Use of soil thaw/freeze depth data to verify hydrological modelling at poor gauged basins in permafrost regions

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Verwendung von Tau- und Gefrierdaten des Bodens zur Überprüfung eines hydrologischen Modells in schlecht beobachteten Permafrostgebieten

1 Introduction

Most basins in cold regions have scarce data availability. They are characterized by complex interaction of climate, water, permafrost, soil and vegetation and show a high vulnerability to land use and climate changes. Therefore there is an urgent need to improve our understanding of land hydrological cycle in cold environments and its model representation.

In recent years extensive both field and modelling studies of the hydrological processes affected by permafrost were conducted. Data of the research basin Wolf Creek in Canada were used for analysis of the snow redistribution processes (Pomeroy et al., 2006), of the soil thawing/freezing and of water balance patterns in different slopes (Carey & Woo, 2001; Quinton et al., 2005) and for the development of the hydrological model (Pomeroy et al., 2007; Dornes et al., 2008).

Field studies in Kuparuk research basin in Alaska revealed different mechanisms of runoff generation in permafrost terrain from headwater to low gradient areas (Kane et al., 2000) and served as a base for ARHYTHM (arctic hydrological and thermal model) testing (Zhang et al., 2000).

The Kolyma water balance station (KWBS) situated in the Russian North-East within the Kolyma River basin is the oldest research watershed in permafrost zone. As showed

Zusammenfassung

Das verteilte, prozessbezogene Abflussbildungsmodell *Hydrograph* wurde anhand von Tau- und Gefrierdaten des Bodens sowie anhand von Abflussdaten des Permafrostgebiets der Kolyma-Wasserbilanzstation (KWBS) getestet. Die Parameterisierung für verschiedene Permafrostbedingungen wurde geprüft. Die Tiefen der Tau- und Gefriervorgänge im Boden wurden an drei Standorten (Geröll, Gebirgstundra, Lärchenwald) simuliert und das Abflussmodell anhand des Kontaktovy-Einzugsgebiets (21,2 km^2) kalibriert. Die Abflusssimulation erfolgte an drei schlecht beobachteten Einzugsgebieten (1820 bis 9560 km^2) unter Verwendung des kalibrierten Parametersatzes. Die Ergebnisse zeigen die zuverlässige Anwendbarkeit des Modells Hydrograph in Permafrostgebieten bei eingeschränkter Datengrundlage.

Schlagworte: Permafrost-Hydrologie, Modell Hydrograph, Kolyma-Wasserbilanzstation.

Summary

The distributed process-based runoff formation model *Hydrograph* was applied and tested against soil thaw/freeze depth and runoff data in different 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 the Kontaktovy Creek watershed (21.2 km^2), which is covered by these respective land cover types. Runoff simulations were carried out for three poorly-gauged river basins (areas ranging from 1820 to 9560 km^2) using the same soil and vegetation parameters of the calibrated model. The results have shown that the *Hydrograph* model can be reliably applied in the conditions of data limitation considering permafrost-related hydrological processes.

Key words: Permafrost hydrology, Hydrograph model, Kolyma water-balance station.

by BOYARINTSEV (1988), the conditions and hydrological regime at the KWBS are representative for mountainous territory of North-Eastern Russia. In this study the data obtained at the KWBS were used to parameterize the process-based hydrological model Hydrograph (VINOGRADOV & VINOGRADOVA, 2010; VINOGRADOV et al., 2011). The model was validated against soil thaw/freeze depth and discharge data. Adjusted model parameters were transferred to three poorly gauged basins in permafrost-affected mountainous region in the upper part of the Kolyma river basin.

2 Study basins

The KWBS is situated in the headwater region of the Kolyma River in the mountainous region of continuous permafrost. The watershed area is 21.2 km^2. The elevation varies within 800–1700 m range. Averaged mean annual temperature is –11.6 °C, annual precipitation varies within the watershed from 205 to 440 mm (1948–1989). Main types of landscapes are rocky talus, mountain tundra, sparse forest and wet larch forest. From 1948 to 1997 special observations of water balance components, state variables of frozen soil and snow and other characteristics were carried out at this station. The data such as meteorological input (daily values of air temperature, humidity, precipitation), runoff and thaw/freeze depths were used to run and test the *Hydrograph* model. Thaw/freeze depths were measured in three sites related to three main types of landscapes. Each site was equipped with a cryopedometer of Danilin type to measure the depth of thaw/freeze in soil. A cryopedometer of Danilin is an instrument consisting of a rubber tube 1 cm in diameter and a centimeter ruler. The tube, closed at both ends, is filled with distilled water, lowered in an ebonite pipe and placed into soil bore-hole. The depth of freeze is determined by the lower end of ice column in the tube (SNYDER et al., 1971).

