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Process-based hydrological modelling in different permafrost environments

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Abstract: More than 60% of Russia and 20% of land surface in Northern Hemisphere is covered by permafrost. Hydrological cycle is influenced by time-variable frozen aquiclude, limited connectivity between surface and ground water, long snow season and period of river ice cover. Hydrological models developed for the temperate regions are not applicable in the permafrost river basins. The aim of the study is to make use of historically collected experimental hydrological data for modelling poorly-gauged river basins on larger scales in different Russian permafrost environments using process-based modelling approach.

The Hydrograph model used in the study explicitly simulates heat and water dynamics in the soil profile thus is able to reflect ground thawing/freezing and change of soil storage capacity through the summer in permafrost environments. The key model parameters are vegetation and soil properties that relate to land surface classes. They are assessed based on field observations and literature data, do not need calibration and could be transferred to other basins with similar landscapes. Model time step is daily, meteorological input are air temperature, precipitation and air moisture.

Parameter set is initially developed in the small research basins located in mountains and lowlands. The Hydrograph model was tested against ground thawing and freezing depth, soil moisture, ground temperature and snow characteristics in different permafrost landscapes in Central Yakutia and North-Eastern Siberia.

Shestakovka River basin (area 170 km^2) is a left tributary of the Lena River in the vicinity of Yakutsk city. The climate is very dry and continental. Mean air temperature (MAT) is -9.5°C, precipitation is 240 mm/year. The Kontaktovy Creek basin (area 21.2 km^2) is located in the Upper Kolyma plateau in North-Eastern Siberia. It is characterized by colder (MAT -11.4°C) and wetter (290-460 mm/year) climate. Both of the watersheds have been monitored for several decades. For both Shestakovka and Kontaktvy watersheds simulated soil and snow variable states have satisfactory agreement with observed ones. The river runoff simulation results for the Shestakovka River show very high variability from year to year. Results for mean and wet years are generally better than for dry years. Modelling results for the Kontaktovy Creek are satisfactory. The largest deviations occur in the spring flood period when presumably underground water pathway exist even in the frozen ground but are not accounted for by the model.

Refined set of model parameters was transferred to middle and large river basins characterized by similar landscapes and dominant hydrological processes. Model application to three rivers in Central Yakutia with basin areas between 3 380 and 65 400 km^2 and six river basins in North-Eastern Siberia with areas from 65 to 42600 km^2 suggests that the Hydrograph model is suitable tool for hydrological process investigation in permafrost zone.

We conclude that data about internal catchment processes on the smaller scale is essential for the increasing model realism on small and large scales in the dynamic and vulnerable permafrost environments.

Keywords: *Hydrological modelling, permafrost river basin, the Hydrograph model*

1. INTRODUCTION

More than 60% of Russia and 20% of land surface in Northern Hemisphere is covered by permafrost. The largest Russian rivers are affected by perennially frozen ground. Hydrological cycle is influenced by time-variable frozen aquiclude, limited connectivity between surface and ground water, long snow season and period of river ice cover (Woo, 2012; Walvoord and Kurylyk, 2016). Hydrological models developed for the temperate regions are not applicable in the permafrost river basins. Representation of the above-mentioned physical processes and their spatial variability across a hierarchy of scales remains a challenge. Air temperature-induced permafrost degradation leads to significant landscape transformation and hydrological consequences. New hydrological modelling tools that are able to cope with non-linear response of coupled permafrost-hydrology system to climate change are needed.At the same time the cold regions are characterized by lowest density of the observational network that restricts ability to test different modelling approaches and parameter sets.

The aim of the study is to make use of historically collected experimental hydrological data for modelling poorly-gauged river basins on larger scales in different Russian permafrost environments using process-based modelling approach.

