Run-off modelling in an Arctic unglaciated catchment (Fuglebekken, Spitsbergen)

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ABSTRACT. The goal of this study is to test applicability of the conceptual catchment run-off HBV model to simulate discharge in small non-glaciated Arctic catchment. Within two ablation seasons, 2014 and 2015, in the Fuglebekken catchment (Spitsbergen, Svalbard), selected hydro-meteorological measurements were conducted, including discharge measurements in 10 min interval by Nivus PCM-F device with active Doppler sensor. The model parameters were calibrated on discharge measurements from both years separately and verified independently. As the transformation from rainfall to runoff includes a number of processes with different dynamics and timescales, the proper description of the processes and their simulation of discharge depend on the temporal resolution of the data. For that purpose, the relationships between the calibration and validation results, and optimal model parameters with different time steps were analyzed. It was found that calculated fit of simulated to observed discharge, depends on the year, time step and data averaging. The best results were obtained for the model from year 2015 for 3 and 6 h using averaged input data.

KEYWORDS: HBV, run-off modelling, Svalbard, temporal aggregation

INTRODUCTION

The functioning of river catchments is the crucial indicator of climate variability and environmental changes occurring in the Arctic. Understanding the determinants of the processes taking place under the influence of changing elements of the water cycle requires identification of the spatial dynamics of the snow cover disappearance, rainfall and changes of runoff in summer season. The derivation of relationships between meteorological conditions over a catchment area and the resulting outflow in a stream is a fundamental problem. Higher air temperatures and the increased precipitation observed in Svalbard in the last two decades lead to prolongation of the ablation season (Osuch and Wawrzyniak, 2016b). Future changes in the length of ablation season, precipitation and river outflows can alter fluxes of fresh water, sediments and nutrients. This would have implications for aquatic ecosystems (Blaen and others, 2014; Osuch and Wawrzyniak, 2016a).

For decades, ongoing international research activities aimed at improving knowledge and understanding of the processes involved. Hydrological recognition of the Arctic region still remains far less developed than it is at lower latitudes. Limited data availability is mainly due to extreme weather conditions and difficult accessibility (Sund, 2008). Hydrological modelling studies for Arctic catchments are not common. The published studies include an application of different hydrological models. Among them three-dimensional coupled MIKE SHE-MIKE 11 model was used for the ice-free Two Boat Lake catchment, Western Greenland (Johansson and others, 2015); CPIsnow model for 12 boreal catchments located in Northern Finland (Akanegbu and others, 2017); and WATCLASS used to simulate spring snowmelt run-off in a Trail Valley Creek in Canada (Pohl and others, 2005). The research efforts carried out in previous years in Svalbard were focused primarily on glaciated catchments, including Bayelva (Hodgkins, 1997; Sund, 2008), Ebbaelva (Rachlewicz, 2009; Dragon and others, 2015), Scottelva (Franczak and others, 2016), Waldemarelva (Sobota, 2014), and Breelva (Majchrowska and others, 2015). Nowak and Sobota (2015) used artificial neural networks for glaciated Waldemar catchment. The Deterministic Modelling Hydrological System (DMHS) helped to complete missing hydrological data for Werenskiöld glacier catchment (Majchrowska and others, 2015).

In this paper, the conceptual catchment run-off HBV (Hydrologiska Byråns Vattenbalansavdelning) model (Bergström, 1995) was applied to describe small non-glaciated Arctic catchments, specifically Fuglebekken. This hydrological model introduced by Swedish Meteorological and Hydrological Institute (Bergström and Forsman, 1973; Bergström and Lindström, 2015) is currently well recognized and widely used for an increasing number of applications and purposes. The HBV model was used for the first time in Svalbard in 1991 for the Bayelva catchment (Bruland, 1991). It was also applied for modelling of outflows of Endalen/Isdammen, de Geerelva and Bayelva (Bruland and Killingtveit, 2002).

The Fuglebekken catchment well represents the areas of sea terraces and coastal mountains without glaciers that are quite common along the western coast of Spitsbergen. Recent expansion of the ice-free areas is observed, so the recognition of the functioning of river ecosystems and the supply of fresh water to the surrounding fjords and seas becomes more and more essential (Błaszczyk and others, 2009). Discharge measurements from Fuglebekken catchment were carried out in previous years: 1979/80 (Pulina and others, 1984), and partly from 1988 to 1992 (Jania and

Pulina, 1994). However, these measurements were not made on regular basis. For the first time, discharge was measured at 10 min interval throughout most of the summer seasons of 2014 and 2015. High temporal resolution of relevant observations made the first attempt to model the catchment runoff possible. The applied HBV model has a structure with five conceptual storages taking into account dominant processes in the catchment: snow accumulation and melting, soil moisture, fast and slow runoff. The appropriate description of those processes and their simulations results at small catchment scale requires the input of hydro-meteorological data at appropriate temporal scale. The time required for runoff to travel from the hydraulically most distant point to the outlet or gauging station is described by the time of concentration (TC). It is a primary parameter recommended in hydrological modelling that should guarantee appropriate description of the dynamics of the catchment and an adequate accuracy of simulation results. TC can be computed using many different methods and depends on the stream slope, length of the channel and other morphometric properties of the catchment. An estimate of TC by the Kirpich formula (Kirpich, 1940) for the Fuglebekken catchment is slightly longer than 10 min. Therefore, at least the same temporal resolution is required for catchment run-off modelling. Unfortunately, the estimates of TC are uncertain and the differences in the TC values calculated with different methods can reach up to 500% (Grimaldi and others, 2012). This raises the issue of the appropriate time step of data used as input to hydrological models.

This paper aims to analyze the influence of data time step on the calibration and validation results of the HBV model as well as on the values of parameters. The studies by Littlewood and Croke (2008), Bastola and Murphy (2013), Wang and others (2015) revealed that the time step influences the model performance as well as model parameters. An influence of input data averaging on the discharge modelling results was also investigated. This type of hydrological modelling requires input data (precipitation, air temperature, potential evapotranspiration (PET)) and discharge values at an appropriate time step. Generally, a series of averages or sums over a time period should be applied, but due to limited observations, instantaneous and averaged values of discharges, as well as air temperature and the PET, are used in this study. As it is presented, the choice of instantaneous versus averaged data can influence the modelling results.

STUDY AREA

The Fuglebekken catchment is located in the close vicinity of the Polish Polar Station, Hornsund (PPS) (77°00′N 15°30′E), on the northern shore of the Hornsund fjord in southern part of Spitsbergen, the largest island of Svalbard Archipelago (see Fig. 1). Fuglebekken has been a part of many scientific investigations since 1970s for determination of geomorphology (Karczewski and others, 1990); fluvial processes (Pulina and others, 1984; Jania and Pulina, 1994); chemical denudation (Krzyszowska, 1985; Kozak and others, 2015; Skrzypek and others, 2015); permafrost and active layer thickness (Leszkiewicz and Caputa, 2004; Sobota and Nowak, 2014; Wawrzyniak and others, 2016).

