Water-balance and hydrology research in a mountainous permafrost watershed in upland streams of the Kolyma River, Russia: a database from the Kolyma Water-Balance Station, 1948-1997

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Abstract: As of 2017, 70 years have passed since the beginning of work at the Kolyma water-balance station (KWBS), a unique scientific research hydrological and permafrost catchment. The volume and duration (50 continuous years) of hydrometeorological standard and experimental data, characterizing the natural conditions and processes occurring in mountainous permafrost conditions, significantly exceeds any counterparts elsewhere in the world. The data are representative of mountainous territory of the North-East of Russia. In 1997, the station was terminated, thereby leaving Russia without operating research watersheds in the permafrost zone. This paper describes the dataset containing the series of daily runoff from 10 watersheds with area from 0.27 to 21.3 km^2, precipitation, meteorological observations, evaporation from soil and snow, snow surveys, soil thaw and freeze depths, and soil temperature for the period 1948-1997. It also highlights the main historical stages of the station's existence, its work and scientific significance, and outlines the prospects for its future, where the Kolyma water-balance station could be restored to the status of a scientific research watershed and become a valuable international center for hydrological research in permafrost. The data is available at https://doi.pangaea.de/10.1594/PANGAEA.881731.

Keywords: water-balance and hydrological research, continuous permafrost, Kontaktovy Creek, the Kolyma River, Kolyma water-balance station, streamflow, thaw/freeze depth, precipitation, snow cover, evaporation from soil and snow

1. Introduction

In 2018 we celebrate 70 years since the observations at the Kolyma Water-Balance station (KWBS) began. This hydrological and permafrost research catchment has accumulated standard and experimental data unique both in terms of their amount and duration.

In the paper «Save northern high-latitude catchments» Laudon et al. (2017) recognize the KWBS as a currently functioning scientific station, even though scientific research was suspended here 20 years ago, and nowadays only standard observations at the meteorological site and one runoff gauge are carried out.

Eurasia contributes 75 % of the total terrestrial runoff to the Arctic Ocean and three of the four major Arctic rivers are located in Siberia (Shiklomanov et al. 2002). Peterson et al. (2002) suggested that the net discharge from the six largest Eurasian rivers flowing into the Arctic Ocean (Severnaya Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma) increased by 7% during the 20th century. As it is also mentioned by Laudon et al. (2017), the number of scientific and hydrological research stations in the Northern regions of the world has decreased by 40%, and it happened alongside the most significant climate change in the Arctic in recorded history.

The Kolyma Water-Balance Station (KWBS) is located in the headwaters of the Kolyma River (61.85N, 147.67E), in a mountainous cryolithozone (Fig. 1, 2). Water-balance stations are a historical name of the network of the research watersheds that existed in former USSR. The overall goal of the water-balance stations network was detailed study of water balance components on slope and small scales in different environmental settings for the development of methods of hydrological forecast and flow characteristics assessments for engineering design. The KWBS was one of 26 water-balance stations of the USSR and the only located in the zone of continuous permafrost.

During the period 1948 to 1997, the KWBS accumulated a huge amount of data on hydro-meteorological and special observations of a unique duration (40-50 years). At the KWBS there were 10 hydrological gauges at catchments ranging between 0.27 and 21.3 km^2, two meteorological plots, 55 (in total) precipitation gauges, over 30 frost tubes (cryopedometers), several groundwater wells, evaporation, water-balance and runoff plots. In addition, regular snow surveys were conducted, as well as experimental investigations of specific hydrological and permafrost processes.

After 1997, special water balance and research observations at the KWBS were ceased. One weather station and five runoff gauges functioned at the KWBS up to mid-June, 2013, when an extreme flash flood destroyed four level gauges. Nowadays only standard observations are conducted at the Nizhnyaya meteorological site and at the Kontaktovy (Nizhny) runoff gauge.

The data were published in 40 reports, the first one covering the period 1948-1957. Following issues were published annually (KWBS Observation Reports, 1959-1997).

Though in the last several decades and more recently many research watersheds were established in Arctic zone of the USA and Canada, to the best of our knowledge, the first systematic cold-region hydrology observations in North America began not earlier than the 1960s. Such, the Caribou-Poker Creeks Research Watershed was established only in 1969 (Hinzman et al., 2002), 20 years later than KWBS.

One may mention numerous scientific catchments in Alaska – Fish Creek (Pacific Northwest…, 2014), Toolik station (Hoobbie et al., 2003), Tanana River (Yarie et al., 1998), Kuparuk River (Arp & Stuefer, 2017, Kane & Hinzman, 2009), Imnavait River (Walker & Walker, 1996), Putuligayuk River (Kane & Hinzman, 2009), as well as Arctic monitoring programs (NPR-Hydrology (NPR-A Hydrology…, 2018), Arctic Observatory Network (Arctic Observatory Network…, 2018).

The studies at research watersheds of Canada are integrated into scientific programs and accompanied by data analysis and models development and applications For example, the Changing Cold Regions Network project (Changing Cold…, 2018) includes field studies on 14 watersheds and the use of two Canadian models CHRM and CLASS. The Improving Processes & Parameterization for Prediction in Cold Regions Hydrology (IP3) project (Improving

Processes…, 2018) combined 10 research watersheds and four hydrological models – CHRM (Pomeroy et al., 2007), CLASS (Verseghy, 1991), MESH (Pietroniro et al., 2007), GEM (Yeh et al., 2002).

Although there are large mountainous areas in other cold regions of the world, the combination of extremely severe climate (mean annual air temperature reaches -11.3°C) and continuous permafrost creates unique conditions at KWBS which are not presented at any other research watershed of the world.

Nasybulin (1976) showed that hydrological regime at the KWBS is representative for the whole Upper Kolyma Plateau. Taking into account the similarity of main landscape types across mountainous regions of North-East Russia to those found at the KWBS, the conclusion can be made that hydrological conditions at KWBS are actually representative for vaster ungauged areas, than described by Nasybulin (1976).