2. THE STUDIED REGION

Two sets of small and middle-sized river catchments were chosen in the mountainous upper part of the Kolyma Riverbasin, North-Eastern Siberia,and relatively flat central part of the Lena River basin, Central Yakutia(Figure 1, Table 1). Central Yakut set includesSuola, Tatta and Amga river basins with areas 3380, 8290 and 65400 km^2 and predominant elevation range from 110 to 400 m. The upper part of the Amga river basin reaches 1000 m a.s.l.The climate is very cold, dry and continental. Mean air temperature (MAT) varies from -9 to -11°C, precipitation ranges from 270 to 310 mm/year.The dominant landscapeis larch forest. Upper Kolyma set includes six river basins with areas from 65 to 42600 km^2 and elevation range from 500 to 2200 m a.s.l.Precipitation measured at the meteorological stations varies from 220 to 360 mm/year. Stations are located at the 1190 m a.s.l. as a maximum. Special studies suggest that precipitation amount goes up to 600 mm/year at the higher elevations. MAT varies from -10 to -14°C with distinct air temperature inversion in winters. The dominant landscapes are sparse larch forest and mountainous tundra.

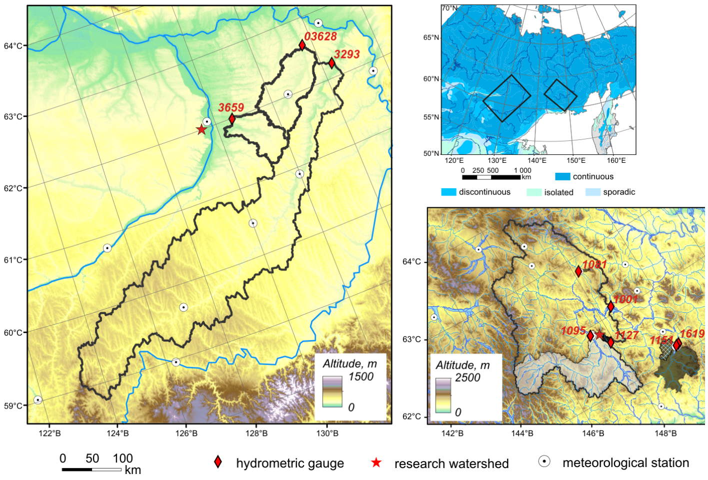

Figure 1. Studied river basins

These two sets of river basins were chosen because two small research watersheds are situated nearby and could be assumed to be representative for the large basins. Shestakovka River basin (area 170 km^2, Figure 1)is a left tributary of the Lena River in the vicinity of Yakutsk city. MAT is -9.5°C, precipitation is 240 mm/year. The Kontaktovy Creek basin (area 21.6 km^2) is located in the Upper Kolyma plateau in North-Eastern Siberia. It's characterized by colder (MAT -11.4°C) and wetter (290-460 mm/year) climate. Both of the watersheds have been monitored for several decades. Observations include both standard hydrometeorological parameters (discharge, meteorology) and special measurements: snow surveys, groundwater level, ground freezing and thawing, ground temperature and water content, etc.

Although both study regions are covered by continuous permafrost they are characterized by contrasting hydrological conditions. The Shestakovka River has slow and postponed reaction to precipitation. The correlation of total river runoff with last-year precipitation is larger than with this-year precipitation. It suggests that large and slow water storages in the basins are important chain in runoff generation. Such storages could be lakes and water-saturated taliks (layer or body of unfrozen ground occurring in a permafrost area).On the contrary, Kontaktovy Creek is a reactive watershed with spiky hydrograph. It does not have considerable storages in the basin except the seasonally developing active layer (AL). Depending on the properties of the landscape and AL snowmelt and rain water is quickly transmitted to the stream by surface or shallow subsurface flow.