The catchment up to outflow measurement point covers an area of 1.27 km². The catchment originates on the southern slopes of the mountain ridge Ariekammen-Fugleberget and elevated marine terraces of abrasion-accumulation

Fig. 1. Study area. Adapted from Jania and others (2002).

plain Fuglebergsletta. Hydrographic cover includes few tributaries of Fuglebekken stream and a small water reservoir of size 0.0048 km². Despite its small size, the catchment is heterogenous in terms of land cover and topography. The elevations range from 522 m a.s.l. just below the summit of Fugleberget and 513 m a.s.l. of Ariekammen to 4 m a.s.l, where the hydrological profile is located. Below this point, Fuglebekken drains into the Isbjørnhamna bay. The slopes of Fugleberget and Ariekammen are covered with washed rubble sediments, solifluction tongues, rock streams, alluvial cones and bare solid rock of Hecla Hoek geological formation (Czerny and others, 1993; Harland, 1997). Below the slopes, marine terraces covered with sea gravel (elevation from 2 to 30 m a.s.l.), raised during Holocene (Lindner and others, 1991) are covered by a diversity of tundra vegetation types (Migała and others, 2014), of which 32.5% of the catchment area is covered by Geophytic initial tundra (Skrzypek and others, 2015). Close to the eastern boundary of the catchment lies the lateral moraine of Hansbreen glacier, which was at its maximum Holocene extent in Little Ice Age (Błaszczyk and others, 2009). The ground here has a continuous permafrost layer down to more than 100 m depth (Humlum and others, 2003; Christiansen and others, 2010; Wawrzyniak and others, 2016).

Meteorological data have been collected continuously at PPS since July 1978. In the period 1979–2015, the mean annual air temperature at PPS was −3.9°C; the warmest month is usually July, with an average air temperature 4.4°C; the coldest month is March with an average temperature of −10.3°C (Osuch and Wawrzyniak, 2016b). The highest air temperature recorded at PPS reached 15.6°C on the 31 July 2015. The mean annual precipitation was 440 mm. Snow covers the ground on lower elevations ~250 days a⁻¹. Snow cover in this area during spring reaches from 0.30 m on flat surfaces of marine terraces, 0.80 m in upper parts of the slopes, up to 2.00 m at the bottom of the slopes (Winther and others, 2003).

HYDRO-METEOROLOGICAL DATA

The flow of water in rivers on Spitsbergen has a seasonal character. During late autumn, winter and early spring, in non-glaciated catchments, rivers freeze. There is a typical large variation of flow of water during ablation season, with very high discharge during the snowmelt and decreases during the summer (Killingtveit and others, 2003). Due to the

higher precipitation in late summer and early autumn, higher flow can be observed before the freezing season (Osuch and Wawrzyniak, 2016b).

Comparison of hydro-meteorological data from two consecutive years 2014 and 2015 is presented in Figure 2. Although the time courses of the air temperature look similar in both years with average monthly temperature differences for each July, August and September no higher than 0.1°C, precipitation amounts differ significantly. August 2014 was one of the driest in the history of measurements at PPS with a monthly sum of precipitation reaching 16.6 mm. Rainfall occurred in the end of August after almost a month with only a trace of precipitation. After such long drought, there was almost no catchment response to the precipitation event on the 28 and 30 August.

Hydrological investigations were conducted in periods from 14 June to 18 September 2014 and from 21 June to 18 September 2015. The water circulation is influenced by a number of factors that are variable in time. The lengths of the measurement periods were conditioned by river icing. Rivers in this area are frozen and covered with thick snowdrift from October until the end of May. The start of the ablation and the melt rate is governed primarily by the variability of the thermal-radiation factors (Sobota, 2014; Majchrowska and others, 2015; Franczak and others, 2016). Snow cover and river ice disappearance create disturbances for flow measurements during a brief but intense snowmelt period, so the discharge data since the beginning of July were

used. In both years, discharge was measured in the same profile (77.0053°N, 15.5561°E) using portable flowmeter Nivus PCM-F, designed for water level, velocity and flow monitoring in rivers and channels. Active Doppler sensor (KDA-KP 10) uncertainty is ±1% of the final value of velocity and ≤0.5% of final value of the water level. This instrument was installed on the bottom of Fuglebekken stream in the deepest point of the profile.

For the first time in the Hornsund region, the catchment runoff was measured with a 10 min time step. The open channel discharge measurement using the Doppler sensor has many advantages as well as some deficiencies. The portable Nivus PCM-F device is designed to record instantaneous velocity components at a single point with a relatively high frequency. Calculations are performed by measurement data of the velocity of particles in a remote sampling volume based upon the Doppler shift effect above the sensor and then automatically multiplied by the cross-section area. These measurements were carried out in unattended way for the entire ablation period. Data are reliable and accurate. They are comparable with results of velocity area method carried out with Electromagnetic Open Channel Flow Meter Valeport Model 801 with a Flat Type sensor. The velocity measurements were performed several times during each season and results between instruments varied only up to 15%.

The uncertainty of the measurement depends mainly on the channel geometry, which is the same during the entire ablation season. The river close to the gauging point is
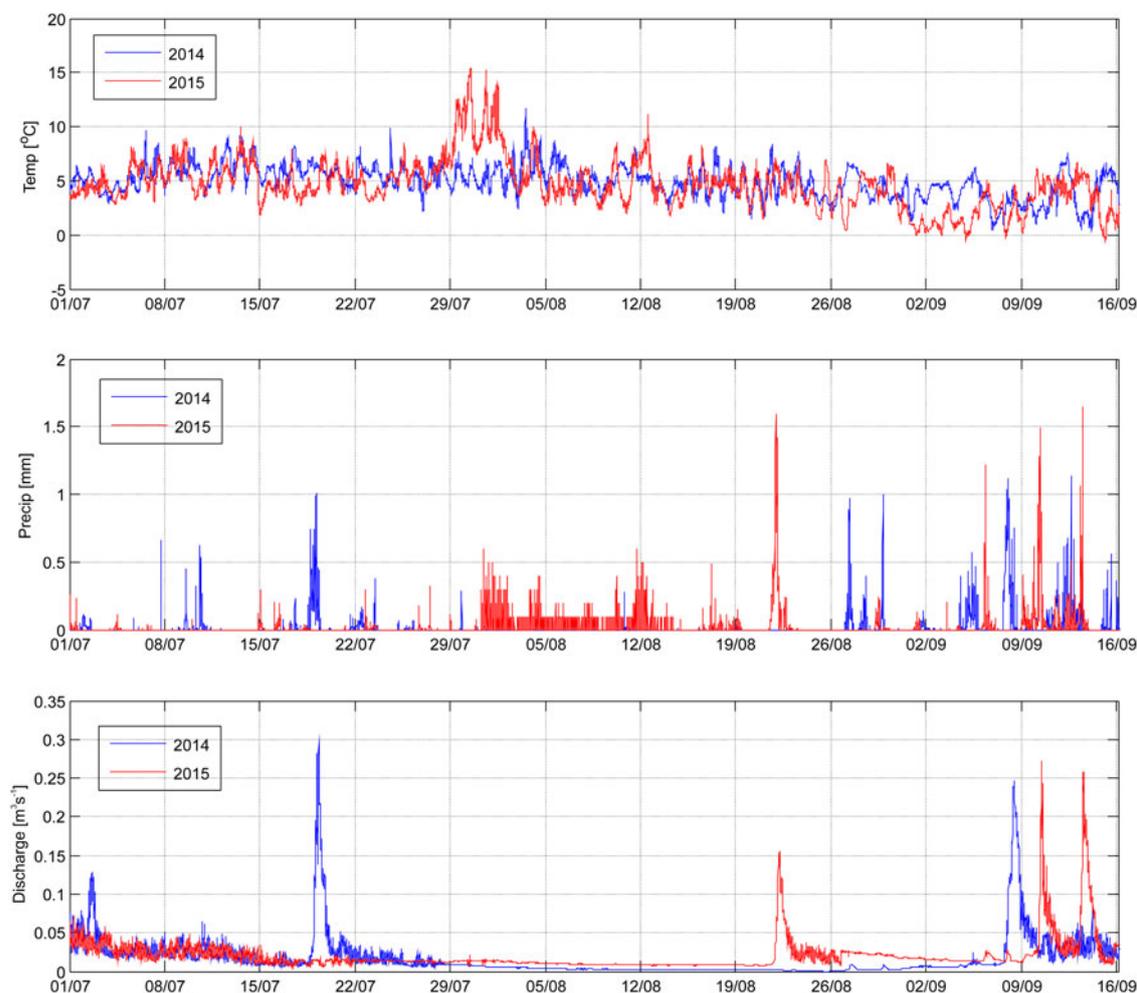

Fig. 2. Air temperature, precipitation and discharge in 10 min interval in 2014 and 2015 at Fuglebekken catchment.

characterized by relatively low-stream gradient and low-sediment transport, so the channel geometry is almost constant during the season.

