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Determination of the soil hydrophysical characteristics and vegetation parameters of a river basin in a permafrost region

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Abstract This paper describes two techniques for estimating the soil hydrophysical and vegetation parameters required for runoff modelling using the land surface model SWAP (Soil Water–Atmosphere–Plants): (1) *a priori* parameter estimation on the basis of information on spatial distribution of different soil and vegetation types within a basin, and (2) optimization of the most influencing parameters by means of model calibration to measured daily streamflow. The estimated sets of parameters were applied for runoff simulations using the SWAP model and the data measured during a 10-year period (1969–1978) at the Kolyma water balance station located within the permafrost zone of the Kontaktovyi Creek basin, in the upper course of the Kolyma River, Russia. The values of runoff from several watersheds and sub-basins (area: from 0.27 to 21.2 km^2) of the Kontaktovyi Creek basin were simulated using *a priori* estimated and calibrated parameters and were compared with each other and with observations. For daily streamflow, application of calibrated parameters, instead of *a priori* estimated, resulted in an increase of the efficiency of simulations, on average from 0.38 to 0.55, and the coefficient of correlation from 0.66 to 0.77. The bias was reduced from 14 to 17%.

Key words *a priori* parameter estimation; land surface modelling; parameter calibration; permafrost zone; river runoff

INTRODUCTION

Recent investigations aimed at physically-based modelling of a complex and multifactor Soil–Vegetation/snow cover–Atmosphere System (SVAS), has resulted in Land Surface Models (LSMs) that treat the processes of heat and water exchange within SVAS from simple parameterization schemes. These models, which were originally intended for setting boundary conditions in atmospheric general circulation models, can be applied, not only in climate modelling in the context of coupled land-atmosphere models, but also for hydrological and environmental studies of broad interest. Currently the implementation of LSMs is moving towards high latitudes and highlands, which are characterized by a long and severe cold season and are among the landscapes most sensitive to natural and anthropogenic effects. Because many of these regions are within the permafrost zone, the modelling community is faced with the need to simulate heat and water exchange between the land surface and the atmosphere under permafrost conditions. Unfortunately, permafrost regions are also among the almost inaccessible and insufficiently known areas and do not have the data on soil and vegetation parameters required for LSM simulations. In this connection, the goals of the present work are to develop techniques for estimation (both *a priori* and by means of model calibration) of the land surface parameters of such basins located within the permafrost zone and to apply the obtained parameters for model simulations.

MODEL

The SWAP model (Gusev & Nasonova, 1998), used in this study, is a physically based land-surface model describing heat and water exchange between the land surface and the atmosphere throughout a year at local to global scales. The model is oriented towards the use of atmospheric forcing data from the lowest atmospheric layers of the GCMs (Global Circulation Models) or from any reference height. Initially, SWAP's parameterizations were designed only for non-frozen and seasonally frozen soils (Gusev & Nasonova, 1998, 2002, 2003). Recently the model was modified for permafrost conditions (Gusev & Nasonova, 2004, 2006).

HYDROLOGICAL OBJECT

The hydrological object under study is the Kontaktovyi Creek basin (area: 21.2 km^2), a highland area located in the upper course of the Kolyma River (61°53′N, 147°43′E) in the permafrost zone of far-eastern Russia. This is an experimental basin of the Kolyma water balance station (KWBS). The absolute elevations within the basin vary from 830 to 1700 m a.m.s.l. The climate of the region is subarctic continental. Between 1969 and 1978 the average mean annual air temperature was negative (–11°C). Mean daily temperature varied from –52 to 23°C. Annual precipitation varied within a basin from 300 to 460 mm. The depth of seasonal soil thawing ranged from 0.3–0.4 to 1.5–2 m, depending on slope exposition, lithological composition of ground, vegetation and air temperature.

For the simulation of streamflow, the Kontaktovyi Creek basin was divided into five sub-basins (Fig. 1(a),(b), Table 1). Because the slopes of the southern and northern expositions of the first, second and fifth sub-basins had different natural conditions, they were modelled separately. More detailed division of the basin seems to be unreasonable because of the lack of reliable data. Three types of land surface were distinguished within each calculational element: sparse larch forest growing below 1000 m, low creeping cedar, and bare areas represented by talus. Model simulations were performed for each of these land surface types and streamflow for each sub-basin was calculated as the weighted average value after accounting for the spatial coverage of each land surface type.