Sufficiently long time series of observations which were continuously conducted by uniform methods and covered pre-warming period are of high importance for the studies of climate change impact on hydrology in the Arctic.

KWBS observation results were reflected in many publications, dedicated to different aspects of runoff formation in the continuous permafrost region, active layer dynamics, underlying surface structure and its influence on hydrological processes. Based on the KWBS data, the following research was carried out:

- water balance formation (Kuznetsov et al., 1969; Boyarintsev, 1980; Boyarintsev, Gopchenko, 1992; Suchansky, 2002; Zhuravin, 2004; Lebedeva et al., 2017),
- peak and spring flood runoff in small rivers in the permafrost zone (Boyarintsev, 1988),
- base flow (Boyarintsev, Nikolaev, 1986; Glotov, 2002),
- principles of runoff cryo-regulation (Alekseev et al., 2011),
- ice content dynamics of rocky talus deposits (Bantsekina, 2001),
- processes of intra-ground condensation (Reinyuk, 1959; Boyarintsev et al., 1991; Bantsekina et al., 2009;),
- floodplain taliks in continuous permafrost (Mikhaylov, 2013) and many others.

Collected data were also used for development and testing different geoscience models of:

- runoff formation (Kuchment et al., 2000; Gusev et al., 2006; Semenova et al., 2013; Lebedeva et al., 2015; Vinogradov et al., 2015),
- climatic aspects (Shmakin, 1998),
- land surface and vegetation dynamics (Tikhmenev, 2008).

In this paper, we present a hydrometeorological and permafrost related dataset for continuous 50 years from 1948 to 1997 for the Kolyma Water-Balance Station (KWBS), the Kontaktovy Creek watershed, which is representative for vast mountainous territories of continuous permafrost zone of Eastern Siberia and the North-East of Russia. This dataset is unique in terms of its volume and duration of hydrometeorological standard and experimental data. It may be used in many research tasks, but is of particular importance in studying runoff formation processes and model development in permafrost regions.

2. Site description

The Kolyma water-balance station is located in the Tenkinsky district of the Magadan region of Russia within the Upper-Kolyma highland. The station's territory – the Kontaktovy Creek catchment with area 21.3 km^2 – is a part of the Pravy Itrikan River which flows into the Kulu River basin, which is the right tributary of the Kolyma River. The station is located 16 km from the Kulu village settlement. It is characterized by a mountain landscape, typical for the upper reaches of the Kolyma River. The territory of the basin is severely cut up with creek valleys. These valleys are narrow, with steep slopes, and watershed lines are mostly well delineated. Absolute elevations of the basin range between 823 m a.s.l. near the Kontaktovy Creek outlet and 1700 m a.s.l. at watershed divides. The length of the creek is 8.9 km. The catchment is extended in the latitudinal direction and has an asymmetric shape. The slopes of the catchment area have mainly southern exposure (53% of the slope area), the slopes of the northern and eastern exposure have a 24% share, the western – 23%. The density of river network in the basin is 2.5 km per square km. The main river canal is meandering. The steepness of the slopes ranges from 200 to 800‰ (Fig. 1).

The station is located in the continuous permafrost zone. Permafrost thickness varies from 120 to 210 m in valleys and can reach 300-400 m in highlands, following the relief. Seasonal soil thaw depth depends on slope exposition, altitude and landscape and changes from 0.2-0.8 m on north-facing slopes to 1.5-3.0 m on south-facing ones.

KWBS is situated in the transitional zone between forest-tundra and coniferous taiga. Soil types vary from stony-rock debris to clayey podzol with partially decayed organic material underlain by frozen soil and bedrock. Most of the KWBS area is covered by rocky talus, practically without vegetation (34%). Dwarf cedar and alder shrubs are common at south-facing slopes and cover about 27% of the territory. Larch sparse woodland with moss-lichen cover is typical for steep north-facing slopes (12%). Open terrain larch wood (15%) and swampy sparse growth forest with minimal permafrost thaw depth, constant excessive stagnant moisturizing, tussock or knobby microrelief (12%) characterize creek valleys. The estimates of landscape distribution are given here after Korolev (1984) (Fig. 2B).

Along the whole length of the Kontaktovy Creek, channel taliks can be found. They go all the way through the layer of alluvial sediments and their depth may reach 15 m in the cross section of the Nizhny hydrological gauge (Mikhaylov, 2013) and 5 m on the flood plain (Glotov, 2002). In summer, the talik forms a single hydraulic system with waters of active layer and the creek channel. In winter it freezes only partially. In the talik located below Kontaktovy-Nizhny gauge, flow exists till the beginning of snowmelt, which is evidenced by continuous drop of levels in hydrogeological wells (Glotov, 2002).

2.1 History of KWBS

The Kolyma water balance station (KWBS) was established on October 15, 1947 and was initially known as the Itrikanskaya runoff station of the Dalstroy (Far North Construction Trust organized in 1931) Hydrometeorological Service. In 1948-1956 and 1957-1969 it was called the Kulinskaya and the Kolyma runoff station respectively. The primary goal of this station was studying runoff formation processes in small river catchments in mountain permafrost landscapes, typical for northeast USSR.

As soon as May, 1948, the first runoff observations at the Kontaktovy Creeks and Vstrecha brook were launched, as well as regular observations at the Nizhnyaya weather station (850 m a.s.l.). A few months later, on September 1, 1948, observations at the Verkhnyaya weather station (1220 m a.s.l.) were started. In 1948, stage gauges Sredny, Nizhny and Vstrecha were equipped with automatic water level recorders, gauging footbridges and flumes.

During the period 1949-1957, at the Vstrecha brook catchment, a rain-gauge network was organized. Runoff gauges at the Severny, Dozhdemerny, Vstrecha brooks were equipped with various hydrometric facilities. Observations on soil, water and snow evaporation, soil freezing and thawing commenced, as well as experimental observations at a runoff plot.