Table 1.The simulated river basins

Code	River - gauge	Basin area, km^2	Altitude range, m	Modelling period	No of meteostations (including those within the basin)
Upper Kolyma region					
01102	Kontaktovy - Nizhniy	21.6	800-1700	1951-1997	1 (1)
01081	Talok - Outlet	65	600-1900	1966-2012	1 (1)
01127	Omchak - Omchak	151	800-1500	1966-1988	2 (0)
01619	Omchuk–Ust'-Omchug	583	500-1600	1966-1988	2 (1)
01151	Detrin–Omchuk River mouth	3490	500-1800	1972-1987	2 (1)
01095	Kulu - Kulu	10300	600-2000	1972-1987	3 (1)
01001	Kolyma - Orotuk	42600	500-2200	1978-1995	9 (6)
Central Yakutia					
03214	Shestakovka - Kamyrdagystakh	170	100-300	1951-2016	1 (0)
03659	Suola – Bedeme	3380	110-380	1980-2012	4 (0)
03628	Tatta – Uolba	8290	115-350	1980-2012	1 (1)
03293	Amga – Teryut	65400	120-1000	1980-2012	9 (3)

3. THE HYDROGRAPH MODEL

Hydrograph is a robust distributed process-based model. The algorithms describing processes on the land surface (e.g. snow accumulation and melting) and in the shallow subsurface zone (e.g. soil heat and water dynamics) have a physical basis since there is usually enough observational data for parameter estimations and model verification. Simulation approach for the deeper subsurface (ground water dynamics) hascertain strategic conceptual simplifications. Such model structure gives it the ability to be applied successfully in many parts of the world (Vinogradov et al., 2011). The key model concepts are presented in Vinogradov et al. (2011) and Semenova et al. (2013).

The studied basins are first delineated into computing elements. In terms of topography the basins are represented by a hexagonal grid of representative points (RPs). Each RP is characterized by altitude, latitude, aspect and slope. In terms of landscapes, the basins are divided into several runoff formation complexes (RFC, equivalent to hydrological response units). RFC parameters such as soil density, porosity, thermal characteristics, water holding capacity, vegetation features etc. reflectthe properties of dominating landscapes and are scale independent.They are not averaged across observed variability within the specific landscape but rather present dominant type of hydrological functioning and cleaned up from those minor details which do not have significant meaning at the level of consideration because of their spatial negligibility. In terms of vertical delineation the soil column is divided into several computational soil layers (CSL). As shown by Semenova et al. (2013, 2015) and Lebedeva et al. (2015), the model uses the properties of soil and vegetation cover as the input parameters. They are not calibrated but manually adjusted based on process analysis when the detailed data on runoff formation processes are available.

The hydrological processes are simulated at RPs that possess unique topographical characteristics and a set of model parameters related to one of the RFCs. Combined heat and water balances are calculated for each soil layer (Semenova et al., 2014; Lebedeva et al., 2015).

Formation of surface, soil and underground flow is modelled according to the concept of runoff elements (Vinogradov et al., 2011). Runoff elements mean the areas of watershed (surface and underground) which are exposed and contribute water to the slope's non-channel or underground drainage system. For each runoff element, there is an exponential relationship between water volume and outflow, with two hydraulic parameters. RPs are not connected to each other, and contribute runoff of different types directly into the channel network. The transmission of flow in the basin's channel network is conducted using a lag-and-route hydrograph method.

To compensate for the lack and unrepresentativeness of meteorological data for high elevation areas, a correction of air temperature and precipitation is introduced. To account for precipitation increases with altitude and air temperature inversions, the procedure of normalizing daily precipitation by annual mean values and correction of daily values of air temperature by gradient value is applied.

4. THE MODELLING PROCEDURE

4.1. Forcing data

Daily air temperature, precipitation and air moisture from 13 meteorological stations were used as input data for the Suola, Tatta and Amga river discharge simulations. There are three stations located within the Amga river basin and one station in the Tatta river basin. Suola river basin does not have any meteorological stations inside. Remaining six stations are situated outside of the studied river basins but nearby their borders.

Input data from 12 meteorological stations were used for the discharge simulations for the Upper Kolyma set of river basins. Five river basins out of six have the only meteorological stations located at the outlet, the lowest point of the basin. The largest Kolyma river basin (area 42600 km^2) at Orotuk has five stations within its borders.