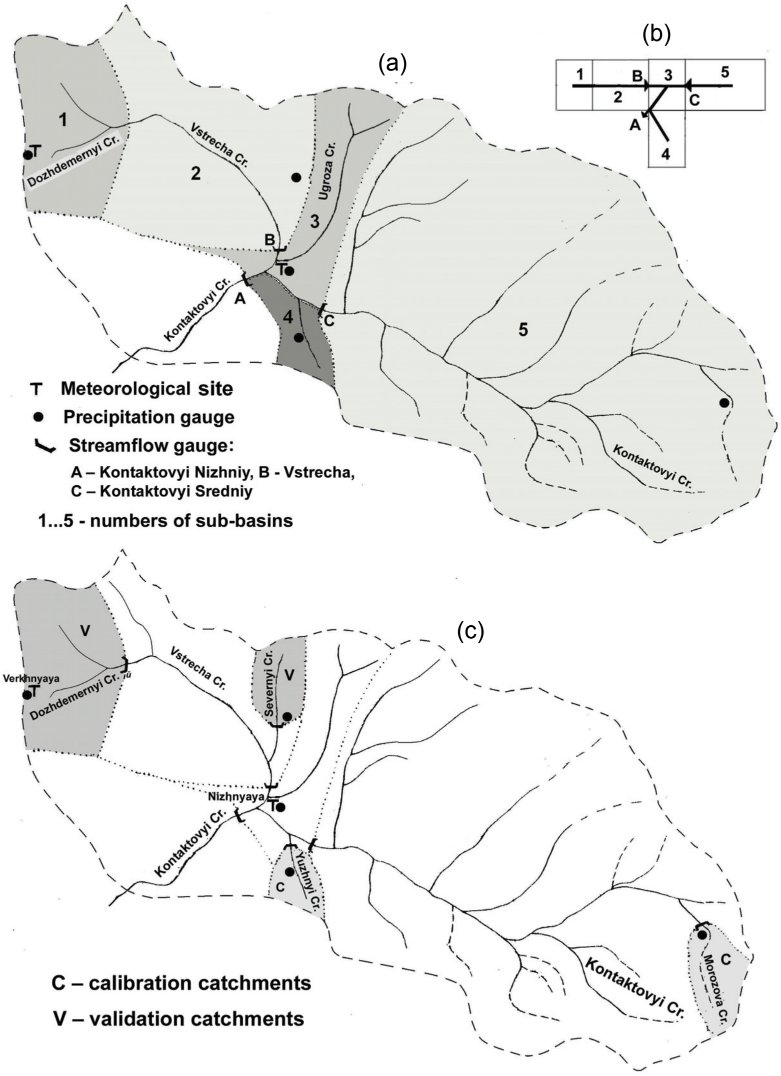

Fig. 1 Schematic representation of the Kontaktovyi Creek basin divided into five sub-basins and streamflow evaluation sites (A, B, C) (a); schematized routing directions (b); location of the four calibration and validation catchments (c).

Table 1 Characteristics of experimental catchments and calculational sub-basins within the Kontaktovyi basin.

Catchment or calculational sub-basin*	Area (km^2)	Mean altitude (m, a.m.s.l.)	The land surface type (%)		
			Talus	Short vegetation	Larch forest
Small catchments for parameters calibration and validation					
Morozova Creek	0.63	1370	100	0	0
Yuzhnyi Creek	0.27	985	25	60	15
Severnyi Creek	0.38	1020	30	45	25
Dozhdemernyi Creek	1.43	1180	68	0	32
Calculational sub-basins of the Kontaktovyi Creek basin					
1a	0.72	1180	68	0	32
1b	0.72	1180	68	0	32
2a	1.96	1050	16	33	51
2b	1.96	1000	16	33	51
3	1.18	920	20	10	70
4	0.47	960	16	38	46
5a	9.94	1150	49	22	29
5b	4.26	1000	49	22	29

*, numbers of sub-basins correspond to those given in Fig. 1; a and b near numbers are related, respectively, to the slopes of southern and northern exposition.

Two small catchments (Morozova Creek and Yuzhnyi Creek) were chosen for parameter calibration. Two other catchments (Severnyi Creek and Dozhdemernyi Creek) were used for validation (Fig. 1(c)). The main characteristics of the catchments are presented in Table 1.