The parameter values were transferred to three middle scale basins situated in the upper mountainous part of the Kolyma River basin (Fig. 1): the Detrin River (basin area 5630 km^2 and mean annual discharge 47 m^3/s), the Tenke River (basin area 1820 km^2 and mean annual discharge 21 m^3/s) and the Ayan-Yuryakh River (basin area 9560 km^2 and mean annual discharge is 67 m^3/s). The basins can be regarded as poorly-gauged because in contrast to the small watersheds in the KWBS there are neither data of non-standard observations, nor information about land cover and process peculiarities. Also meteorological input data are quite limited. Only the Detrin River basin has a meteorological station inside the borders of the basin. Sparse network of meteorological stations requires precipitation interpolation with respect of mountainous relief that was solved by the consideration of precipitation dependence on altitude for studied area.

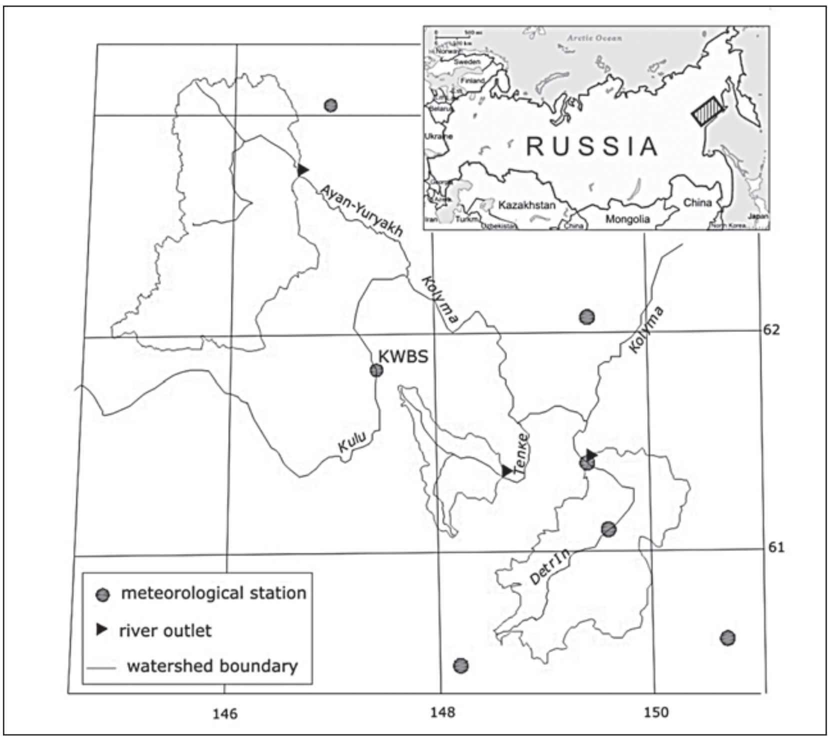

Figure 1: Location of studied objects – the Kolyma Water-Balance station, three middle-scale basins: Ayan-Yuryakh River, Tenke River and Detrin River and meteorological stations

Abbildung 1: Lage der Untersuchungsgebiete – Kolyma Wasserbilanzstation, drei mittlere Testeinzugsgebiete: Flüsse Ayan-Yuryakh, Tenke und Detrin sowie die meteorologischen Stationen

3 Runoff generation and associated processes

The landscapes of the KWBS vary considerably with altitude, slope aspect and inclination. The rocky talus landscape with no vegetation except crustose lichen occupies 35 % of the catchment dominating at the upper parts of slopes and steep slopes. Mountainous tundra spreads over middle parts of watershed slopes (38 %) and consists of cedar elfine wood with moss and lichen ground cover and sparse larches. Swamped larch forest occupies flat valley of the watershed and terraces on taiga cryogenic peaty soils (27 %).

