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Coupled modelling of soil thaw/freeze dynamics and runoff generation in permafrost landscapes, Upper Kolyma, Russia

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Abstract The distributed process-based runoff formation hydrograph model was applied and tested against soil thaw/freeze depth and runoff data in several permafrost landscapes of the Kolyma Water Balance Station (KWBS). The parameterization describing different permafrost conditions was elaborated. Soil thaw/freeze depths were simulated for three sites comprising rocky talus, mountainous tundra and larch forest landscapes. The runoff model was applied and calibrated for three plot-scale homogenous watersheds related to certain landscapes and one larger Kontaktovy Creek basin enclosing the mentioned land surface types (21.2 km^2). The hydrograph model proved its capability to simulate both surface and subsurface processes of runoff formation in different permafrost landscapes.

Key words permafrost hydrology; hydrograph model; Kolyma water balance station

INTRODUCTION

Many studies have been conducted to investigate surface processes such as snow formation, redistribution, ablation and surface-atmosphere energy exchange in different permafrost and alpine landscapes including both field (Boon, 2012; Musselman *et al*., 2012) and modelling studies (Ellis *et al*. 2010; Burles & Boon, 2011; Helgason & Pomeroy, 2012a,b; MacDonald *et al*., 2012).

Physical properties of permafrost soils have a leading role in controlling the depth of seasonal thaw and mechanisms of runoff generation (Quinton *et al*., 2000, 2005; Sugimoto *et al*., 2003; Carey *et al*. 2007). In spite of this, distributed hydrological models often inadequately represent or even neglect the subsurface processes of soil freezing and thawing, with only very few exceptions (Kuchment *et al*., 2000; Gusev *et al*., 2006; Rigon *et al*. 2006; Schramm *et al*., 2007; Mou *et al*., 2008; Schaefer *et al*., 2009; Ye *et al*., 2009; Semenova *et al*., 2013).

This paper aimed at analysing active layer formation and flow generation mechanisms in mountainous permafrost landscapes of the Kolyma Water Balance Station (northeastern Russia), including rocky talus, mountainous tundra and moist larch forest, and simulate the thaw/freeze depths and runoff hydrographs on a daily time step at three active layer observation sites and four small-scale watersheds using the Hydrograph hydrological model (Vinogradov 1988; Vinogradov & Vinogradova, 2010).

STUDY AREA AND PROCESSES OF ACTIVE LAYER AND RUNOFF FORMATION

The Kolyma Water Balance Station (KWBS), 21.2 km^2, is situated in the zone of continuous permafrost at the upper reaches of the Kolyma River (Fig. 1). Various hydrometeorological and related measurements were carried out at the KWBS from 1948 to 1997. KWBS is located in a transitional zone between forest-tundra and coniferous taiga in a high-elevation area with altitudes up to 1700 m. Mean annual temperature for the period of 1950–1990 is estimated as –11.6°C, while total annual precipitation varies from 250 to 440 mm with elevation and slope inclination (Suschanskiy, 1999).

Across KWBS the landscapes differ considerably depending on slope characteristics, and include rocky talus and mountainous tundra at the watershed divide, larch forest in moist river valley bottoms. The studies by Lebedeva & Semenova (2012a) and Semenova *et al*. (2013) have shown that in terms of active layer formation, KWBS land surface may be conditionally divided into four main types corresponding to landscapes of sparse forest-covered north-facing slopes, bog bottom valleys, rocky talus, and mountainous tundra of south-facing slopes. Three plot-scale relatively homogenous watersheds, Severny, Yuzhny and Morozova, related to certain landscapes and one larger Kontaktovy Creek basin enclosing all four mentioned land surface types were the focus of this study. The main characteristics of the watersheds are presented in Table 1, the location within the KWBS territory is shown in Fig. 1.