For the HBV model setup and calibration, meteorological data were provided by the Institute of Geophysics, Polish Academy of Sciences that manages the PPS. Air temperature and precipitation at 1 min resolution are measured routinely at meteorological site of PPS located ~500 m to the southwest from the outflow measurement point. PET was calculated using temperature-based Hamon method (Hamon, 1961).

METHODS

Catchment run-off models

In this study, a conceptual HBV model was applied, which is a general-purpose hydrological model introduced by Swedish Meteorological and Hydrological Institute (Bergström and Forsman, 1973; Bergström and Lindström, 2015) and currently available in different forms and versions used for an increasing number of applications and purposes (Bergström, 1995; Lindström and others, 1997; Booij, 2005; Booij and Krol, 2010; Romanowicz and others, 2013; Osuch and others, 2015; Piotrowski and others, 2017). Conceptual models have moderate data requirements and their parameters are obtained by calibration and validation. A detailed description of the HBV model version applied in this study is presented by Piotrowski and others (2017). As presented in Figure 3, this version includes five conceptual storages as primary hydrological units that take into account the dominant processes in catchment run-off modelling: (a) snowmelting (b) snow accumulation, (c) soil moisture, (d) fast and (e) slow runoff. The input data are precipitation, air temperature and PET. The principal output is discharge; however, the other variables relating to water balance components (evapotranspiration, soil moisture and water storage) are also available from the model.

Similarly to the HBV version used by Piotrowski and others (2017), the model has 13 parameters of which values are estimated by calibration with ranges described in Table 1. Five parameters are related to snow processes: TT, TTI, $CFMAX$, CFR and WHC. Three parameters FC, LP and β are related to the second conceptual storage (soil moisture). $CFLUX$ represents the capillary transport between the fast run-off reservoir and the soil moisture reservoir. KF and α parameters describe the fast runoff. Percolation – the transport between the fast and slow run-off reservoirs – is described by the parameter $PERC$, while the slow run-off reservoir is represented by the KS parameter.

The HBV model was originally developed and is usually operated on daily time step data. In small mountainous catchments, such as Fuglebekken, discharge peaks are maintained only for short periods of time, usually lasting less than an hour. Due to that and the aforementioned the time of concentration parameter in this study, discharge data were recorded with 10 min time step.

Initial conditions for soil moisture and other storages were analyzed beforehand and assumed to be the same for both years. As a result of such testing, we excluded first 3 days of simulation from the time series used for calculation of objective function.

The HBV model is an example of conceptual rainfall-runoff hydrological model that was developed using water balance averaged over time steps. In hydrological practice,
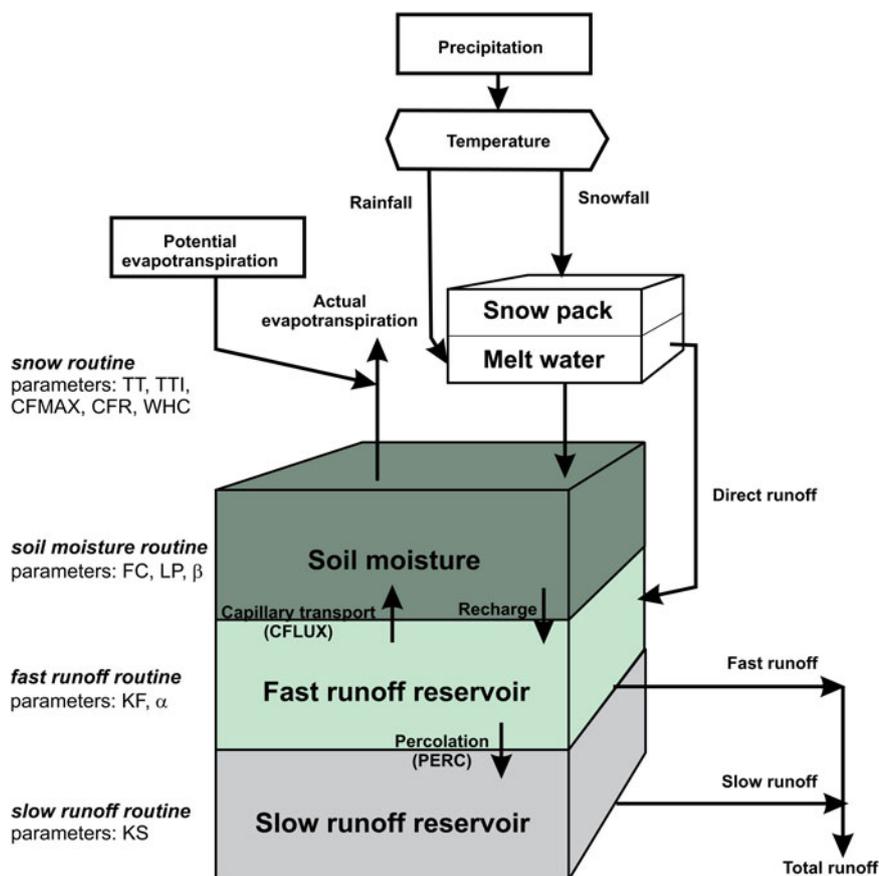

Fig. 3. Structure and parameters of the HBV model.

Table 1. The HBV model parameters and their ranges used for calibration

No.	Parameter unit	Description	Minimum	Maximum
1	FC [mm]	Field capacity, maximum soil moisture storage	0.1	1000.0
2	β [–]	Non-linearity parameter	0.01	7.00
3	LP [–]	Factor limiting potential evapotranspiration	0.1	1.0
4	α [–]	Non-linearity parameter	0.1	3.0
5	KF [1 time step^{-1}]	Fast run-off parameter	0.0005	0.3000
6	KS [1 time step^{-1}]	Slow run-off parameter	0.0005	0.3000
7	$PERC$ [mm time step^{-1}]	Rate of percolation	0.01	6.00
8	$CFLUX$ [mm time step^{-1}]	Rate of capillary rise	0	4
9	TT [°C]	Threshold temperature for snowfall	−3	4
10	TTI [°C]	Threshold temperature interval length	0	7
11	$CFMAX$ [mm °C time step^{-1}]	Degree day factor, rate of snowmelt	0	20
12	CFR [–]	Refreezing factor	0	1
13	WHC [mm mm^{-1}]	Water holding capacity of snow	0.0	0.8

the model is calibrated using discrete instantaneous flow observations that might be different than the averaged values. As detailed discharge observations were obtained for the Fuglebekken catchment, an influence of input data averaging (discharges, air temperature and PET) on the calibration and validation results was investigated.