The processes of soil freezing and thawing and formation of surface, subsurface and ground flow differ in distinct landscapes. The deepest active layer, up to 1.6 m, was formed at the rocky talus landscape. The soil profile has homogenous structure and consists of crushed stones. The water infiltrates quickly and easily, which leads to subsurface flow generation; the drainage capacity is high and the water content of the soil column is rapidly decreasing that explains prevalent dry conditions in rocky talus landscape. The part of snowmelt water percolating to the frozen rocks freezes and is kept till full thaw of soil profile. It causes the flow redistribution within the year.

Minimum depth of thawing (about 0.6 m) is observed in swamped forest where soil profile includes relatively thick peaty layer (about 40 cm) and clay with clayey shale rocks underneath. In winter the soil is usually fully saturated with ice and does not allow water to infiltrate. During spring, right after the snowmelt, when the process of soil thaw starts, the snowmelt water forms surface flow in larch forest. The schematic soil profiles were compiled from the description accompanying the data of observation (observation materials etc., 1966–1991). They are shown in Fig. 1.

4 The Hydrograph model

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). The model was developed with the aim of achieving a general character, so that it could be applicable for basins located in different climate zones, as well as regardless of watershed size.

The model describes all essential components of land hydrological cycle including heat and water dynamics in the soils in daily or hourly time steps explicitly taking into account water phase changes. A simplified differential equation of heat transfer in soil profiles is used to simulate ground thaw-freeze processes. Water dynamics within a soil column is described by applying a water balance equation for each soil layer. Heat dynamics simulation of soil profile is affected by variable state soil moisture/ice, heat transfer/exchange occurring with phase changes and between discretized simulation layers, land cover and atmospheric conditions. The ratio of the soil water that contributes to the runoff depends on soil properties (model parameters) in particular on porosity, water holding capacity and infiltration coefficient. The details of the approach one can find in VINOGRADOV (1988), VINOGRADOV & VINOGRADOVA (2008). The main model parameters are physical soil and

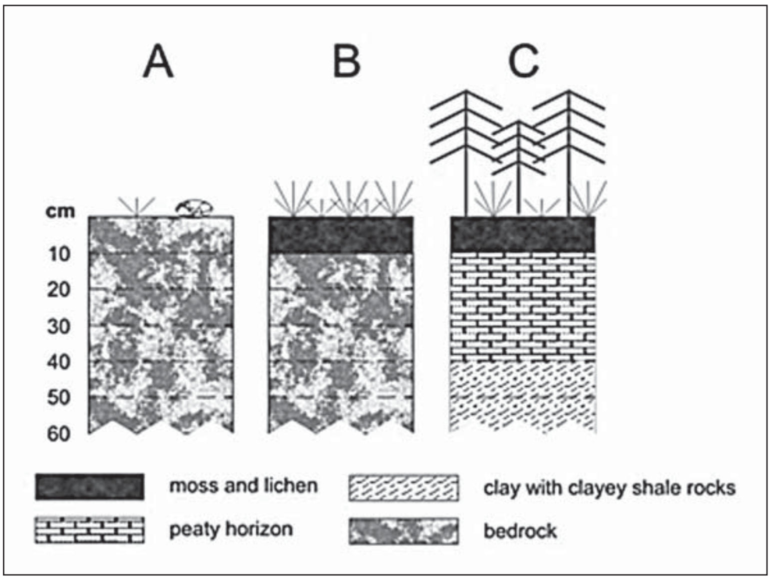

Figure 2: Three schematic soil profiles at KWBS: A – rocky talus, B – mountainous tundra, C – swamped larch forest

Abbildung 2: Schema der Bodenprofile am KWBS: A – Geröll, B – Gebirgstundra, C – sumpfiger Lärchenwald vegetation properties that are derived independently according to available information (description, maps, etc.) and require minimum of calibration. The model input comprises daily or hourly values of the air temperature, humidity and precipitation.

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 could be found in Semenova (2010), Semenova & Vinogradova (2009), Semenova et al. (2012), Lebedeva & Semenova (2012), Pomeroy & Semenova (2010), Lebedeva & Semenova (2012).

5 Parameterization and modelling results

The model parameters related to landscapes (soil and vegetation) were assessed using the observational site's descriptions comprising the data and literature review. Table 1 shows the most important soil parameters that control soil heat and water dynamics. The simulations of thawing depth were performed for three sites in rocky talus, mountainous tundra and swamped forest. Fig. 3 shows the comparison of the results and observations.