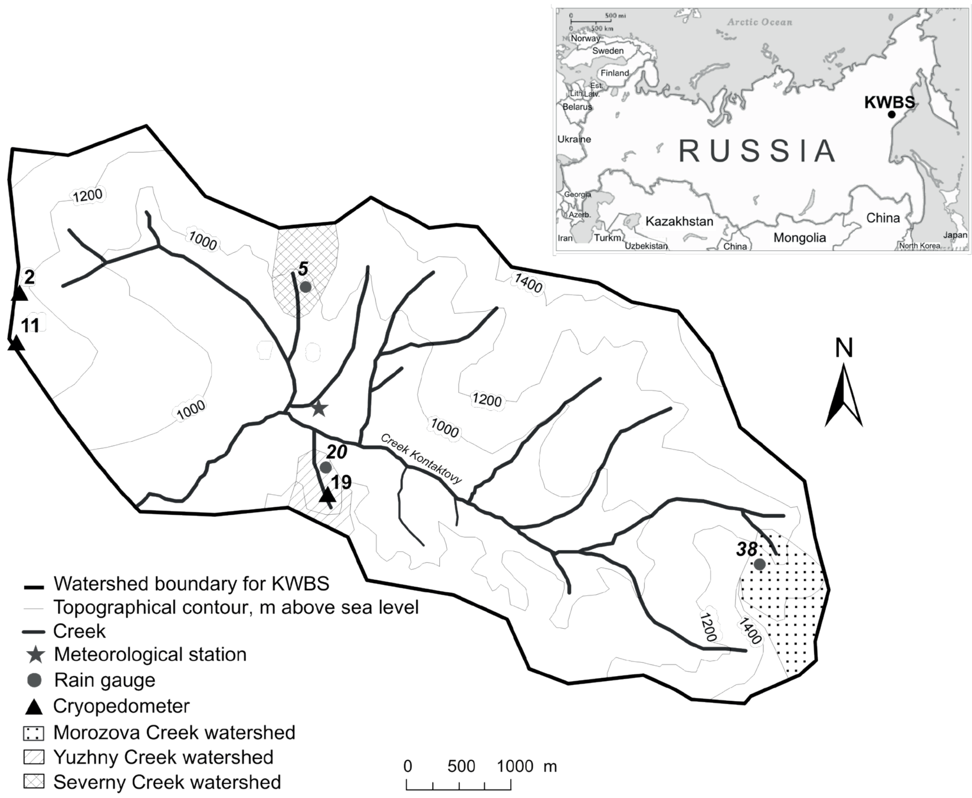

Fig. 1 Location of research sub-basins, cryopedometers, meteorological station, and raingauges at the Kolyma Water Balance Station (KWBS). The inset shows the location within Russia.

Table 1 Main landscape characteristics of the studied basins.

Creek	Area, (km^2)	Average (and maximum) elevation (m)	Average (and maximum) slope (º)	Area occupied by a certain landscape (%)			
				Rocky talus	Mountain tundra	Sparse trees	Forest and bogs
Morozova	0.63	1370 (1700)	33 (50)	98	2	0	0
Severny	0.33	1020 (1300)	21 (40)	24	63	0	13
Yuzhny	0.27	985 (1100)	17 (30)	5	17	56	22
Kontaktovy	21.2	1070 (1700)	25 (50)	34	27	12	27

The watershed of the Morozova Creek is a unique research spot because it is completely covered by rocky talus with no vegetation. Stone fragments vary from 4 to 20 cm diameter with 10 cm mean value. Total porosity is approx. 0.35. At depths coincidental to the active layer lower boundary, the composition of sediments changes abruptly: the talus is filled by fine-grained sand and sandy loam (Bantsekina & Mikhailov 2009). Due to low water storage capacity and high values of thermal conductivity in coarse rock, the ground thaws quickly and deeply here, allowing water to infiltrate easily and drain above the frozen impermeable horizon at the depth range of 1.5 to 2 m. Ground ice developed from frozen percolated melt water in cold ground in spring, or from infiltration of autumn precipitation into freezing soil, becomes an additional source of water during warm periods leading to flow dependence on air temperature variations (Boyarintsev, 1986).