At the end of the 1940s and early 1950s, technical staff of the station were mainly former convicts. During the first few years, the workers of the station built houses for themselves, collected firewood and organized the household. The winter of 1955-56 appeared to be especially severe for the staff, since due to the deep snow cover it was difficult to move around the territory of KWBS, there was no transport connection with the Tenkinskaya highway, delivering of firewood, needed for heating houses and service buildings, was also difficult. When it was impossible to get to the highway by car, bread and mail were delivered from the Kulu village settlement utilizing horses once every 7-10 days.

Twenty to twenty five staff members were accommodated in three small huts, hardly suitable for living. That winter they mainly had to collect and prepare firewood in the afternoon;

in the morning everybody had to go (despite their rank or position) in deep snow and at -50°C to the nearest small river valley looking for firewood, then they pulled it back home, where they were firing furnaces. Only by the time it got dark, it became warm enough to stay in the work-room and they could start observation data processing.

The working day lasted until 10 or 11 p.m. Since there was no electricity, they used kerosene lamps filled with a mixture of petrol and salt. In summer 1956 there were only 13 people left at the station, some of them were taken to help with haymaking to prepare hay for their subsidiary holding that consisted of two cows and a horse (as recollected by the Chief of the station V.G. Osipov and the hydrologist-technician A.I. Ipatieva, Informational letter…, 1988).

In 1957 the station was handed over to the jurisdiction of the Kolyma Hydro-meteorological service administration, and in 1958 the electrification of the station has started. At that time there were active steps taken toward fitting out the station with new types of devices and equipment, engaging new specialists in hydro-meteorology, and building accommodation facilities.

In 1960 runoff observations at the Yuzhny brook were begun. The optimization of the precipitation network was continued meaning the establishment of rain gauges in new locations and shutting down some non-representative rain gauges. Radio rain gauges were installed.

In 1963 two new water-balance sites (##2 and 3) were organized.

In 1968 runoff measurements were started at the unique research object, at the Morozova brook catchment, which has no vegetation cover and is composed of rocky talus.

In 1969 the Kolyma runoff station was renamed into the Kolyma Water Balance station (KWBS). In these years there was a transition to broad experimental water balance observations of all elements and to an enhanced technical level of research.

Since 1970, the KWBS carried out snowpack observations at avalanche sites of the Tenkinskaya road, as well as stratigraphy, temperature and physical and mechanical properties of snow at four sites. Since 1980 there were introduced additional observations on dynamics of icing formation at the Kontaktovy creek. In 1982 observations on soil moisture were started at 3 agro-hydrological sites at the fields of the «Kulu» state farm.

In 1976 the station hosted a delegation of USA scientists. They highly praised the professional and personal qualities of the station's staff members, their commitment, on which extensive field studies and theoretical works were based, despite the equipment being rather simple and living conditions extreme. According to Slaughter and Bilello (1977), the data recorded at the KWBS, were unique and unprecedented for world practice.

Since the beginning of the 1990s, the research program at the station has been gradually cutting back. After 1997, water balance observations at the KWBS were ceased. One weather station and five runoff gauges functioned at the KWBS up to mid of June, 2013, when an extreme flash flood destroyed four level gauges. Nowadays only standard observations are conducted at the Nizhnyaya meteorological site and at the Kontaktovy (Nizhny) runoff gauge.

3. Data description

3.1 Meteorological observations

The observations of meteorological elements were carried out at three meteorological stations in different periods (Fig. 2A). The database includes daily values of air temperature, water vapour pressure, vapour pressure deficit, atmospheric pressure, wind speed, low and total cloud amount, and surface temperature (Table 1).

The meteorological station Verkhnyaya (1220 m a.s.l., 1948-1972) was located in the upper reaches of the Dozhemerny brook in the saddle between two hills. The horizon is closed by the hills from the south and north which are at 30-40 m distance from the site. The horizon is open from the east and west, strong winds are observed here. The surface at the station plot is hummocky, covered with grassy vegetation with no woody vegetation around it. The nearest building – the station house – was located 48 m away from the station plot. The depth of seasonal thaw of permafrost reaches 1.5 m.

The meteorological station Nizhnyaya (850 m a.s.l., 1948-1997) is located on the edge of a larch forest, on the terrace-watershed between the Kontaktovy creek and the Ugroza brook, which has a slight slope to the SW. The nearest trees are located 50 m away, the buildings – 100 m from the station. The site is surrounded by mountains up to 1400 m a.s.l., the nearest of them are at a distance of 200-500 m. The height of the weather vane is 11.3 m. The surface of the station plot is covered by hummocks, with moss, peat and individual bilberry and blueberry bushes. The area is surrounded by a sparse larch forest from the north, east and south. The depth of permafrost seasonal thaw reaches 1.5 m.

The meteorological station Kulu (670 m a.s.l., 1981-1991) was located on the right slope of the broad valley of the Kulu river. The slope has a western exposure (4-6 degrees). The height of the weather vane is 10.7 m. The area is surrounded by larch trees of 6-8 m height from the west, north and east. The soils are loamy with the inclusion of small gravel. The underlying surface consists of berry, grass and sphagnum mosses, sometimes bare soil. The depth of seasonal thawing of permafrost reaches 1.8-2 m.

In September 1992, the Kulu station (635 m a.s.l., 1992-1997) was moved to the residential building of the KWBS at the south-eastern part of the Kulu village. Residential and technical buildings are located around the meteorological plot. There was a road to the south of the station. The soil is marshy, covered with rubble and grass. This new location of the Kulu station is marked as Kulu2 station in the database.

The list of used devices and the accuracy of observations for each meteorological element is presented in the description files of the database.