As one can see from observations (Fig. 3) soil thaws and freezes with different intensity in the three studied landscapes. The quickest process is observed in rocky talus where thawing of the top soil stratum 0.75 m depth takes approximately two weeks. After that the observational curve slightly changes its form, showing a deceleration in thawing intensity because of change of the conditions between 0.75 and 1 m depths (supposed presence of the ground ice). Soil thawing up to 0.70 m in the swamped forest takes approximately three months due to low heat conductivity, high heat capacity and high water/ice content of the peaty soils. The soil starts to freeze from the surface in autumn and freezes completely in some depth in late autumn or early winter. Peaty soils (Fig. 3c) show there very slow propagation of the frost front from the surface to 0.2 m depth likely due to high moisture that takes much heat energy to cool and freeze. Rocky stratum on the contrary (Fig. 3a) is very dry in the beginning of autumn frosts that leads to quick soil freezing.

Table 1: Main model parameters controlling soil heat and water dynamics
Tabelle 1: Hauptparameter des Modells für Bodentemperatur und Bodenwasserdynamik

Soil layer	Porosity, m^3/m^3	Heat capacity, J/kg*°C	Heat conductivity, W/m*°C	Water holding capacity, m^3/m^3
Moss	0.80	1930	0.5	0.60
Peat	0.80	1930	0.8	0.50
Loam with crushed stone	0.50	750	1.7	0.15
Crushed stone	0.55	750	2.3	0.13
Crumbling rock	0.50	750	2.3	0.13

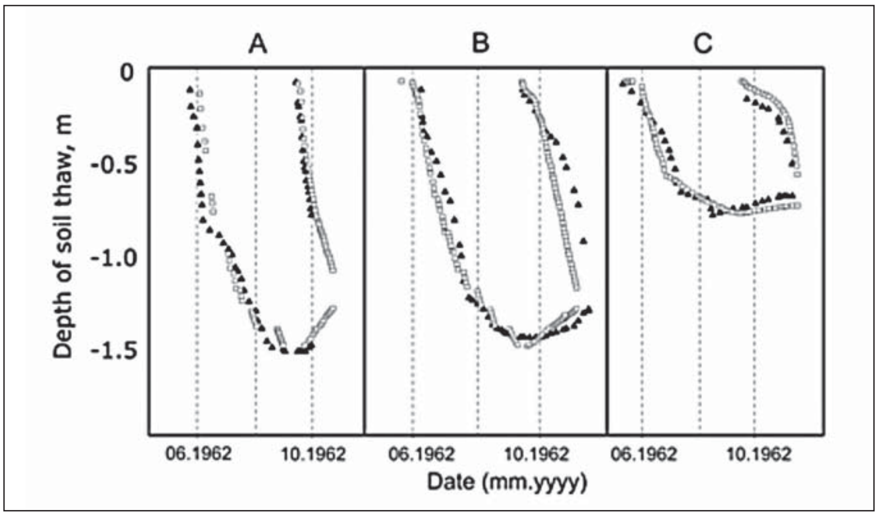

Figure 3: Observed and simulated thawing depths at three sites of the KWBS: A – rocky talus, B – mountainous tundra, C – swamped forest
Abbildung 3: Beobachteter und simulierter Auftaubereich (Tautiefe) am KWBS: A – Geröll, B – Gebirgstundra, C – sumpfiger Lärchenwald