Yuzhny Creek is covered by larch forest. Continuous ground cover is presented by sphagnum mosses and lichens with peat-humus gravelly loam characterized by high content of organic material underneath (Boyarintsev *et al*. 2006). Ice thaw in the soil profile occurs during the warm season. The soil is characterized by high moisture content, often close to full saturation (Mikhailov *et al*., 2007). Due to low thermal conductivity of saturated soils, the depth of the active layer does not exceed the depth of the organic-mineral layer and averages 0.7 m. Impedance for vertical infiltration of snowmelt water causes formation of surface flow that could also be generated due to intensive summer rains.

Distribution of vegetation in the Kontaktovy Creek basin (21.2 km^2) has clear dependence on elevation with significant differences between southern and northern slopes. Below 1000 m the territory is covered by larch forest. Above 1000 m it is replaced by dwarf cedar trees on southern slopes and sparse trees on northern ones. Higher parts are covered by rocky talus.

The Severny Creek watershed is covered mainly by dwarf cedar trees with moderate to high density. Soil-vegetation cover is dispersed and fragmentary. Within the active layer, which is more than 1.5 m deep, the soil profile is largely homogenous and composed of crushed stones of clayey shale with a sand and sandy-loam matrix. In the absence of precipitation, the thawed layer remains dry above the frozen impermeable layer (Mikhailov *et al*., 2007).

THE HYDROGRAPH MODEL AND PARAMETERIZATION SCHEME

The hydrograph model is a distributed process-based runoff formation model. Its detailed description, including the approaches for discretization of the watershed, can be found in Vinogradov *et al*. (2011) and Semenova *et al*. (2013). The model could be applicable for basins located in different climate zones, regardless of watershed size. The model was successfully tested in different permafrost and non-permafrost environments in Russia and Canada. The results of the model applications to basins of different scales can be found in Semenova & Vinogradova (2009), Semenova (2010), Lebedeva & Semenova (2012a,b) and Semenova *et al*. (2013).

The model describes all essential components of the land hydrological cycle, including heat and water dynamics in soils at hourly to daily time steps explicitly taking into account water phase changes. A simplified differential equation of vertical heat transfer in a soil is used to simulate ground thaw–freeze processes. Water dynamics within a soil column are described by applying a water balance equation for each soil layer; the number of the layers usually equals 10. Soil moisture/ice phase changes, heat exchange between discretized simulation layers, land cover and atmospheric conditions are taken into account in the heat dynamics simulations in the soil profile. The ratio of the soil water that contributes to the runoff at each time step depends on soil properties (model parameters): porosity, water holding capacity, infiltration coefficient (saturated conductivity). The details of the approach can be found in Vinogradov (1988) and Vinogradov & Vinogradova (2008). The main model parameters are physical soil and vegetation properties that are derived independently according to available information (general and thematic descriptions of natural conditions, maps, etc.) and require minimum calibration. The model input is daily or hourly values of the precipitation, air temperature and humidity.

Daily input meteorological data used for the simulation in each watershed of KWBS were compiled as follows: summer precipitation was taken from the raingauges located within the each watershed (Fig. 1), while air temperature, air moisture and snow precipitation were used from the only meteorological station. Elevation correction factors for air temperature and solid precipitation were introduced.

Table 2 shows the most important properties of soil layers constituted the soil profiles that correspond to the four studied land surface types. They were assessed using the observational site descriptions comprising the measured data and literature review. The properties were used as the model parameters in simulation of soil heat and water dynamics in soil columns, and subsequent runoff modelling.

Table 2 Generalized hydraulic and thermal properties of four main types of soil horizons.