4.2. Parameter estimation

After Semenova et al. (2013) and Lebedeva et al. (2014) four RFCs were introduced to represent the variability of permafrost landscapes in the Upper Kolyma region: rocky talus, sparse growth of larch trees, dwarf cedar tree brush and larch forest. It was shown that distribution of these landscapes depends on altitude and slope aspect. Areas located at the elevations higher 1100 m are occupied by rocky talus. Northern slopes between 900 and 1100 m a.s.l. are covered by sparse growth of larch trees and continuous moss and lichen cover. Dwarf cedar tree brush is developed on the southern slopes at the same elevation range. River valleys below 900 m are occupied by larch forest. These landscapes are characterized by specific hydrological processes. Setof model parameters that includes soil (density, porosity, water holding capacity, hydraulic conductivity, witting point, heat capacity and heat conductivity) and vegetation (albedo, shadowiness, evaporation coefficient, phenological dates) properties was developed for each of them. One RFC, larch forest, was used for simulations of the Central Yakut river basins.Thesoil profile depth was taken as 2m for all simulated basins.Thesoil profile wasdiscretized into 20 CSLs, each 10 cm thick.

We used theannual course of soil temperature at 3.2m depth as the lowerboundary condition, assuming it to be the climate norm. Theannual variation of soil temperature at 3.2m depth wasapproximated by two-harmonic sinusoid based on dailyobservations atmeteorological stations. Soil temperature observations are available at four stations out of 12 in the Upper Kolyma region and 8 out of 13 stations in Central Yakutia. All stations within the studied river basins have negative soil temperatureat 3.2 m depth: -2.7…-3.1°Cin Central Yakutia and -3.7…-7.6 °Cin the Upper Kolyma region.

4.3. Simulation results on slope scale

Verification of the model algorithms and parameter sets was conducted using point data on snow accumulation and melting, soil temperature and water (ice) content, ground thawing and freezing depths in different permafrost landscapes of the Shestakovka River and Kontaktovy Creek basins. The model was applied in a lumped manner to simulate vertical fluxes of water and energy. Soil and vegetation model parameters were adjusted on this step to minimize deviation between observed and simulated values. Comparison between observed and simulated snow depth, water/ice content and ground temperature at the Shestakovka River basin is presented in the Fig.2 (right). There is good model performance regarding the snow depth. Simulated water and ice content deviates from some of the observations but reflects general course of water and ice dynamics in the profile. Agreement between observed and simulated soil temperature is high in the upper part of the profile and lower at the deeper horizons.

Results of the ground thawing and freezing modelling for rocky talus, sparse growth of larch trees and dwarf cedar tree brush are shown at the Fig.2 (left). The model represents high variability of thawing depths among the different permafrost landscapes in the Kontaktovy Creek watershed. We can conclude that quality of model performance in relation to snow, soil moisture, temperature and ground thawing is satisfactory for both ShestakovkaRiver and Kontaktovy Creek basins.

4.4. Simulation results on small scale

The soil and vegetation parameter sets identified during the previous step were transferred and verified to the small Shestakovka River and Kontaktovy Creek basins. The modelling was performed in distributed manner taking into account landscape and relief heterogeneity.

