participating in PILPS 2a. Thus, averaged over 23 schemes root-mean-square deviation from monthly observation is equal nearly to 7.8 W m^{-2} for H and 9.8 W m^{-2} for λE, whereas for the model SWAP the corresponding values are 4.5 W m^{-2} and 4.7 W m^{-2}, respectively.

Analysis of the results obtained allows us to predict that SWAP is suitable for parameterization of mid-latitude homogeneous grassland under non-water-stressed condition on a local scale.

Basin scale validation

Basin scale validation was carried out using forcing and streamflow data for the years 1979–1987 for two basins with different climatic conditions (Mulberry River and Black Bear basins with drainage areas of 966 and 1494 km^2, respectively) situated within the Arkansas-Red River basin (USA). Full descriptions of the data provided and parameters are presented in (Wood *et al.*, 1997). Calibration was carried out for one year when streamflow was close to its mean value (1980 for the Black Bear and 1987 for the Mulberry River); the remaining years were used for verification.

When performing calibration, we followed PILPS 2c instructions according to which most of the soil parameters and land surface characteristics were fixed. The modelling groups were allowed to adjust only model-specific parameters. For SWAP two parameters were determined by means of calibration, namely, the effective roughness coefficient by Manning n and the effective ground water table depth h_g. These parameters were estimated by calibration because with their values were not provided. An adjusted n was equal to 0.06 and h_g was 2.4 m for the Black Bear basin and 4 m for the Mulberry River. These values were used for model validation.

Comparison between the modelled and observed monthly streamflow volume for the Black Bear basin is given in Fig. 2. The coefficient of correlation between monthly observations and simulations is equal to 0.92 for the Black Bear and 0.74 for the Mulberry River basin. The coefficient of correlation for daily values is 0.81 and 0.63 for the Black Bear and Mulberry River, respectively. The ratio between the modelled

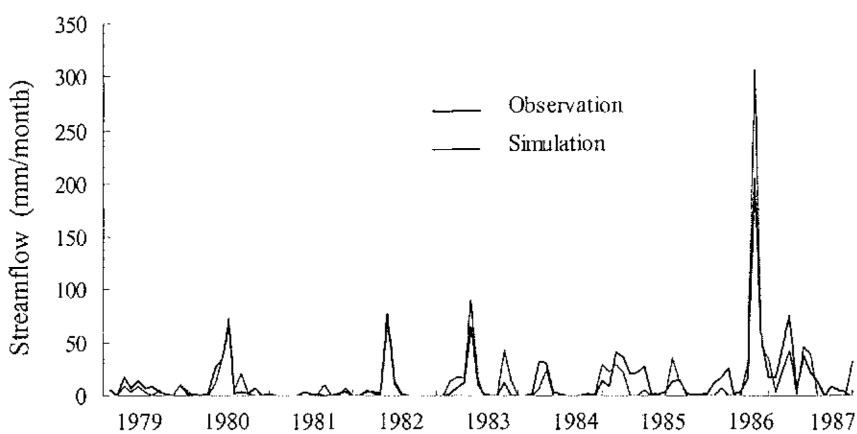

Fig. 2 Observed and simulated monthly streamflow for the Black Bear basin.

and observed streamflow volume over the whole period is 1.0 for the Black Bear and 0.8 for the Mulberry River basin.

Discrepancy between simulations and observations for the Mulberry River basin may be explained by application of the fixed (non-calibrated) soil parameters and land surface characteristics, influencing the runoff formation more than the calibrated parameters n and h_g, for the calculations at regional scale. The provided values may be not optimal for the basin. To improve the results obtained the more influential characteristics (in particular, hydraulic conductivity at saturation) should be calibrated to determine their "effective" values.

CONCLUSIONS

The model SWAP, which describes the heat and water exchange processes within a soil–vegetation/snow cover–atmosphere system throughout the whole year and is oriented towards use of atmospheric forcings from the lowest atmospheric layer of a GCM, has been developed. Testing the model at the local and small basin scales has shown that: (a) SWAP performed fairly well without any calibration at the local scale for mid-latitude homogeneous grassland under non-water-stressed condition; (b) at the basin scale SWAP needs calibration of some soil parameters and land surface characteristics.