3.2 Precipitation

In total, the precipitation was observed at 47 gauges within KWBS territory during different periods. Continuous daily all-year around precipitation data is available for the period 1948-1997 for the gauge (#12) at meteorological station Nizhnyaya and for the gauge (#54) at meteorological station Kulu for 1981-1997. Four gauges have the data of daily totals during warm season for the period for more than 30 years and another 18 gauges for different shorter periods. Usually the start of daily observations at those gauges was initiated by the beginning of snowmelt period and lasted until the end of September. Monthly sums of precipitation were measured at 30 gauges, 10-days and 5-days sums – at 21 and 18 gauges respectively.

In 1948 precipitation gauge stations for measuring daily precipitation were equipped with the Nipher-shielded and Tretyakov-shielded precipitation gauges (Fig. 3A). In 1948-1958 the observations were carried out with both devices in parallel, after 1959 only Tretyakov gauges were used. Tretyakov precipitation gauges were also used for measurements precipitation totals in 5 and 10 days periods.

The other types of precipitation gauges applied at the KWBS are the Kosarev and ground rain gauge (GR-28) (Fig. 3B, 3C). GR-28 gauge with receiving area 500 cm^2 was installed into the special box several cm above the ground. GR-28 were usually installed on the 1st of June and dismantled on the 1st of September and used for rain measurements over the longer period, typically one month. Only those GR-28 which were installed at the soil evaporation plots measured precipitation every day. The Kosarev precipitation gauges were used for monthly precipitation measurements from the 1st of October to the 1st of May. Different precipitation gauges are shown at Fig. 5.

In 1960-1963 there was an attempt to register precipitation with automatic radio-precipitation gauges, but due to improper performance of the devices those observations were stopped.

In 1988, precipitation observations at the KWBS were carried out with 36 precipitation and rain gauges, distributed relatively evenly throughout the area and altitudinal zones. Average density of the precipitation network at that time accounted for 1.6 units per 1 km^2.

For the period 1948-1968 precipitation data was published in Observation Reports as it was without any correction. Starting from 1969, all daily, 5-days and 10-days totals data from

Tretyakov rain gauges have been corrected for wetting losses according to Manual (1969). The correction value for precipitation event varied from 0.0 to 0.2 mm depending on the amount of observed precipitation and weather conditions. In average annual value of wetting losses correction did not exceed 5 % of total amount of precipitation, though in some years it could reach up to 9-10 %. In 1948-1983 monthly sums data obtained from GR-28 and Kosarev gauges were published without any correction. In 1984 wetting losses correction was introduced to GR-28 observations as well. In the database the precipitation data is presented in original form without any changes.

The analysis of water balance, climate change impact on river runoff or hydrological modelling requires accurate and reliable precipitation data. Arctic and mountainous regions are characterized by high bias of precipitation measurements because of significant amount of snowfall precipitation (WMO Report #67, 1998). Monthly estimates of this bias often vary from 5% to 40%. Biases are larger in winter than in summer largely due to the deleterious effect of the wind on snowfall (Groisman et al., 2015). Three main methods of winter precipitation bias correction are suggested for the Tretyakov gauge which was the main type of precipitation gauge at KWBS. They are the WMO methodology (Yang and Goodison et al., 1995), Northern European countries method (Forland et al., 2000) and the approach developed by Golubev (WMO Report #67, 1998). The basis of all three methods for correcting measured precipitation is the dependence of the aerodynamic coefficient on wind speed, air temperature, precipitation type and wind protection.

In described database each precipitation gauge (if it was available) has the description of its location, altitude, slope exposure, vegetation type. Additional characteristic is the degree of protection characterized by five types of Schwer (1976) classification (Ia, Ib – protected; IIa, IIb – half-protected; III – open; IV – shore station). The database also contains the series of daily wind speed for three meteorological stations which combined with the information on location gauges can be used as a proxy for introducing bias corrections.

3.3 Snow surveys

Snow cover observations were started in 1950 and initially conducted at two catchments, at two meteorological plots and four typical squares. In 1959-1960 the number of catchments with snow surveys reached five. Up to 1971, snow surveys were conducted once per month starting in November and finishing in May at small catchments (the Severny, Yuzhny, Dogdemerny and Vstrecha) and once before spring snowmelt at the Kontaktovy – Nizhny. Since 1972, the observations were reduced to one survey per year (usually at the end of April) for all watersheds. Table 2 shows the number of snow routes, their total length and number of measurement points, including their distribution among different landscapes of the catchments (Fig. 4). Snow depth was measured every 10 m, snow density – every 100 m at most of the watersheds, and 5 and 50 m respectively at the Morozova brook watershed.

Based on the data about measured snow height and snow weight with the account for landscape and elevation distribution average SWE for individual watersheds and landscapes was calculated and published in the Observation Reports.

Average depth of snow cover is presented with accuracy of 1 cm, density and SWE – 0.01 g cm^{-3} and 1 mm respectively.

3.4 Soil evaporation

Three types of evaporimeters were used at the KWBS.

Evaporimeter GGI-500-50 (later modified to GGI-500-30) is a standard device for the soil evaporation measurements in Russia and former USSR (Fig. 5B). It consists of two cylindrical vessels, one inside the other, and a water-collecting vessel. The bottom of the inner cylinder has openings; the core sample is placed in it. The quantity of water evaporated is determined from the difference in weight of the sample as measured over two successive observation periods.

Rykachev evaporimeter was used for the soil evaporation measurements in 1950s. It consists of a sealed square rectangular box with a core sample (Fig. 5A). The box was placed inside another box installed in the ground. Since the inner box was sealed the device did not allow for water infiltration (Chebotarev, 1939).

The description of Gorshenin evaporimeter was not found.

From 1950 to 1953, five soil evaporation plots were opened at the sites with diverse underlying surfaces and different expositions and altitudes. The plots were equipped with the Rykachev and Gorshenin evaporimeters with evaporation area 1000 cm^2. The observations until 1958 are considered to be approximate due to the absence of accompanying rain gauges and scales of required accuracy.