Model calibration

Model calibration was carried out using the Differential Evolution with Global and Local neighbours (DEGL), a global optimization method described by Das and others (2009) and Piotrowski and Napiorkowski (2012). Following the literature review, the parameters of DEGL method were established (population size $N = 5 \times M$; scale factor $F = 0.8$; the cross-over rate $CR = 0.9$). As a stopping criterion, maximum number of iterations were used, namely 30 000. The applied method for parameter optimization provides reliable estimates of model parameters (Piotrowski and others, 2017); however, in some cases the method suffers of premature convergence to the local optima instead of proceeding to the global optimum (Das and others, 2009). To analyze this problem, the DEGL algorithm was run independently 30 times starting from different, randomly generated initial conditions.

As an objective function, the Nash–Sutcliffe coefficient (NS) of efficiency was applied (Nash and Sutcliffe, 1970). It is defined as:

$$NS = 1 - \frac{\sum_{t=1}^{n} \left(Q_{\mathrm{obs},t} - Q_{\mathrm{m}} \right)^2}{\sum_{t=1}^{n} \left(Q_{\mathrm{obs},t} - \overline{Q_{\mathrm{obs}}} \right)^2} \tag{1}$$

where Q_{obs} is observed discharge, Q_{m} is modelled values of discharge at time t and $\overline{Q_{\mathrm{obs}}}$ denotes mean observed discharge.

NS values can range from minus infinity ($-\infty$) to 1. A value of 1 corresponds to a perfect match between model and observations.

In this study, the HBV model was calibrated independently for:

- two ablation seasons (2014 and 2015);
- 11 time steps (10, 20, 30, 40, 60 and 90 min; 2, 3, 6, 12 and 24 h);
- discrete (instantaneous) and averaged over time interval data.

In addition, the HBV model was validated for each year (2014, 2015) using the HBV model developed on other year (2015 and 2014, respectively) with the same time step and averaging.

RESULTS

The results of the HBV model calibration for 11 different time steps and for 2 years were analyzed taking into account the effect of time step on model calibration and validation (maximum fit and also spread in the results) and the effect of time step on the values of parameters.

The effect of time step on the model fit

The results of calibration using data from year 2014 and 2015 are presented in the upper row of Figure 4 in the form of boxplots that represent the spread of the NS obtained for 30 runs of calibration procedure. In each boxplot, the bottom and the top of the box represent the first and third quartiles and the red line inside the box represents the median of the calculated model fit (NS values). The error bars represent the minimum and maximum NS from 30 runs of calibration procedure. The applied calibration procedure for each time step resulted in different values of objective function as well as model parameters. It is visible that the values of NS depend on the data time step as well as on the calibration year.

In the case of calibration results for year 2014 (upper left panel in Fig. 4), the best match between observations and simulations was obtained for 60 min time step (0.88). The maximum values of NS for time steps 10, 20, 30, 40 and 90 min are > 0.85, just slightly smaller than for 60 min. The results for longer time steps (6, 12 and 24 h) are characterized by lower maximum values of NS (smaller than 0.80) from the sample of calibration runs.

The maximum values of NS obtained at the calibration stage for year 2015 resemble tendencies as for year 2014. In this case, the maximum NS value was obtained for 20 min time step (0.89). In both years, the results for time steps shorter than 6 h are larger than 0.80. The NS values for longer time steps decrease with increasing time step.

The results of validation are presented in the bottom row of Figure 4. The panel on the left shows results of model validation from 2014 on data from 2015, while on the right
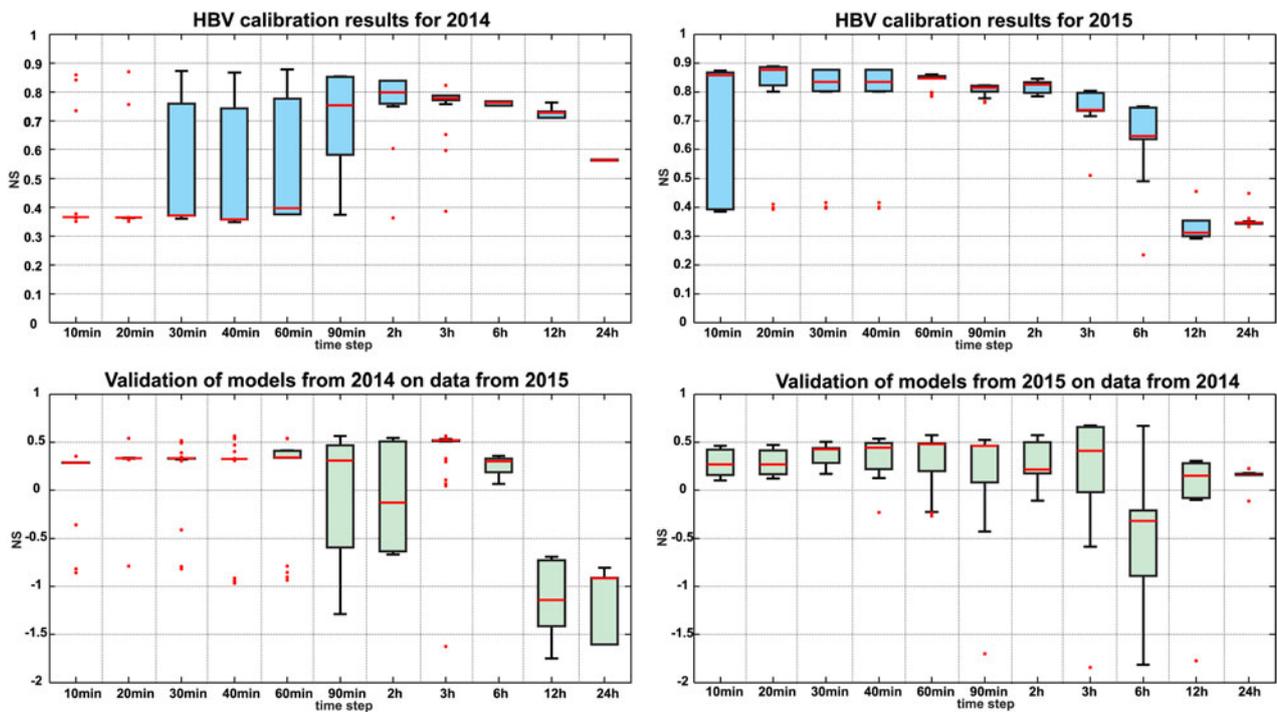
Fig. 4. A comparison of the calibration (upper row) and validation (bottom row) results for discrete data from year 2014 (on the left) and 2015 (on the right). Boxplots present the *NS* obtained for different data time steps. In each boxplot, the bottom and top of the box represent the first and third quartiles and the red line inside the box represents the median. The error bars represent the minimum and maximum from 30 runs of calibration procedure.

results of model validation from 2015 on data from 2014. The best results of validation (*NS* higher than 0.67) were obtained for two time steps (3 and 6 h) for validation of models from 2015 on data from 2014. Good results of validation (*NS* higher than 0.50) were obtained for time steps from 20 min till 3 h for models from 2014 and from 30 min till 6 h for models from 2015. Negative values of *NS* were obtained at validation stage for time steps 12 and 24 h for models from 2014. The validation results of models from 2015 for all tested time steps gave positive *NS* values.

Spread in the model fit (*NS* values)

A comparison of *NS* values for 30 runs of calibration and validation are characterized by spread in the obtained results that depend on data time step and also on the year.