	Moss-lichen cover	Peat	Clay with fragments of clayey shale	Crushed stones of clayey shale
Density (kg m^{-3})	500	1720	2610	2610
Porosity (m^3 m^{-3})	0.90	0.80	0.55	0.35
Field capacity (m^3 m^{-3})	0.60	0.20–0.40	0.13	0.07
Infiltration coefficient (saturated conductivity) (10^{-5} m sec^{-1})	17	0.00085–8.5	0.00085	0.1–1.7
Specific heat capacity (J kg^{-1} (ºC)$^{-1}$)	1930	1930	840	750
Specific heat conductivity (W m^{-1}(ºC)$^{-1}$)	0.8	1.0	1.2	1.7

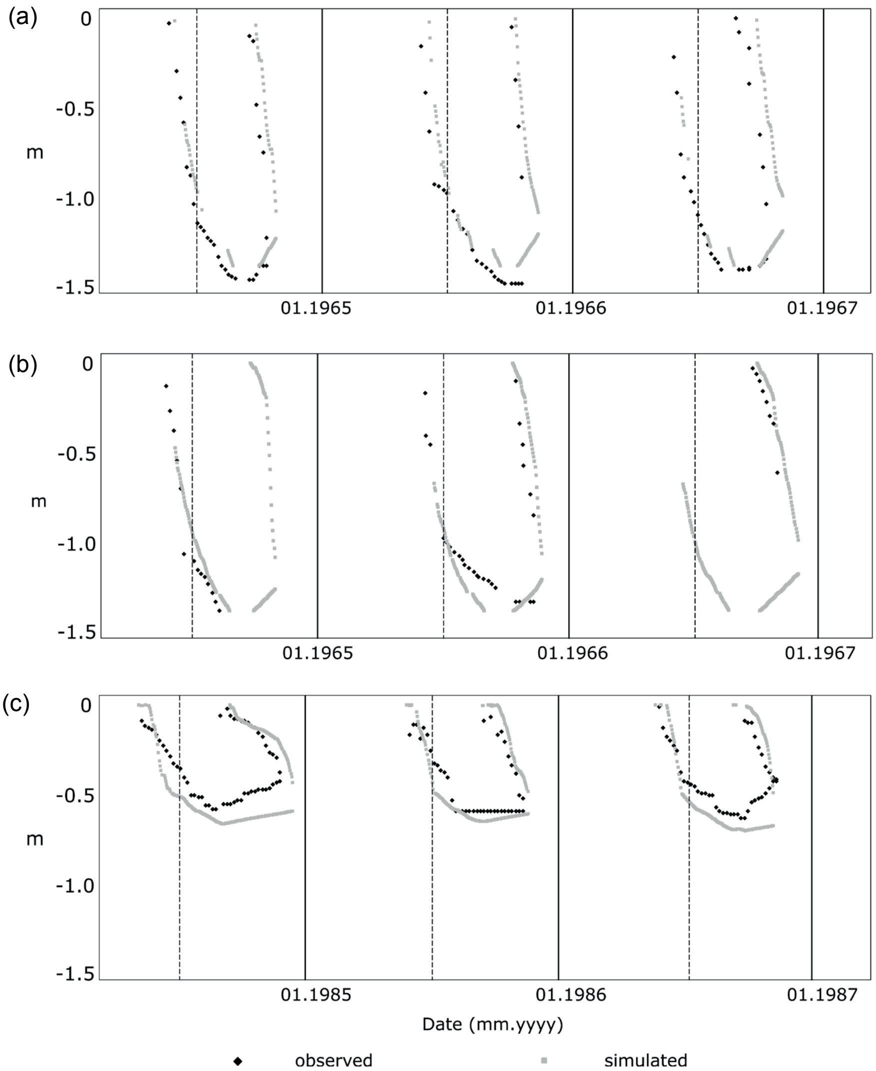

Fig. 2 Observed (black points) and simulated (grey points thawing depths at three sites of the KWBS: (a) rocky talus, (b) mountainous tundra, (c) swamped forest, m).