From 1958 to 1966, the measurements were conducted at the soil evaporation plot, located near the Nizhnyaya weather station. The observations of evaporation were carried out with two evaporimeters GGI-500 and the Rykachev evaporimeter, precipitation – with a ground rain gauge.

Three soil evaporation sites were established in different landscapes – in the Vstrecha (1967), Morozova (1971) and Yuzhny (1977) brooks basins. The measurements were carried out with standard weighing evaporimeters GGI-500-50, which, due to the physical proximity of permafrost, were changed to GGI-500-30, meaning that their height was decreased to 30 cm.

The accuracy of observations was 0.1 mm (Konstantinov, 1968).

3.5 Snow evaporation

Snow evaporation observations were conducted at the KWBS from 1951, but only the data for the period 1968-1992 is considered to be consistent and reliable and is published in the described database. From 1968 to 1981, the observations were conducted with standard evaporimeter GGI-500-6 at weather plot Nizhnyaya. In 1981 the snow evaporation observations were transferred to the Kulu weather plot and lasted until 1992.

This measurement accounts for the snow evaporation on the ground. In the conditions of the KWBS with the larch as the main tree type, intercepted snow was only temporary phenomena because of cyclonic activity in January and February. Wind during the cyclones blow away snow from all trees except dwarf cedar that is under snow for the most part of the winter.

Observations of evaporation from snow were made mainly in the fall (September, October) and in the spring (May – March). During winter months (January – February), the observations were made only until 1973, because the amount of evaporation from snow proved to be extremely insignificant for water balance. In the spring, during the intensive snowmelt, additional weighing of the evaporimeters was carried out every 3-6 hours. In the database, the evaporation values for night (20-8 hours) and daytime (8-20 hours) intervals are presented, only those values that correspond to a full 12-hour period of observations are published.

The accuracy of measurements is 0.01 mm.

3.6 Thaw/freeze depth

Since 1952, the observations on permafrost seasonal thaw dynamics were conducted at the KWBS. Danilin cryopedometers (frost tubes) were installed at permafrost observation sites (Snyder et al., 1971) which mostly were located in the approximate vicinity of Nizhnyaya and Verkhnyaya weather stations at the slopes with different aspects and landscapes.

Cryopedometer designed by A.I. Danilin consists of a rubber tube 1 cm in external diameter and calibrated to an accuracy of 1 cm. The tube is filled with distilled water, closed at both ends and lowered into a casing (an ebonite pipe) installed in a borehole in the soil. In order to measure the depth of freezing, the rubber tube is taken from the casing and the lower end of the ice column in the tube is determined (Manual, 1973).

Despite the fact that permafrost observation sites were equipped with special bridges for observers to come close, eventually surface damage in the area where the device was installed began to influence thaw depth (Sushansky, 1988).

During 1952-1997 38 cryopedometers were functioning in total.

3.7 Streamflow

Runoff observations were carried out at 10 catchments: the creek Kontaktovy (the gauges Verkhny, Sredny, Nizhny), brooks Morozova, Yuzhny, Vstrecha, Vstrecha (the mouth), Dozhdemerny, Severny, Ugroza (Fig. 6). Key characteristics of the catchments are listed in Table 7.

All the water level gauges were equipped with «Valdai» water level recorders, as well as needle and hook water level gauges. In spring and autumn, when recorders did not work properly due to ice on the creeks, discharge was measured more frequently, every 4 hours. To prevent the recorder floats from freezing, the wells were heated with electric bulbs.

At the micro-watersheds of Morozova and Yuzhny brooks runoff was measured by means of a V-notch weir, at Severny brook – with a flow measuring flume.

In the database, mean daily values of streamflow are presented.

Originally daily discharges were published in Observation Reports in l s^{-1} with accuracy of three significant figures, but not more accurately than 0.01 l s^{-1} for runoff gauges equipped with weir or flume. For gauges with a natural channel for discharges more than 1000 l s^{-1} the rounding to three significant figures was performed, for discharges less than 100 l s^{-1} – to two significant figures, but not more precise than 1 l s^{-1}.

Small discharges which are less than 0.05 l s^{-1} for the gauges equipped with hydrometric facilities and less than 0.5 l s^{-1} for larger watersheds gauges were published in Observation Reports as 0.00 and 0, respectively. The periods with no runoff because of drying and freezing were marked with special symbols.

In the database, water discharges are converted to $m^3 s^{-1}$, the number of significant figures was preserved but the values 0.00 and 0, as well as special symbols for freeze and dry periods are indicated as 0.

In 1984-1997 the information on the accuracy of discharge data was published for several runoff gauges In Observation Reports. It included the percentage of stage curve extrapolation in both directions which was published for one or several runoff periods per year depending on how many stage curves were applied. Also information about measured and estimated instant maximum and minimum discharges was available for the same period. Fig. 7 shows the boxplots of these characteristics for 7 runoff gauges for the period 1984-1997.

4. Results

4.1 Meteorological variables and precipitation

The climate of the study area is severely continental with harsh long winters and short but warm summers. Average annual temperature at the Nizhnyaya meteorological plot during 1949-1996 is -11.3 °C. Mean monthly temperature in January was -33.6 °C, in July +13.2 °C (Fig. 8-9). The absolute minimum daily temperature of -53.0 °C was registered in 1982 and the absolute maximum daily temperature was +22.8 °C (1988). The period of negative air temperatures lasts from October to April, freeze-free period is, on average, 130 days long.

Air temperature inversions are observed at the KWBS. In December air temperature gradient reaches +2.0, in May it accounts for -0.5°C per 100 m of elevation respectively.

The average air humidity at the Nizhnyaya station is 3.6 mb, reaching its maximum and minimum values of 9.8 and 0.4 mb in July and December respectively.

Total cloudiness at the Nizhnyaya station has average annual value of 7.0 and does not change considerably through the year. Its minimum and maximum values are 5.9 and 8.0 points in March and July. Lower cloudiness dynamic is more significant, its mean monthly values changes from 0.5 to 4.7 in March to July with average value of 2.2 points.