The median values of calibration with *NS* higher than 0.70 were estimated for time steps from 90 min up to 12 h for discharge data from 2014 and from 10 min up to 3 h for 2015. Median values of *NS* for calibration were higher than 0.81 for time intervals from 10 min up to 2 h for data from 2015. The worst median results were obtained in this year for 12 and 24 h, reaching slightly above 0.30. Median values for calibration of discharge data from 2014 were below 0.40 in case of 10, 20, 30, 40 and 60 min interval.

The spread in the results described as a difference between maximum and minimum values of *NS* for each time interval is presented in Figure 4. The highest differences in some cases amounted slightly above 0.50. These results indicate that in some cases, the DEGL algorithm converged to the local optima. This problem occurred more frequently for smaller time steps.
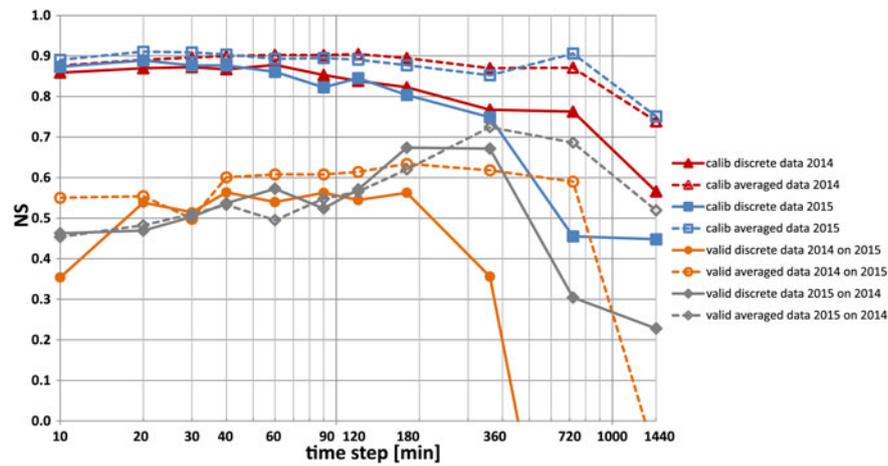
The effect of input data averaging on calibration and validation results

The best calibration and validation results from 30 runs of optimization procedure using HBV model for discrete and time-averaged hydro-meteorological data are presented in Figure 5. It is visible that in almost all cases, a better fit was obtained for averaged data (shown as dotted lines) than for discrete data (shown as continuous lines). Differences in the model fit are larger for longer time intervals (360, 720 and 1440 min). The results of model validation for both seasons, higher than 0.50, were obtained for averaged over time intervals between 30 and 720 min. The best fit at validation stage (*NS* = 0.72) was estimated for 360 min for model from year 2015 validated on data from year 2014.

The influence of input data averaging on the spread of *NS* values obtained at 30 runs of calibration procedure was also tested. The results in the form of boxplots are shown in Figure 6. A comparison of the outcomes for averaged (Fig. 6) and discrete input data (Fig. 4) indicate that application of averaged data resulted in a higher median from 30 runs of the optimization procedure for almost all time steps and seasons. The highest improvements in median *NS* were obtained for 1, 6, 12 and 24 h time step.

The effect of time step on parameter values

The obtained results of multiple runs of model calibration allowed for analysis of data time step on the model parameters. Those analyses were carried out independently for two seasons (2014 and 2015) and for discrete and averaged input data. Scatterplots showing the influence of data time step on 13 HBV model parameters are presented in

Fig. 5. Comparison of the best calibration and validation results from 30 runs of optimization procedure for discrete (continuous lines) and averaged (dotted lines) over time step data.

Figure 7. The optimum values of *KF*, *KS*, *PERC*, *CFLUX* and *CFMAX* were transformed into the same units (1 day^{-1}, 1 day^{-1}, mm day^{-1}, mm day^{-1} and mm °C day^{-1}, respectively).

It is shown that the relationships depend on parameter and also on the season and data averaging. These results allowed for classification of the parameters into a few groups. In the first group of parameters (*KF*, *PERC*, *ALFA* and *CFMAX*), consistent changes of parameter values together with an increase of time step is visible for both seasons and for discrete or averaged input data. Little change of the input data with time was found for *KS*, *TT*, *FC* and *BETA*. The third group of parameters (CFR, TTI, WHC, and CFLUX) had no consistent dependences between time step and parameter values.

In addition to visual inspection, the results were quantified using a variance decomposition technique following an analysis of variance (ANOVA) approach (Von Storch and Zwiers, 2001). We considered the following ANOVA model:

$$IN_{ijk} = \mu + TS_i + YR_j + FI_k + (TS \times YR)_{ij}$$
$$+ (TS \times FI)_{ik} + (YR \times FI)_{jk} + \varepsilon_{ijk} \tag{2}$$