DATA

The model requires the following forcing data: air temperature and humidity, atmospheric precipitation, wind speed, air pressure and incoming short- and longwave radiation. All the forcing data, with the exception of radiation, were measured at the Nizhnyaya (1969–1978) and Verkhnyaya (1969–1972) meteorological sites located at 850 and 1220 m a.m.s.l., respectively (Fig. 1); their daily values are given in Kolymskoye UGKS (1977). Meteorological measurements (with the exception of precipitation) from the Nizhnyaya site were adjusted to the mean elevation of each calculational element using additional data from the Verkhnyaya site and accounting for the difference in the elevation of these two sites. Precipitation gauges were also located within each small experimental catchment (Fig. 1(c)) where measurements were performed daily during the warm season (May–September). During the cold season, precipitation measurements were carried out only at the Yuzhnyi and Severnyi Creek catchments once in a 10-day period. For model simulations, daily precipitation was restored for each catchment and then uniformly adjusted to 3-hr time steps. Incoming short- and longwave radiation values for each calculational element were calculated on the basis of meteorological data (with accounting for cloudiness), latitude, solar declination, view factor, average slope in meridional and latitudinal directions, and mean monthly values of atmospheric transmissivity.

Application of the SWAP model requires soil and vegetation parameters. Soil hydrophysical parameters include field capacity W_{fc}, wilting point W_{wp}, soil porosity W_{sat}, and relations of soil hydraulic conductivity k and soil matric potential ϕ with soil moisture W, i.e. $k(W)$ and $\phi(W)$. In SWAP, Clapp and Hornberger (1978) parameterizations for $k(W)$ and $\phi(W)$ are used. These parameterizations require information on soil matric potential at saturation ϕ_0, B-parameter, W_{sat}, and soil hydraulic conductivity at saturation k_0. Besides that, snow-free albedo of bare soil α_{soil} and soil depth h_{soil} are also required. As to vegetation parameters, the SWAP model needs root depth h_{root}, leaf and stem area indexes (LAI and SAI, respectively), roughness length of vegetation, zero plane displacement height, snow-free albedo of vegetation, albedo of vegetation with intercepted snow on crowns, effective linear leaf size, interception capacity of vegetation for liquid and solid precipitation. Since these parameters were not available for the selected basins, we had to estimate them by ourselves by means of techniques described in the next section.

PARAMETER ESTIMATION

A priori estimation

A priori estimation of soil and vegetation parameters was based on qualitative description of the soil and vegetation types and their spatial distribution within the Kontaktovyi Creek basin. Two soil classes (following the USDA soil texture classification) were found within the basin: sandy loam in the bottom and middle parts of the basin, and sand in its upper parts. These classes were used as predictors to determine $k(W)$ and $\phi(W)$ (including W_{sat} and k_0) in accordance with van Genuchten (1980) and the Rosetta code (Schaap *et al.*, 1998). The values of ϕ_0 and B were then obtained on the basis of interpolation of the estimated $\phi(W)$ by the Clapp and Hornberger equation within the range –33 to –1500 kPa. The values of W_{wp} and W_{fc} were determined as soil moisture at $\phi = -1500$ kPa and at $\phi = -33$ kPa, respectively. In such a manner, the hydrophysical parameters were estimated for the two soil classes. For each catchment and sub-basin, soil parameters were calculated as weighted average values accounting for the spatial coverage of each soil class. For k_0, logarithms of k_0 were averaged. For vegetation parameters, we assigned their typical values for each vegetation type (on the basis of literature data and our experience) and then calculated their weighted average values for each catchment and sub-basin.

Calibration

To improve runoff simulations based on *a priori* parameters, six parameters (W_{fc}, W_{wp}, W_{sat}, k_0, h_{soil}, h_{root}), were optimized by minimization of the root-mean-square-deviation (*RMSD*) between the simulated and measured (during 1969–1978) daily total runoff from the two calibration catchments (Morozova Creek and Yuzhnyi Creek). Four parameters (W_{fc}, W_{wp}, W_{sat}, k_0) were optimized for two soil layers (SWAP uses two soil layers: root zone and the layer between the lower boundary of the root zone and the upper boundary of impermeable layer). Each parameter was calibrated for three land surface types. In all, 30 parameters were optimized. The model calibration was performed by means of automatic procedure for optimization based on a stochastic or Monte-Carlo technique.

RESULTS

First of all, the obtained set of optimized parameters was validated by comparison of simulated and measured runoff from the two validation catchments (Severnyi Creek and Dozhdemernyi Creek). The results of calibration and validation were close to each other, so the optimized parameters could be applied for the other sub-basins of the Kontaktovyi Creek basin. Simulations of river runoff from the Kontaktovyi Creek basin were performed for a 10-year period (1969–1978) with the two sets of parameters (*a priori* estimated and calibrated). All the results of streamflow simulations (including the calibration and validation cases) on a daily and annual basis are summarized in Table 2, which contains mean observed $\bar{x}_{obs}$ and simulated $\bar{x}_{cal}$ values, bias, *RMSD*, the Nash-Sutcliffe efficiency of simulation (*Eff*), and the coefficient of correlation (*r*).