Mean wind velocity is more than twice higher at Verkhnyaya station (1220 m a.s.l.) in comparison with Nizhnyaya station (850 m a.s.l.) and amount to 3.0 and 1.3 m s^{-1} accordingly. Average monthly values changes from 0.83 in December to 1.70 in May at Nizhnaya, and from 2.7 in November, February to 3.4 in May. Maximum daily wind speed amounted to 16 and 36 m s^{-1} at Nizhnyaya and Verkhnyaya.

Precipitation at Nizhnyaya meteorological plot from 1969 (the year when wetting losses were introduced) to 1997 varied from 229 (1991) to 474 (1990) mm per year with mean value of 362 mm. After introducing wetting losses correction to the period 1949-1968 and computing average mean amount from 1949 to 1997, its value decreased to 351 mm. Maximum and minimum monthly amount of precipitation at Nizhnyaya station was observed in July and March and correspond to 72 and 8 mm respectively for the whole period of observations 1949-1997 (Fig. 8-9).

Maximum daily amount of precipitation at Nizhnyaya station was observed in June 1968 reaching 48.1 mm. In average for the period of 50 years this statistic amounted to 26 mm.

4.2 Snow cover

Stable snow cover at KWBS in average is formed in the first weeks of October, and melts in the third week of May (1949-1996). The KWBS area is characterized by an increase in the thickness of the snow cover due to the absence of thaws during the whole snow season. In the open treeless and watershed divide areas, the redistribution of snow pack due to wind blow is observed.

Average for the watershed mean, maximum and minimum snow water equivalent (SWE) before spring freshet estimated based on snow survey results at the Kontaktovy – Nizhny amount to 121, 213 (1985) and 59 (1964) mm respectively in the 1960-1997 period. In general, rocky talus and tundra bush landscape are characterized by lower SWE due to wind blowing. Much snow is accumulated in the forest landscape. However, at the Morozova brook watershed which is fully covered by rocky talus landscape, mean SWE before snowmelt was estimated as 161 mm with the maximum value of 298 mm observed in 1985 reaching in average 0.99 m snow height (Table 3, Table 4, Fig. 10).

4.3 Soil and snow evaporation

The highest values of soil evaporation during the summer period were observed at the larch forest (site 9) and reached 136 mm. At a similar landscape (site 1), this value is lower, at 119 mm, which indicates the influence of local factors. The lowest values of soil evaporation are 104 mm at the plot located at dwarf cedar tree bush (site 7). In July, soil evaporation values range from 33 to 40 mm, depending on the landscape. In September, the contribution of evaporation decreases to 14-24 mm (Table 5).

Average values of annual soil evaporation were previously estimated by Semenova et al. (2013) and Lebedeva et al. (2017) based on partial KWBS data set as the following: 140 mm for larch and swampy sparse growth forest, 110 mm in dwarf cedar and alder shrubs of tundra belt, and about 70 mm for rocky talus.

The average values of evaporation from snow in mm per day are determined from measurement data as follows: January-February – -0.04; March – +0,09; April – +0,40; May – +0.74; September – +0,20; October – +0,01. Typical values of evaporation from snow for 1976-1977 are presented at Fig. 11.

4.4 Thaw/freeze depth

The longest observation period is 33 continuous years (cryopedometer 17.5 located at the forest with bushes, maximum thawing is 130 cm, 1964-1997). The deepest values of thawing were observed in rocky talus landscape and can reach more than 240 cm. The shallowest values of thawing range from 60 to 70 cm at swampy forest. Thawing of soils at the forest zone varies in large ranges and depends on the location of the cryopedometer at a slope (Table 6, Fig. 12).

Lebedeva et al. (2014) reviewed the patterns of soil thaw/freeze processes and their impact on hydrological processes based on the analysis and modelling of the data at the cryopedometers in main landscapes of KWBS: rocky talus, mountain tundra with dwarf tree brush, moss-lichen cover and sparse-growth forest or larch forest.

4.5 Streamflow

Flow at KWBS begins in May, most of it occurs in summer. At the outlet of KWBS Kontaktovy creek at Nizhny 33, 24 and 20 %% of flow occurs in June, July and August respectively. For the summer period, rainfall floods are typical (Fig. 13).

Small brooks freeze completely in October. Surface flow stops at the channel of Kontaktovy creek at Nizhny gauge in November, but there is the evidence that the river valley talik located lower than the Kontaktovy-Nizhny gauge, the runoff exists till the beginning of snowmelt, which is evidenced by continuous drop of levels in hydrogeological wells (Glotov, 2002).

Annual runoff of the Kontaktovy stream basin with area 21.3 km^2 (average altitude 1070 m) is 281 mm for the period 1948-1997, it increases with the elevation and at the Morozova catchment (mean elevation 1370 m, basin area 0.63 km^2) reaches 453 mm (1969-1996). The flow from south-facing (Severny) and north-facing (Yuzhny) micro-watersheds with area of 0.38 and 0.27 km^2 are 227 and 193 mm for the period 1960-1997 respectively.

Maximum daily discharge was observed in August, 1979 and amounted to 7.6 m^3s^{-1} (daily flow 30 mm) and 0.438 m^3s^{-1} (60 mm) at the Kontaktovy – Nizhny and at the Morozova watersheds respectively.

4.6 Changes of hydrometeorological elements in 50 years, 1948-1997

The time series of flow characteristics and basic meteorological elements were evaluated for stationarity, in relation to presence of monotonic trends, with Mann-Kendall and Spearman rank-correlation tests, at the significance level of $p < 0.05$ (Mann 1945; Kendall 1975). If both tests proved a trend, a serial correlation coefficient was tested. With the serial correlation coefficient $r < 0.20$, the trend was considered reliable. In the case of $r \geq 0.20$, to eliminate autocorrelation in the input series «trend-free pre-whitening» procedure (TFPW), described by Yue (Yue et al. 2002), was carried out. «Whitened» time-series were repeatedly tested with Mann-Kendall non-parametric test. Trend value was estimated with Theil-Sen estimator (Sen 1968).