where IN_{ijk} is a value of parameter (e.g. FC) for *i*th time step (10, 20 min, …, 24 h), *j*th year (2014, 2015) and *k*th data averaging (without/with). The first element on the right-hand side of Eqn (2) denotes the overall mean. The next three elements represent the principal contributions to the variance corresponding to the time step (TS), year (YR) and
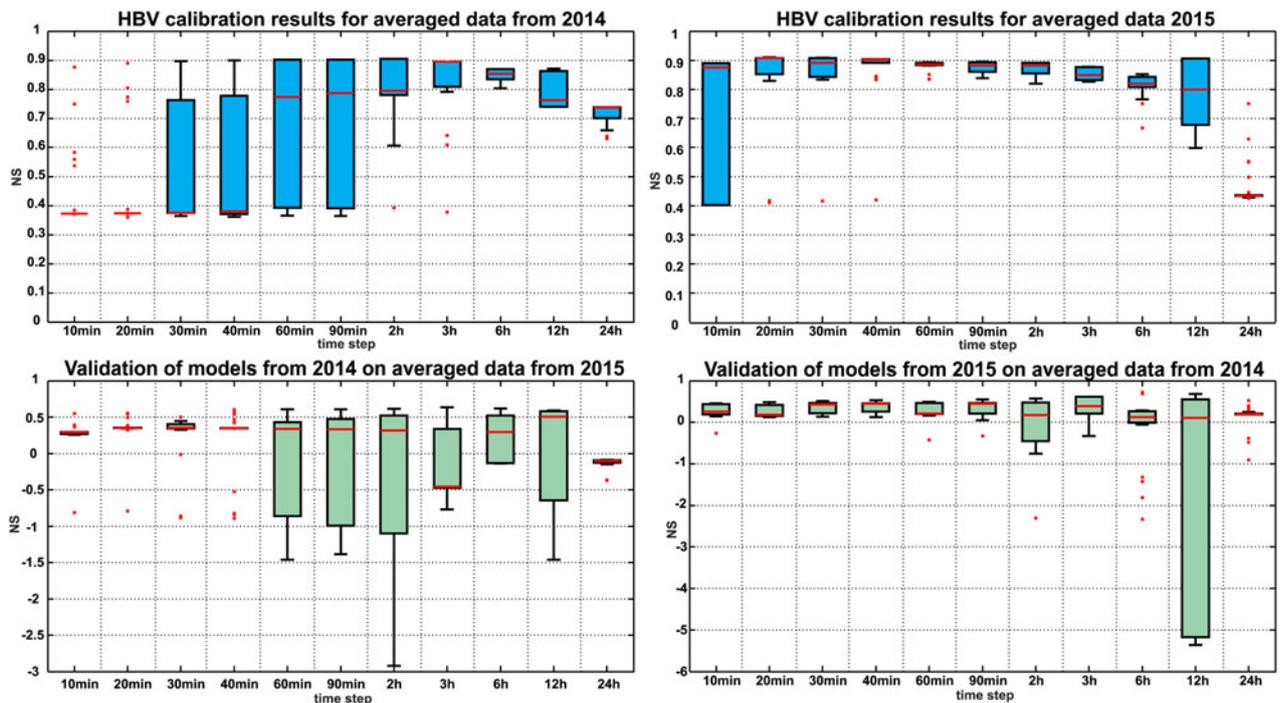
Fig. 6. A comparison of the calibration (upper row of panels) and validation results (bottom row of panels) for averaged data from year 2014 (panels on the left) and 2015 (panels on the right). Boxplots present the *NS* obtained for different data time step. In each boxplot, the bottom and top of the box represent the first and third quartiles and the red line inside the box represents the median. The error bars represent the minimum and maximum from 30 runs of calibration procedure.
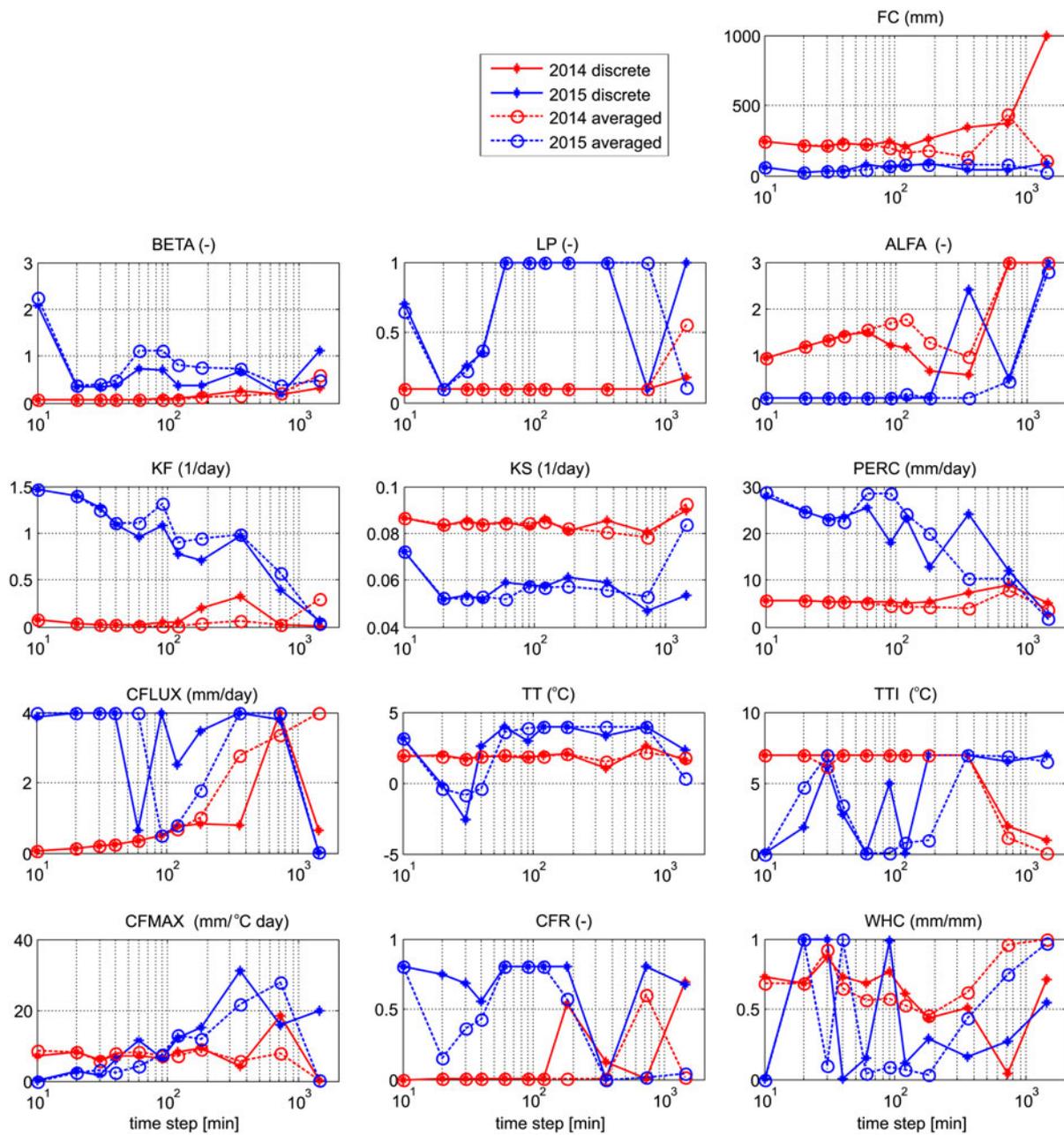
Fig. 7. Dependence of discrete (blue lines) and averaged (red lines) parameter values on time step of data.

data averaging (FI). The following three elements describe the interactions between them (TS × YR, TS × FI, YR × FI). The last element represents errors (i.e. the unexplained variance). The *N*-way ANOVA analysis was supplemented by Tukey's honestly significant difference criterion procedure (Tukey, 1949) to test the equality of the mean response for groups. The results of the test allowed for statistical comparison of differences between time steps, seasons and data averaging.

According to *N*-way ANOVA and Tukey test, statistically significant differences between two analyzed seasons (years 2014 and 2015) were found for all parameters but *CFMAX*. The opposite results of testing were obtained for the case of data averaging. There are no differences in parameter values for the averaged and discrete data for all parameters but *CFR*. Differences in parameter values between time steps were estimated as statistically significant for *BETA*, *ALFA*, *KF*, *KS*, *PERC* and *TT*. For other parameters (*FC*, *LP*, *CFLUX*, *TTI*, *CFMAX*, *CFR*, *WHC*), there are no statistically

significant differences in optimum values between different time steps.

SUMMARY AND CONCLUSION

This paper presents results of catchment run-off modelling in the Arctic unglaciated catchment using the HBV model. The estimated value of the *TC* by the Kirpich formula was ~10 min. Therefore, it was assumed as an initial choice of time step for catchment run-off modelling. As the estimates of *TC* are highly biased, the analysis included an aggregation of hydro-meteorological input data to 20, 30, 40, 60 and 90 min; 2, 3, 6, 12 and 24 h.

High-quality 10 min time step discharge measurements, precipitation and air temperature data were available for Fuglebekken catchment for two ablation seasons (2014 and 2015), which made testing an influence of data time step on the calibration and validation results as well as values

of parameters possible. HBV has 13 parameters calibrated on discharge measurements from 2014 and 2015 separately and verified on both years independently.

The obtained results (best fit from 30 runs of optimization procedure by DEGL method) indicated that calibration and validation results depend on the time step and season. Better results of calibration were obtained for year 2015. In the case of validation, higher NS values were obtained for model from year 2015 validated on data from year 2014. These differences in model performances could be explained by the hydro-meteorological conditions in the catchment in these two seasons. The ablation season 2014 and in particular August 2014 was very dry, almost without precipitation events throughout the month. As a result, for a few days, after 20 August, water ceased to flow in the channel. Such conditions led to the weaker identifiability of the model parameters and worse calibration and validation results.