RESULTS AND DISCUSSION

Active layer depths at three observation sites and river runoff in four small watersheds were simulated for the periods 1950–1990 and 1969–1990, respectively. The comparison between modelled and observed thaw/freeze depths in rocky talus, mountainous tundra and moist larch forest is shown in Fig. 2. Measured and simulated hydrographs for the years with highest and lowest Nash–Sutcliffe model efficiency coefficients for the Kontaktovy, Morozova, Severny and Yuzhny watersheds are presented at Fig. 3. It can be seen that calculated and observed values of thaw/freeze depths and flow have satisfactory agreement. Mean annual Nash–Sutcliffe model efficiencies of the hydrograph simulations are 0.65, 0.49, 0.22 and 0.65 for the Morozova, Severny, Yuzhny and Kontaktovy watersheds, respectively. Modelling results for the Yuzhny watershed are of lower accuracy that could be explained by a high interannual variability of soil column storage capacity before the snowmelt, which depends on autumn soil saturation. The problem of autumn soil moisture modelling is explained by the fact that autumn snowfall registered in raingauges in the higher part of the basin along with positive air temperatures in the meteorological plot, lead to modelling of water infiltration in soil and even flow peaks. In reality, due to uneven air temperature distribution across the slopes the first solid precipitation does not melt but forms snow cover and keeps the ground unsaturated before the spring snowmelt. It allows more snowmelt water to infiltrate into the ground and prolong the freshet.