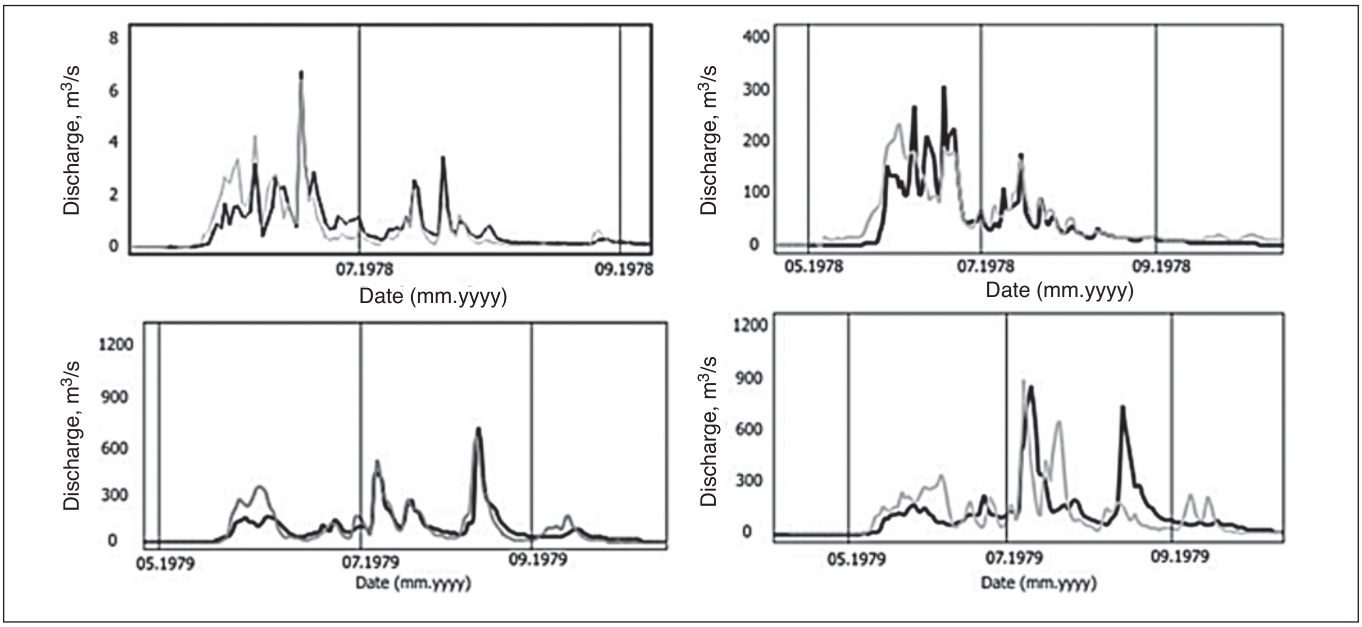

Figure 4: Observed (black) and simulated (grey) flow at the KWBS (top left), Tenke (top right), Detrin (bottom left) and Ayan-Yuryakh (bottom right) river basins, m^3/s

Abbildung 4: Beobachteter (schwarz) und simulierter (grau) Abfluss am KWBS (oben links), Tenke (oben rechts), Detrin (unten links) und Ayan-Yuryakh (unten rechts)

The simulation of the active layer depths captured all mentioned peculiarities of soil thawing and freezing processes at the three studied landscapes.

The runoff at several sub-catchments and whole KWBS was simulated using the same soil and vegetation model parameters as for active layer depth simulations. The detailed description of the modelling case and analysis of the results are presented in SEMENOVA et al. (2013, in press). Top left graph in Fig. 4a shows computed and observed discharges at the KWBS outlet. Adjusted values of the soil and vegetation model parameters were transferred to the Ayan-Yuryakh, Detrin and Tenke rivers basins. The results of runoff modelling for those poorly gauged basins are presented at Fig. 4 b–d.

For the test at poorly gauged basins the simulated hydrographs satisfactory agree with observed ones showing the greatest divergence in spring time. Overestimation of simulated flow in snowmelt period and just after is explained by the following reasons. According to the model algorithms the presence of ice in the ground reduces the infiltration coefficient and therefore the water contributes to the quick surface flow immediately after melting. As we know from literature, in reality the melting water infiltrates into the frozen soil, freezes and is partly stored there for days to one or two months. The Hydrograph model doesn't capture this process in full because of the imperfection of the water infiltration algorithm and parameterization.

Another reason is a lack of quantitative assessment of the water/ice content in different ground depths, thus we don't have the possibility to validate the simulated soil moisture values.

6 Conclusions

Detailed measurements of different components of land hydrological cycle and associated processes (soil moisture and temperature, snow depths, density, water equivalent, spatial distribution, ground water levels) in cold environments provide insight into runoff generation processes. They can be successfully used in parameterization and testing of process-based hydrological models and gained knowledge could be transferred to poorly gauged basins of permafrost zone. The *Hydrograph* model satisfactory represents soil thaw/freeze processes in different conditions of the KWBS as well as runoff formation in small and middle scale basins within permafrost zone using physical properties of soil and vegetation for the parameterization. Further research should be carried out for additional verification of the model performance using soil moisture observations.

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