A comparison of the calibration and validation results between different time steps indicated that the best results for the model from year 2015 were obtained for 3 and 6 h. Those time steps are recommended for further use in hydrological simulations, though the time steps differ significantly from the estimated TC value (10 min). These differences could be explained by the higher observation errors at smaller time steps than for aggregated data. Aggregation and data averaging lead to improvement of model performance. Such behaviour is visible for time steps up to 6 h. Further increases in time step cause a decrease in NS values.

The chosen calibration procedure (30 runs of the DEGL method) allowed for analysis of spread in the objective function (NS values). These results indicate that there is a significant spread in the NS values that depends on the time step and season. The outcomes indicate that for catchment modelling for the Fuglebekken catchment, the DEGL algorithm converged to the local optima. This problem occurred more frequently for smaller time steps. Therefore, multiple runs of optimization procedure are required for finding global optimum.

The results of analyzing the influence of input data averaging, input data temporal resolution, and calibration season (2014 and 2015) on the modelling results were tested using N-way ANOVA analysis supplemented with Tukey test. The outcomes of such testing indicated that input data averaging has a statistically significant influence on the obtained values of objective function (NS values) but not on the values of the HBV model parameters. The population marginal means of model parameters are not statistically different for instantaneous and averaged input data.

Statistically significant differences between two analyzed seasons (years 2014 and 2015) were found for all parameters but $CFMAX$. No differences in parameter values were found for data with and without averaging for all parameters except CFR. In case of time steps, statistically significant differences between parameter values were estimated for $BETA$, $ALFA$, KF, KS, $PERC$ and TT.

The obtained results may partially depend on the objective function used during model calibration, validation and optimization method. In this study, the Nash-Sutcliffe objective function was applied. That choice results in better fit of high and mean discharges and poor performance in low discharges. In addition, the presented results may be influenced by overparametrization of the model, which could lead to poor parameter identification and increased uncertainty. In this study, we applied full version of the model; however,

the results of sensitivity analysis by the Sobol method indicated that mainly three parameters (KS, $BETA$ and FC) have significant influence on model fit (Nash-Sutcliffe values). The influence of other parameters is small. We have found that the estimated values of sensitivity indices depend on the time step. The choice of full model instead of simplified one was dictated by the differences of obtained sensitivity indexes between years (2014 and 2015) and differences in input data (instantaneous and averaged). It is important to mention than the sensitivity analysis as well as model calibration and validation were performed for model output aggregated over the full time series of discharges. We suspect that an influence of parameters is also varying with time as it is presented by Pianosi and Wagener (2016).

Hydrological modelling presented in this paper leads to the development of knowledge about the temporal and spatial variability of water balance components in non-glaciated Arctic catchments. Significant results of calibration and validation were obtained, which can justify the application of the HBV model in other years at Fuglebekken catchment and may give the opportunity to assess the actual state, as well as simulate future changes in other areas of the circumpolar zone.

REFERENCES

Akanegbu JO, Marttila H, Ronkanen A-K and Kløve B (2017) A current precipitation index-based model for continuous daily runoff simulation in seasonally snow covered sub-Arctic catchments. *J. Hydrol.*, **545**, 182–196 (doi: 10.1016/j.jhydrol.2016.12.020)

Bastola S and Murphy C (2013) Sensitivity of the performance of a conceptual rainfall-runoff model to the temporal sampling of calibration data. *Hydrol. Res.*, **44**(3), 484–494 (doi: 10.2166/nh.2012.061)

Bergström S (1995) The HBV model. In Singh VP ed. *Computer models of watershed hydrology*. Water Resources Publications, Highlands Ranch, CO, 443–476

Bergström S and Forsman A (1973) Development of a conceptual deterministic rainfall-runoff model. *Nord. Hydrol.*, **4**(3), 147–170

Bergström S and Lindström G (2015) Interpretation of runoff processes in hydrological modelling – experience from the HBV approach. *Hydrol. Process.*, **29**, 3535–3545

Blaen PJ, Hannah DM, Brown LE and Milner AM (2014) Water source dynamics of high Arctic river basins. *Hydrol. Process.*, **28**, 3521–3538

Błaszczyk M, Jania JA and Hagen JO (2009) Tidewater glaciers of Svalbard: recent changes and estimates of calving fluxes. *Pol. Polar Res.*, **30**(2), 85–142

Booij MJ (2005) Impact of climate change on river flooding assessed with different spatial model resolutions. *J. Hydrol.*, **303**, 176–198

Booij MJ and Krol MS (2010) Balance between calibration objectives in a conceptual hydrological model. *Hydrol. Sci. J.*, **55**(6), 1017–1032

Bruland O (1991) Water balance and runoff in permafrost areas (*In Norwegian*) Unpublished Thesis. D-1991-28 (Department of Hydraulic and Environmental Engineering, NTH, The University of Trondheim, Trondheim, Norway)

Bruland O and Killingtveit Å (2002) Application of the HBV-model in Arctic catchments – some results from Svalbard. *XXII Nordic Hydrological Conf., At Røros, Norway, Volume: II*. Conference paper. https://www.researchgate.net/publication/299601263

Christiansen HH and 17 others (2010) The thermal state of permafrost in the Nordic area during the international polar year. *Permafrost Periglacial Process.*, **21**, 156–181

Czerny J, Kieres A, Manecki M and Rajchel J (1993) *Geological map of the SW part of Wedel Jarlsberg Land, Spitsbergen 1:25 000*. Institute of Geology and Mineral Deposits, Krakow.

Das S, Abraham A, Chakraborty UK and Konar A (2009) Differential evolution using a neighborhood-based mutation operator. *IEEE Trans. Evol. Comput.*, **13**(3), 526–553 (doi: 10.1109/TEVC.2008.2009457)

Dragon K, Marciniak M, Szpikowski J, Szpikowska G and Wawrzyniak T (2015) The hydrochemistry of glacial Ebba River (Petunia Bay, Central Spitsbergen): groundwater influence on surface water chemistry. *J. Hydrol.*, **529**, 1499–1510 (doi: 10.1016/j.jhydrol.2015.08.031)

Franczak L, Kociuba W and Gajek G (2016) Runoff variability in the Scott River (SW Spitsbergen) in summer seasons 2012–2013 in comparison with the period 1986–2009. *Quaest. Geographicae*, **35**(3) (doi: 10.1515/quageo-2016-0025)

Grimaldi S, Petroselli A, Tauro F and Porfiri M (2012) Time of concentration: a paradox in modern hydrology. *Hydrol. Sci. J.*, **57**(2), 217–228 (doi: 10.1080/02626667.2011.644244)

Hamon WR (1961) Estimation potential evapotranspiration. *J. Hydraul. Div. Proc. Am. Soc. Civ. Eng.*, **87**(HY3), 107–120

Harland WB (1997) *The geology of Svalbard*. The Geological Society, London, ISBN 1-897799-93-4

Hodgkins R (1997) Glacier hydrology in Svalbard, Norwegian high Arctic. *Quat. Sci. Rev.*, **16**(9), 957–973 (doi: 10.1016/s0277-3791(97)00032-2)

Humlum O, Instanes A and Sollid JL (2003) Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. *Polar Res.*, **22**, 191–215 (doi: 10.3402/polar.v22i2.6455)

Jania J and Pulina M (1994) Polish hydrological studies in Spitsbergen, Svalbard: a review of some results. In Sand K and Killingtveit A eds. *Proceedings. 10th International Northern Research Basins Symposium and Workshop, Norway*. SINTEF Norwegian Hydrotechnical Laboratory, Trondheim, 47–76

Jania J, Kolondra L and Aas HF (2002) *Werenskioldbreen and surrounding area. Orthophotomap 1:25 000*. Wydział Nauk o Ziemi, Uniwersytet Śląski, Sosnowiec and Norsk Polarinstitutt, Tromsø.