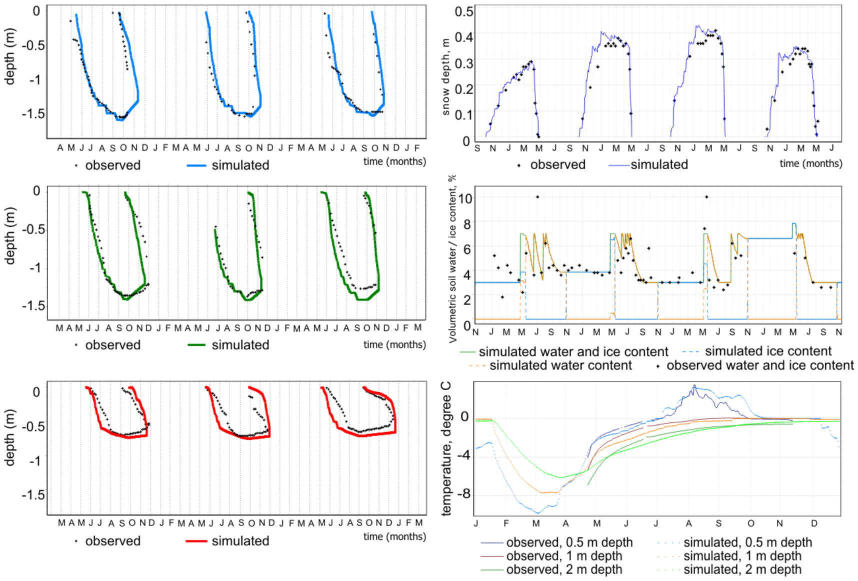

Figure 2. Simulation results on slope scale: left– thawing depths at the rocky talus, dwarf cedar tree brush and larch forest, Kontaktovy Creek, right – snow depth, soil water and ice content and ground temperature at different depths, Shestakovka River

The Kontaktovy Creek watershed was represented by 28 representative points and four RFCs. According to landscape scheme rocky talus took 32% of the basin area, sparse growth of larch trees – 21%, dwarf cedar tree brush – 29% and larch forest – 18%. One RP related to the larch forest was parameterized as if it does not have any permafrost in order to reflect channel talik.Modelling was performed for the period 1951-1997.Observed and simulated annual flow is 280 and 302 mm. The deviation is +8%. According to the simulation results the dominant water source of the Kontaktovy Creek is subsurface flow in the seasonally thawing layer. Deeper talikgroundwater and surface flow contribute 1.3 and 9 mm/year respectively. Deviation of the maximum discharges is higher and reach +64%. The probable reason is high variability of the rainfall within the basin. Observed amount of rain could differ in four times in different rain gauges in the basin during some storm events. The timing of flood rise and recession is usually well simulated.

The Shestakovka river basin was represented by 11 RPs. The basin area was divided into three RFCs – pine forest (47%), larch and birch forests (39%) and mire (14%). The simulation period was 65 years (1951-2016). Observed and simulated annual flow is 24 and 20 mm/year. Annual water balance components are modeled satisfactory. There is underestimation of maximum discharges during the extreme storm events. Quality of simulation in the daily time scale varies significantly from year to year. Model performs better in wetter years. Extreme minimum flow is usually overestimated.

General satisfactory agreement between observed and simulated hydrographs allows transferring of the parameter sets to the larger basins in the Upper Kolyma and Central Yakut regions.

4.5. Simulation results on middle scale

The model was applied to smaller and then larger river basins in Upper Kolyma and Central Yakut regions in a distributed manner. Soil and vegetation parameters were transferred without any change from the Kontaktovy Creek and Shestakovka River watersheds.

The mean annual flow of the studied basins varies from 169 to 335 mm/year in the Upper Kolyma region. Correction coefficients (CCs) were introduced to precipitation, snowmelt parameter and hydraulic parameters of surface and subsurface runoff elements for the basins. CCs turned out to be stable among the six simulated river basins. CC to precipitation was assumed to be 1.1 for five out of six basins. Lack of meteorological stations in the upper altitudes did not allow developing correlation between precipitation amount and elevation. Adopted CC reflect general tendency of precipitation increase with elevation. Precipitation CC for the smallest Talok river basin (area 65 km^2) was 0.9. The basin has elongated and narrow shape between mountain ridges from eastern, northern and western directions. Presumably the basin accepts less precipitation than observed at the nearest meteorological station outside of the valley due to specific orographic location. Snowmelt CC was taken as 1.5 for the southern Detrin and Omchug river basins. Other four basins have snowmelt CC equal to 1.1. Subsurface runoff elements contribute dominant part of the water to the river in permafrost basins. Hydraulic parameters of the subsurface runoff elements have correlation with the basin area: CC of 0.05-0.1 for the smaller Talok, Omchug and Omchak rivers and 0.2 for the larger Detrin, Kulu and Kolyma rivers,