It should be noted that further testing will be required at other sites with different types of land surfaces, different climatic conditions and at various scales before the model can be considered to be comprehensively validated and suitable for coupling with GCMs.

Acknowledgements The present work was supported by the Russian Foundation for Basic Research (grant 98-05-64218). We acknowledge the PILPS 2a and 2c organizers and all the people who contributed to the provision of data for model validation.

REFERENCES

Budagovskiyi, A. I. (1964) *Isparenie pochvennykh vod* (Evaporation of Soil Water, in Russian). Nauka, Moscow.

Budagovskiyi, A. I. (1989) Principles of the method of calculating the duty of water and irrigation regimes. *Wat. Resour. (Russia)* 16(1), 27–35.

Budyko, M. I. (1956) *Heat Balance of the Earth's Surface*. US Weather Bureau, Office of Climatology, Washington, DC.

Chen, T. H., Henderson-Sellers, A., Milly, P. C. D., Pitman, A. J., Beljaars, A. C. M., Polcher, J., Abramopoulos, F., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C. E., Dickinson, R. E., Dumenil, L., Ek, M., Garratt, J. R., Gedney, N., Gusev, Y. M., Kim, J., Koster, R., Kowalczyk, E. A., Laval, K., Lean, J., Lettenmaier, D., Liang, X., Mahfouf, J.-F., Mengelkamp, H.-T., Mitchell, K., Nasonova, O. N., Noilhan, J., Robock, A., Rosenzweig, C., Schaake, J., Schlosser, C. A., Schulz, J.-P., Shao, Y., Shmakin, A. B., Verseghy, D. L., Wetzel, P., Wood, E. F., Xue, Y., Yang, Z.-L. & Zeng, Q. (1997) Cabauw experimental results from the project for intercomparison of land-surface parameterization schemes (PILPS). *J. Climate* 10(6), 1194–1215.

Dzhogan, L. Ya. (1990) *Isparenie c Oroshaemykh Poleyi Sredneyi Azii* (Evaporation from Irrigated Fields in the Middle Asia, in Russian). Nauka, Moscow.

Gusev, E. M. (1988) Simplified calculation of soil freezing depth with consideration of water migration to the freezing boundary. *Wat. Resour. (Russia)*. 15(1), 9–17.

Gusev, E. M. (1989) Infiltration of water into soil during melting of snow. *Wat. Resour. (Russia)* 16(2), 108–122.

Gusev, E. M. (1993) *Formirovanie Rezhima i Resursov Pochvennykh Vod v Zimne-Vesenniyi* Period (Formation of Regime and Resources of Soil Water during Winter-Spring Period, in Russian). Fizmatlit Publishing Company, Nauka

Publishers, Moscow.

Gusev, E. M., Busarova, O. E. & Yasinskij, S. V. (1993) Impact of mulch layer composed by organic remains on the soil thermal conditions following snowmelt. *J. Hydrol. Hydromech. (Slovak Republic)* **41**(1), 15–28.

Gusev, E. M. & Nasonova, O. N. (1998) Parameterization of heat and water exchange at the land surface for coupling hydrological and climatic models. *Wat. Resour. (Russia)* **25**(4), 383–393.

Kalyuzhnyi, I. L. & Pavlova, K. K. (1981) *Formirovanie poter' talogo stoka* (Formation of melted snow losses, in Russian). Gidrometeoizdat, Leningrad, USSR.

Wood, E., Lettenmaier, D., Liang, X., Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C., Duan, Q., Ek, M., Gusev, Y., Habets, F., Irannejad, P., Koster, R., Nasonova, O., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y., Shmakin, A., Verseghy, D., Wang, J., Warrach, K., Wetzel, P., Xue, Y., Yang, Z.-L. & Zeng, Q. (1998) The project for intercomparison of land-surface parameterization schemes (PILPS) phase-2(c) Red-Arkansas River basin experiment: 1. Experiment description and summary intercomparisons. *Global and Planetary Change* **19**(1–4), 115–135.

Zilitinkhevich, S. S. (1970) *Dinamika Pogranichnogo Sloya Atmosfery* (Dynamics of the Boundary Layer of the Atmosphere, in Russian). Gidrometeoizdat, Leningrad, USSR.