Comparison of streamflow simulation with the two sets of parameters for all sub-basins and small catchments has shown that the main differences are related to runoff hydrograph (whereas for annual values of runoff, the statistics obtained are very close). Thus, for daily streamflow, application of calibrated parameters instead of *a priori* estimated resulted in increase of *Eff*, on the average, from 0.38 to 0.55, *r* – from 0.66 to 0.77. In both cases, the bias was negative (i.e. runoff was underestimated) and its decrease, on the average, was small (3%). Only in one case (for the Dozhdemernyi Creek catchment) the bias decreased greatly (from 43 to 17%). The results mean that *a priori* estimated parameters are quite adequate and optimization of the more important of them improves the simulated streamflow with respect to timing rather than volume.

In general, the agreement between streamflow simulations and observations is not quite satisfactory, even in the case of application of the calibrated parameters. Underestimation of streamflow, by 14% in the case of calibrated parameters, can be mainly connected with poor precipitation measurements. First, measured precipitation is usually underestimated due to wind, especially during the cold season which lasts up to 7 months in this region. According to the climatic data, such underestimation may reach as much as 14–25% in the given region, which is

Table 2 Statistical characteristics of comparison of simulated and observed daily (numerator) and annual (denominator) streamflow.

Catchments	Number of years	$\bar{x}_{obs}$ (mm)	$\bar{x}_{cal}$ (mm)	Bias (%)	*RMSD* (mm)	*Eff*	*r*
Calibrated parameters							
Morozova Creek	8	1.20/440	1.04/380	–13.5	2.46/69.1	0.45/0.53	0.74/0.95
Yuzhnyi Creek	10	0.52/189	0.46/167	–11.8	1.04/35.5	0.58/0.76	0.77/0.92
Severnyi Creek	10	0.60/219	0.48/175	–20.1	1.14/51.2	0.47/0.44	0.72/0.93
Dozhdemernyi Creek	3	0.44/161	0.36/133	–17.2	0.94/ –	0.61/ –	0.79/ –
Vstrecha Creek, B	10	0.58/212	0.46/168	–20.4	1.02/50.7	0.57/0.60	0.76/0.97
Kontaktovyi Creek, C	10	0.76/277	0.74/268	–3.0	1.28/45.8	0.53/0.56	0.78/0.84
Kontaktovyi Creek, A	7	0.73/266	0.64/235	–11.4	1.10/48.7	0.64/0.63	0.81/0.88
Mean		0.69/252	0.60/218	–14.1	1.28/50.2	0.55/0.59	0.77/0.92
A priori estimated parameters							
Morozova Creek	8	1.20/440	1.03/376	–14.5	2.69/72.6	0.34/0.48	0.65/0.95
Yuzhnyi Creek	10	0.52/189	0.48/174	–7.9	1.36/43.9	0.29/0.63	0.61/0.82
Severnyi Creek	10	0.60/219	0.50/181	–17.2	1.33/46.5	0.29/0.54	0.62/0.92
Dozhdemernyi Creek	3	0.44/161	0.25/91	–43.2	1.23/ –	0.33/ –	0.59/ –
Vstrecha Creek, B	10	0.58/212	0.45/166	–21.5	1.17/53.9	0.42/0.55	0.66/0.96
Kontaktovyi Creek, C	10	0.76/277	0.74/268	–3.0	1.37/47.0	0.46/0.54	0.72/0.82
Kontaktovyi Creek, A	7	0.73/266	0.64/232	–12.5	1.23/51.3	0.55/0.59	0.75/0.86
Mean		0.69/252	0.58/213	–17.1	1.48/52.5	0.38/0.56	0.66/0.89

$\bar{x}_{obs}$ and $\bar{x}_{cal}$ are mean observed and simulated values, respectively; *RMSD* is the root-mean-square deviation; *Eff* is the Nash-Sutcliffe efficiency of simulation and *r* is the coefficient of correlation.

comparable with our results. Second, as mentioned above, most of the basin precipitation values during the cold season were estimated. Third, adjustment of daily precipitation to 3-hour time steps also contributes to underestimation of streamflow during the warm season when showers occur. Besides that, inaccuracy of the estimated incoming radiation may also influence the results. Nevertheless, after taking into account such uncertainties in the forcing data, the results obtained can be considered as satisfactory and the technique of *a priori* parameter estimation is suitable for application for ungauged basins located in the permafrost zone.

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