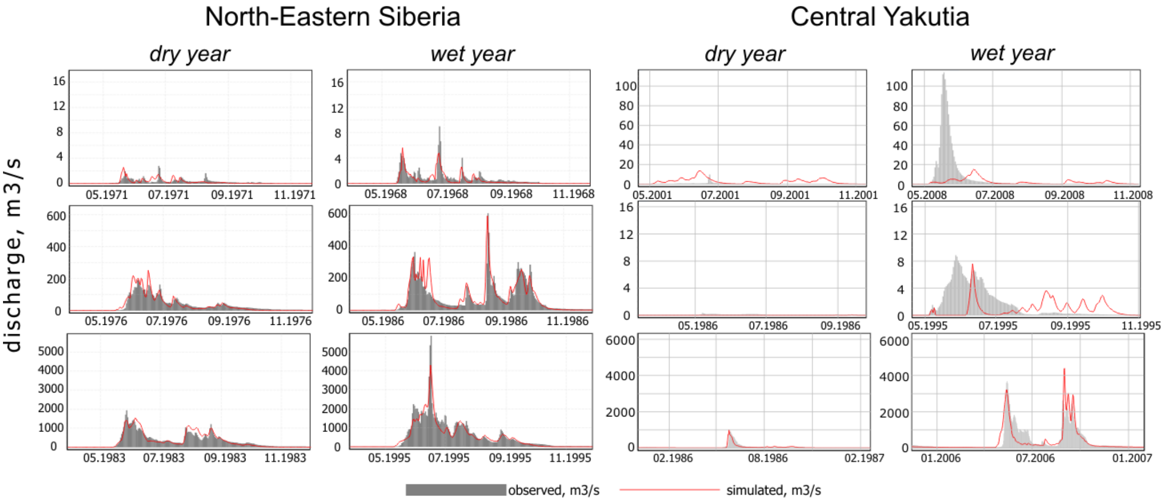

Figure 3. Simulation results on middle scale, North-Eastern Siberia (left: the Talok, Detrin and Kolyma Rivers) and Central Yakutia (right: the Suola, Tatta and Amga rivers)

Figure 3 shows observed and simulated hydrographs for the wet and dry years for the studied river basins. Observed and simulated water balance elements and Nash-Sutcliffe efficiency (NSE) for the simulated river basins are presented in the Table 2. Deviation between observed and simulated mean annual flow depth does not exceed 10 mm or 6%. There is systematic underestimation of the flow during extreme wet years at all simulated basins and overestimation of the low flow at the four out of six rivers. Precipitation varies from 244 to 427 mm/year. Simulated evapotranspiration ranges from 84 mm at the Kulu river basin, which is dominated by rocky talus, to 100 mm/year at the Omchuk river basins that is largely covered by larch forest. Mean squire error and Nash-Sutcliffe efficiency (NSE) suggest that accuracy of simulation is higher at the larger Omchuk, Detrin, Kulu and Kolyma river basins than smaller Omchak and Talok river basins. Annual NSE values calculated on the daily simulated and observed discharges for every year from the modelling period 1978-1995 does not drop down lower 0.45 for the Kolyma River and reach 0.89 in some years. Some storm events are overestimated and underestimated that could be explained by local rainfall in mountains and lack of precipitation data. Simulated and observed daily discharges satisfactorily agree with each other regarding the timing of peak and recessions.

The mean annual flow of the studied basins varies significantly in Central Yakutia: 0.99 mm/year for the Tatta River, 15 mm for the Suola River and 114 mm for the Amga River. There is satisfactory efficiency of simulation results for the Amga River regarding both timing and volume of flood events (Figure 3, Table 2). Mean NSE is 0.61 with extreme values from -0.26 to 0.95. Mean annual values of observed and simulated flow depth coincide (114 and 113 mm/year). Maximum discharges are systematically underestimated by 15%.