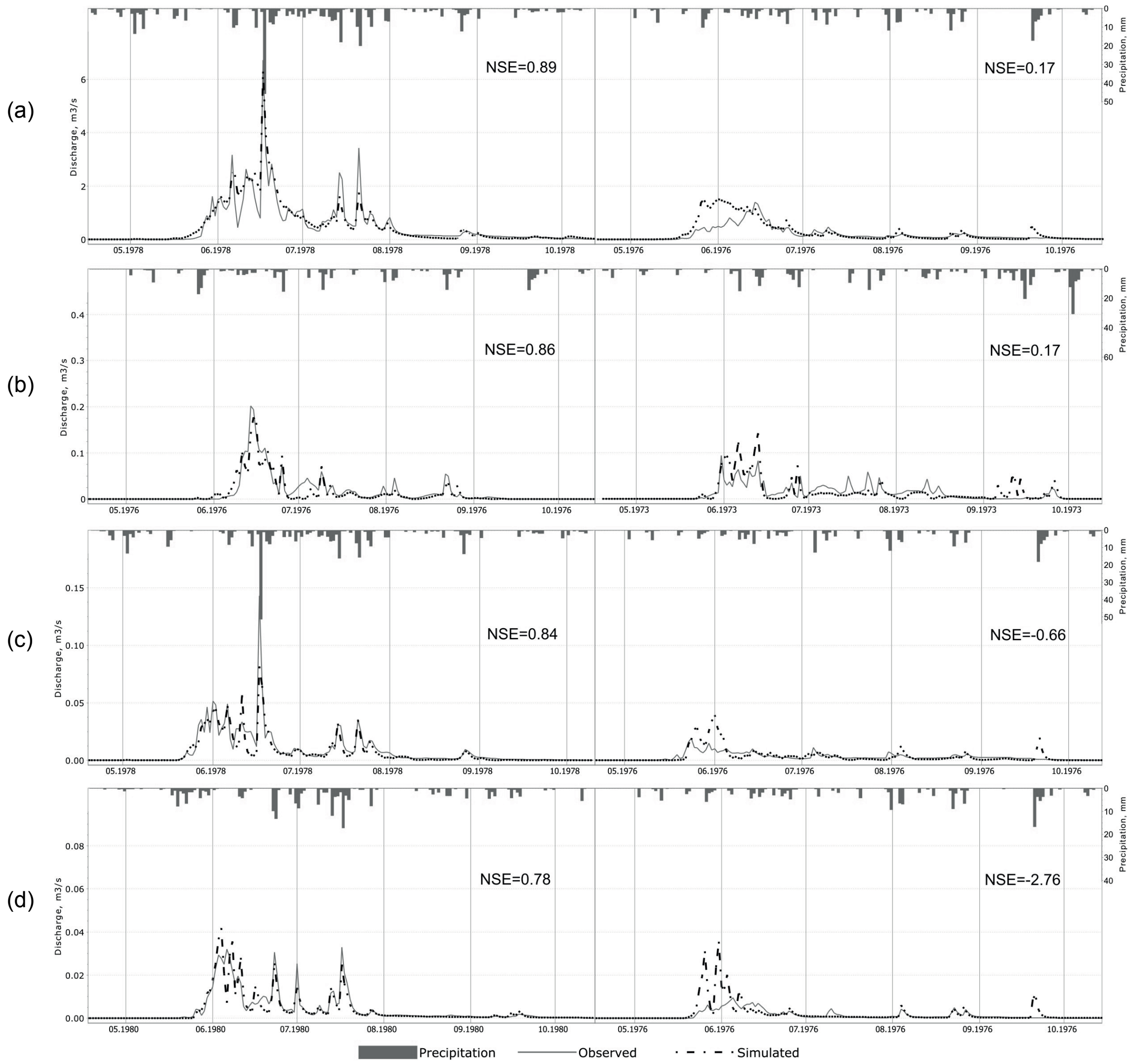

Fig. 3 Observed and simulated flow at: (a) Kontartovy Creek, (b) Morozova Creek, (c) Severny Creek, (d) Yuzhny Creek, m^3/s. Left column corresponds to the years with highest NSE, right column – with lowest NSE for the period 1969–1990.

Generally, the accuracy of calculations for wet years is higher than that for dry years. Each of the four studied watersheds has a quick and pronounced response to a large rain event, therefore its successful modelling mainly depends on input data. During dry years the discharge is a function of many other uncertain variables rather than precipitation, such as evaporation, soil water storage, talik development and suprapermafrost water dynamics, that are not adequately described by the model.

The results of multiple modelling runs have shown that proper simulation of summer floods for plot-scale watersheds relies entirely on precise meteorological input. Although the distance between the Severny, Yuzhny and Morozova watersheds hardly reaches 3 km, flood timing and maximum discharge formed by the same rain event significantly differ due to uneven precipitation distribution in the mountainous area. Moreover, some rain events forming the maximum annual flood at one watershed do not cover the whole station territory and do not lead to a significant rise in water discharge at other plot-scale catchments. Involvement of observational data from raingauges located within each watershed considerably improved the modelling results compared to the use of meteorological plot data only.

Precipitation data from the meteorological plot adjusted by an elevation factor served as the model input for each watershed in winters. Spring flow generation is controlled by snowmelt and subsurface processes including water infiltration, ground ice formation and soil thawing. Snowmelt patterns are complicated by non-simultaneous warming and uneven snow cover distribution across the basins. Statistical accounting of the snow redistribution with variation coefficients from 0.4 in larch forest to 0.8 in rocky talus, allowed improving modelling results in spring. The runoff at the Severny Creek starts 3–5 days before that at the Yuzhny Creek (Boyarintsev 1986). In the Morozova Creek, spring flow is delayed on average by 17 days in comparison to the Severny Creek (Suschanskiy, 1999). Surface flow considerably contributes to the spring flood at the Yuzhny Creek watershed whereas water reaches the Severny and Morozova Creeks only under the land surface. The reason is the quick thawing and high ground permeability of the rocky talus and tundra landscapes. Frozen, usually saturated, peaty soils in larch forest prevent substantial water infiltration and lead to surface flow formation.

CONCLUSION

It was shown that precipitation distribution, snow cover redistribution, snowmelt and soil thawing patterns are of the highest importance for hydrograph modelling for historic time periods in the studied basins. Data of the detailed measurements of precipitation, flow, soil thawing and comprehensive process description serve as a reliable base for application of a process-based hydrological model to several small permafrost watersheds. The proposed hydrograph model is supposed to be able to simulate both surface and subsurface processes of runoff formation in different permafrost landscapes, including poorly gauged and ungauged basins.

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