The annual air temperature at Nizhnyaya station increased by 1.1˚C, positive trends are observed in March and October accounting for the rise of temperature by 2.3 and 3.3 °C correspondingly. Annual sum of precipitation has grown by 74 mm (21%). Maximum annual daily precipitation has also increased by 8 mm, or 31%.

The analysis of monthly and annual flow (mm) for the Kontaktovy creek – Nizhny from 1948 to 1997 has revealed the changes of hydrological regime in those 50 years of runoff observations (Fig. 14). Positive trends of monthly flow are identified in May amounting to 29 mm, or 92%, as well as in October (5.7 mm, 166%) and November (0.35 mm, 252%). The annual flow trend increased by 67 mm, or 24%. These results confirm general situation of increasing low flow which is observed in Siberia (Tananaev et al., 2016) and North America (Yang et al., 2015; St. Jacques and Sauchyn, 2009).

5. Water balance estimation

The study of the water balance of watersheds is aimed at assessing the quantitative changes in its components, which makes it possible to study the main regularities in the runoff formation. In the northern regions, where climate change is more pronounced than in other parts of the world (Arctic Climate…, 2004) and standard hydrological network is shrinking (Shiklomanov et al, 2002), the assessment of the water balance and its future change is important.

The book Northern Research Basins Water Balance (2004) compiles the main results of water balance studies in the northern watersheds in last century such as Wolf Creek (Janowicz, et al., 2004), Kuparuk River (Lilly et al., 1998), Scotty Creek (Quinton et al., 2004), Nelka river (Vasilenko, 2004), including Kontaktovy Creek of KWBS (Zhuravin, 2004).

In this section the results of rough estimation of mean annual water balance for three micro-watersheds with area less than 1 km^2 and representative for main landscapes of studied territory (Severny, Yuzhny, Morozova) are presented and compared with the assessments made by other authors.

The estimation of water balance for the whole watershed of Kontaktovy cr. requires special analysis and does not lie in the scope of this paper; only the results of other authors are shortly summarized.

A general form of water balance equation (in mm) is used as the following:

$$SWE + P_{rain} + \Delta P_{corr} - ET - E_{snow} - R = \eta. \quad (1)$$

Here SWE is average value of snow water equivalent before spring freshet from snow surveys data. For Morozova watershed SWE is increased by 36 mm which is the average precipitation in May at ground rain gauge #42 (1400 m a.s.l.).

P_{rain} is total sum of daily rainfall precipitation during warm period from the rain gauges located within studied watersheds. The data before 1969 was corrected for wetting losses according to (Manual for hydrometeorological stations …, 1969). For Severny and Yuzhny watersheds rainfall precipitation P_{rain} is calculated as total sum of precipitation in May-August period and half of average precipitation in September accounting for air temperature transition from positive to negative which usually occurs in the mid of September at rain gauges #5 (880 m a.s.l.) and #20 (900 m a.s.l.) respectively. For Morozova watershed which is in average 300 m higher than Severny and Yuzhny ones, P_{rain} consists of sum precipitation for the period from June to August estimated based on the data from daily precipitation data of rain gauge #38 (1200 m a.s.l.).

ΔP_{corr} is wind and evaporation correction of warm period rainfall precipitation calculated using the wind speed data from Nizhnyaya and Verknyaya stations based on the recommendations of Manual for hydrometeorological stations …, 1969).

ET, soil evapotranspiration, is calculated using average annual values for main landscapes of KWBS estimated by Semenova et al. (2013) and Lebedeva et al. (2017) with the account of their distribution across the studied watersheds.

Evaporation from snow E_{snow} is assessed as the following:

$$E_{snow}=0.40*d_{Apr} + 0.74*d_{May} \quad (2)$$

where d_{Apr} and d_{May} are average numbers of days in April and May between the date of maximum SWE and its full melt; 0.40 and 0.74 are average values of snow evaporation in April and May estimated based on observed data.

R is observed runoff; and η is an error term.

Possible members of water balance equation such as the changes in surface storage (lakes, wetlands, reservoirs, channels, etc.), subsurface storage of groundwater and the storage of unsaturated zone are estimated as zero and not accounted for long-term annual estimation.

Table 8 shows the distribution of water balance components for three small watersheds. All main components of water balance were assessed independently on the basis of data of direct observations. At two watersheds, the water balance discrepancy calculated as the difference between precipitation, runoff and total evaporation, is positive and varies from 43 to 57 mm which is about 11 and 14 % of calculated total precipitation. The water balance error at the Morozova watershed, which is completely formed of rocky talus, is negative and amounted to 68 mm or 14% from total precipitation. Though we did not use for calculations the data of solid precipitation, Sushansky (2002) assessed snow under-catch at Morozova watershed as 25-30 mm per year. Zhuravin (2004) mentioned that significant errors are possible at the sampling depth of snowpack profile in the areas covered with the Siberian dwarf-pine which is covered by snow during winter. He assessed the error of SWE estimation in such areas as 15% of the measured value. We would suggest that measuring SWE at rocky talus watershed where some areas are covered by boulders could cause the error of compared magnitude.

Estimated runoff coefficient amounts to 56, 51 and 95 % of precipitation for Severny, Yuzhny and Morozova watersheds respectively. Considering high runoff coefficient for rocky talus landscape, large proportion of the KWBS area (34%) covered by this type of underlying surface (Fig. 2B) and significant uncertainty of water balance estimation for Morozova Creek given the availability of observed data, correct assessment of water balance for larger areas seems rather complicated.