Modelling results for the Suola and Tatta river basins were not satisfactory using Shestakovka River parameter set. The mean annual flow of the Tatta River is 100 times lower than nearby Amga River flow. It suggests that dominant part of the precipitation falling on the Tatta river basin does not contribute to the river but goes to other storages. Such storages could be thermokarst lakes that are not presented at the Amga River basins but widely spread at the Suola (appr. 1600 lakes) and Tatta (appr. 2300 lakes) river basins. Three possible explanations were hypothesized: i) thermokarst lakes and their catchments are closed drainage area that does not contribute to the river; ii) higher snow and land surface evaporation: iii) water losses to the lake taliks and penetration to the deeper groundwater horizons that are not drained by the river.

To take into account influence of the thermokarst lakes on the river flow generation the following actions were performed: i) approximate fraction of the thermokarst lake was estimated. Fraction of the basin contributing to the river flow was assessed as 400 km^2 (appr. 5%) and 2280 km^2 (appr. 67%) for the Tatta and Suola river basins, ii) the values of the evaporation coefficients were increased, iii) part of the underground flow was directed to the underground water horizons that are not drained by the river and could be considered as water losses.

Such approach leaded to better model performance for the Tatta and Suola river basins on the mean and annual flow characteristics. Daily hydrograph dynamics regarding both timing and volume is still underrepresented.

Table 2. Observed and simulated water balance elements and Nash-Sutcliffe efficiency (NSE) for the simulated river basins, mean, maximum and minimum values for the modelling period.

River basin	01081	01127	01619	01151	01095	01001	03293	03628	03659
Simulated flow depth, mm	159 67-220	291 166-391	245 137-353	328 186-455	310 205-393	223 153-294	113 25-220	12.8 0.1-51.1	18 3.7-52.2
Observed flow depth, mm	169 63-430	297 139-460	241 105-407	335 185-489	301 162-432	225 136-300	114 29-232	0.99 0.01-3.3	15 0-70
Precipitation, mm	244 164-364	379 269-549	343 226-424	427 259-514	400 272-536	318 208-457	320 197-429	243 166-329	265 160-320
Evapotranspiration, mm	100 82-118	92 82-103	100 90-114	95 89-104	84 78-89	96 86-102	204 187-230	200 170-213	250 202-276
Maximum simulated discharge, m^3/s	5.2 2.6-12.4	26 12-44	82 48-135	405 252-590	1020 580-1431	2763 1528-4458	3300 1003-6176	4.1 0.06-16.5	11 6.5-82.2
Maximum observed discharge, m^3/s	5.7 1.6-17.5	27 10-53	84 23-181	448 172-641	999 381-1470	3228 1410-5840	2893 910-5290	3.6 0.07-9.2	33 1.35-114
NSE	0.13 -2-0.81	0.37 -0.8-0.74	0.56 -0.23-0.89	0.74 0.28-0.93	0.65 -0.3-0.88	0.75 0.45-0.89	0.61 -0.26-0.95		

5. CONCLUSIONS

Model application to six river basins in North-Eastern Siberia with areas from 65 to 42600 km^2 suggests that the Hydrograph model is suitable tool for hydrological simulation in permafrost zone in the region.Transfer of the parameter set from small well-studied Kontaktovy Creek watershed allowed avoiding model calibration on discharge data in the large poorly-studied river basins. This approach is one of the possible ways forward to overcome problem of calibration in modelling hydrology when efficiency criteria become more important than internal catchment processes.

Modelling results on three rivers in Central Yakutia with basin areas between 3 380 and 65 400 km^2 suggest that careful investigation of runoff generation processes are needed for successful parameter transfer and any use of analogue method in hydrology. The modelling experience could be considered as a tool for identification of azonal and unexpected catchment processes and evaluation of their influence on the river runoff.

We conclude that data about internal catchment processes on the smaller scale is essential for the increasing model realism on small and large scales in the dynamic and vulnerable permafrost environments.

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