Johansson E and 6 others (2015) Data evaluation and numerical modeling of hydrological interactions between active layer, lake and talik in a permafrost catchment, Western Greenland. *J. Hydrol.*, **527**, 688–703 (doi: 10.1016/j.jhydrol.2015.05.026)

Karczewski A and 13 others (1990) *Hornsund, Spitsbergen geomorphology, 1:75 000*. (With commentary to the map by Karczewski A) Polish Academy of Sciences, Silesian University, Katowice.

Killingtveit A, Pettersson LE and Sand K (2003) Water balance investigations in Svalbard. *Polar Res.*, **22**, 161–174

Kirpich ZP (1940) Time of concentration of small agricultural watersheds. *Civ. Eng.*, **10**(6), 362

Kozak K and 7 others (2015) The role of atmospheric precipitation in introducing contaminants to the surface waters of the Fuglebekken catchment, Spitsbergen. *Polar Res.*, **34**, 24207 (doi: 10.3402/polar.v34.24207)

Krzyszowska A (1985) Chemistry of the freshwater of the Fugleberget drainage basin. *Pol. Polar Res.*, **6**(3), 341347

Leszkiewicz J and Caputa Z (2004) The thermal condition of the active layer in the permafrost at Hornsund, Spitsbergen. *Pol. Polar Res.*, **25**(3–4), 223–239

Lindner L, Marks L, Roszczynko W and Semil J (1991) Age of raised marine beaches of northern Hornsund Region, South Spitsbergen. *Pol. Polar Res.*, **12**(2), 161–182

Lindström G, Johansson B, Persson M, Gardelin M and Bergström S (1997) Development and test of the distributed HBV-96 hydrological model. *J. Hydrol.*, **201**(1–4), 272–288

Littlewood IG and Croke FW (2008) Data time-step dependency of conceptual rainfall – streamflow model parameters: an empirical study with implications for regionalisation. *Hydrol. Sci. J.*, **53**(4), 685–695 (doi: 10.1623/hysj.53.4.685)

Majchrowska E, Ignatiuk D, Jania J, Marszałek H and Wąsik M (2015) Seasonal and interannual variability in runoff from the Werenskioldbreen catchment, Spitsbergen. *Pol. Polar Res.*, **36**(3), 197–224

Migała K, Wojtuń B, Szymański W and Muskała P (2014) Soil moisture and temperature variation under different types of tundra vegetation during the growing season: a case study from the Fuglebekken catchment, SW Spitsbergen. *Catena*, **116**, 10–18

Nash JE and Sutcliffe JV (1970) River flow forecasting through conceptual models part I – a discussion of principles. *J. Hydrol.*, **10**(3), 282–290

Nowak M and Sobota I (2015) Artificial neural networks in proglacial discharge simulation: application and efficiency analysis in comparison to the multivariate regression; a case study of Waldemar River. *Geografiska Ann. Ser. A Phys. Geography*, **97**(3), 489–506 (doi: 10.1111/geoa.12089)

Osuch M and Wawrzyniak T (2016a) Climate projections in the Hornsund area, Southern Spitsbergen. *Pol. Polar Res.*, **37**(3), 379–402 (doi: 10.1515/popore-2016-0020)

Osuch M and Wawrzyniak T (2016b) Inter- and intra-annual changes of air temperature and precipitation in western Spitsbergen. *Int. J. Climatol*. (doi: 10.1002/joc.4901)

Osuch M, Romanowicz RJ and Booij M (2015) The influence of parametric uncertainty on the relationships between HBV model parameters and climatic characteristics. *Hydrol. Sci. J.*, **60**(7–8), 1299–1316 (doi: 10.1080/02626667.2014.967694)

Pianosi F and Wagener T (2016) Understanding the time-varying importance of different uncertainty sources in hydrological modelling using global sensitivity analysis. *Hydrol. Process.*, **30**, 3991–4003

Piotrowski AP and Napiorkowski JJ (2012) Product-units neural networks for catchment runoff forecasting. *Adv. Water Resour.*, **49**, 97–113 (doi: 10.1016/j.advwatres.2012.05.016)

Piotrowski AP, Napiorkowski MJ, Napiorkowski JJ, Osuch M and Kundzewicz ZW (2017) Are modern metaheuristics successful in calibrating simple conceptual rainfall–runoff models? *Hydrol. Sci. J.*, **62**(4), 606–625 (doi: 10.1080/02626667.2016.1234712)

Pohl S, Davison B, Marsh P and Pietroniro A (2005) Modelling spatially distributed snowmelt and meltwater runoff in a small Arctic catchment with a hydrology land-surface scheme (WATCLASS). *Atmos. Ocean*, **43**(3), 193–211 (doi: 10.3137/ao.430301)

Pulina M, Krawczyk WE and Pereyma J (1984) Water balance and chemical denudation in the unglaciated Fugleberget basin (SW Spitsbergen). *Pol. Polar Res.*, **5**(3), 183–205

Rachlewicz G (2009) *Contemporary sediment fluxes and relief changes in high Arctic glacierized valley systems (Billefjorden, Central Spitsbergen)*. Wyd. Nauk, UAM, Geografia, 87, Poznań

Romanowicz RJ, Osuch M and Grabowiecka M (2013) On the choice of calibration periods and objective functions: a practical guide to model parameter identification. *Acta Geophys.*, **61**(6), 1477–1503

Skrzypek G and 5 others (2015) Diversification of nitrogen sources in various Tundra vegetation types in the high Arctic. *PLoS ONE*, **10**(9), e0136536 (doi: 10.1371/journal.pone.0136536)

Sobota I (2014) Changes in dynamics and runoff from the High Arctic glacial catchment of Waldemarbreen, Svalbard. *Geomorphology*, **212**, 16–27 (doi: 10.1016/j.geomorph.2013.04.001)

Sobota I and Nowak M (2014) Changes in the dynamics and thermal regime of the permafrost and active layer of the High Arctic coastal area in north-west Spitsbergen, Svalbard. *Geografiska Ann. Ser. A Phys. Geography*, **96**, 227–240 (doi: 10.1111/geoa.12045)

Sund M (2008) Polar hydrology. *Norwegian Water Resources and Energy Directorate's work in Svalbard. NVE Report* 2. Water Resources and Energy Directorate, Oslo.

Tukey J (1949) Comparing individual means in the analysis of variance. *Biometrics*, **5**(2), 99–114

Von Storch H and Zwiers FW (2001) *Statistical analysis in climate research*. Cambridge University Press, Cambridge, UK, ISBN 0521012309

Wang H, Li X and Hao A (2015) Effects of rainfall data resolution on watershed-scale model performance in predicting runoff. *J. Water Clim. Change*, **6**(2), 227–240 (doi: 10.2166/wcc.2014.153)

Wawrzyniak T, Osuch M, Napiórkowski JJ and Westermann S (2016) Modelling of the thermal regime of permafrost during 1990–2014 in Hornsund, Svalbard. *Pol. Polar Res.*, **37**(2), 219–242 (doi: 10.1515/popore-2016-0013)

Winther JG and 7 others (2003) Snow research in Svalbard – an overview. *Polar Res.*, **22**, 125–144