Table 8 presents the comparison of water balance calculations for three micro-watersheds of KWBS performed by different authors. While in this research SWE from snow surveys was taken as the estimate of winter precipitation, both – Lebedeva et al. (2017) and Zhuravin (2004) used observed precipitation data for assessing this component of water balance. The estimates of total precipitation vary due to different correction procedure applied (or not applied) by different authors. One may see that though all the authors used the same observed data on evaporation, its interpretation has provided the variation of results (Table 8). Also low closure error does not always confirm the correctness of estimation as, for example, Lebedeva et al. (2017) did not apply any bias correction to precipitation neither accessed the value of snow evaporation.

For the main KWBS watershed, the Kontakovy Creek (21.3 km^2), Zhuravin (2004) provided the following estimates of water balance for the period 1970-1985: precipitation – 405 mm, evaporation – 137 mm, runoff – 296 mm, discrepancy error - -28 mm (7%). Lebedeva et al. (2017) calculated the same values for 1949-1990 as 390, 281, 114 and -5 mm (-1%) respectively.

Presented results confirm that accurate numerical estimation of water balance elements even using available measurements is complicated (Kane and Yang, 2004) and subjective. Therefore it is important to make raw observational data available for scientific community as described in this paper.

6. Data availability

All data presented in this paper are available from the “PANGAEA. Data Publisher for Earth & Environmental Science” (see Makarieva et al., 2017, https://doi.pangaea.de/10.1594/PANGAEA.881731).

The directory includes 12 elements:

1. daily precipitation time series at 25 gauges within Kolyma Water-Balance Station (KWBS), 1948-1997;
2. daily runoff time series at ten gauges of KWBS, 1948-1997;
3. evaporation time series at 9 sites at KWBS, 1950-1997;
4. meteorological observations at three sites of KWBS, including the values of air temperature, water vapour pressure, vapour pressure deficit, atmospheric pressure, wind speed, low and total cloud amount, and surface temperature, 1948-1997;
5. monthly precipitation time series at 30 gauges within KWBS, 1948-1997;
6. precipitation (10 day sum) time series at 21 gauges within KWBS, 1962-1997;
7. precipitation (5 day sum) time series at 14 gauges within KWBS, 1966-1997;
8. snow survey line characteristics at KWBS, 1959-1997;
9. snow survey time series at different sites and landscapes within KWBS, 1950-1997;
10. soil temperature time series at the Nizhnyaya meteorological station at KWBS, 1974-1981;
11. thaw depth and snow height time series at different sites of KWBS, 1954-1997;
12. snow evaporation time series at two sites of KWBS, 1968-1992.

7. The future of the KWBS

In summer 2016, with the assistance of Melnikov Permafrost Institute of Siberian Branch of Russian Academy of Science, a group of specialists, consisting of representatives of different scientific institutions, conducted a reconnaissance survey of the KWBS in order to find out if it was possible to carry out scientific research and stationary monitoring of permafrost and hydrological processes at the station. Despite rather difficult logistic access to the KWBS, it was considered possible to organize accommodation and provision of the station for the period of summer expeditions. At first, the main goal of research resumption at the station would be a renewal of regular observations of runoff, meteorological elements and active layer dynamics at three small catchments (Morozova, Yuzhny, Severny) and the KWBS main-stream outlet (Nizhny gauge) using advanced equipment with automatic data recording. As a result, some unique runoff observations series – over 60 years long – will be continued, which will allow for evaluation of climatic impact on permafrost and provide a scientifically based forecast on current and future climate change impact on the hydrological regime.

During short 3-4 week field trips at the beginning and at the end of the warm (and hydrological) season, it would be also possible to study specific processes of runoff formation under permafrost conditions. Slope runoff occurs unevenly, and is concentrated in particular areas, the drainage zones or preferential path flows. Reconnaissance surveys of the Kontaktovy creek catchment at the KWBS territory, 2016, revealed that there are several types of such zones of slope runoff concentration. Another possible scientific task is to evaluate the role of cryogenic redistribution of runoff, which regularly occurs due to ice freezing-melting in coarse-grained slope deposits. Similar studies have already been carried out in mountain regions of permafrost, including the KWBS (Sushansky, 1999; Bantsekina, 2001; Bantsekina, 2002; Boyarintsev et al., 2006). Another research issue is the study of floodplain taliks (Mikhaylov, 2013) and aufeises (Alexeev, 2016) and their impact on hydrological processes in the mountainous part of the continuous permafrost zone. Field trips for a limited group of scientists could be covered with relatively modest financial support through research grants. In the future, the aim for the KWBS is to get back its status of a research station, to receive state funding, obtain sponsor support from gold mining companies of the Magadan region and become an international center for complex studies in the field of permafrost hydrology.

The KWBS is situated in the region where monitoring of natural processes is extremely sparse. From 1986 to 1999, the number of hydrological gauge stations in Far-East parts of Siberia decreased by 73% (Shiklomanov et al., 2002). Resumption of water balance observations and organization of complex research of permafrost, climate, and landscape, hydrological and hydrogeological processes based on data collected at the KWBS would make it possible to get new data, representative for the understudied territory of the Arctic in the context of environmental changes. Considering the insufficient knowledge about this territory and available long-term data, the KWBS has the prospect to become a highly demanded complex international center for testing natural process models at different scales – from point to regional, – validation of remote sensing products and a place for multidisciplinary field research.

More than 20% of the Northern Hemisphere is covered by permafrost. Three of the four largest rivers of the Arctic Ocean basin flow through Siberia. Many studies highlight ongoing and intensifying changes of water, sediment and chemical fluxes at all spatial scales but mechanisms of changes and future projections are highly uncertain. There are no research centers that could conduct focused studies of hydrological processes at catchments in the permafrost region in Russia. The KWBS incorporation into the international network for monitoring natural processes in cold regions (Interact, SAON, CALM, GTN-P, etc.) could significantly enhance international cooperation for better understanding of cold-region hydrology for the last 70 years, present and future.

Nowadays, the resumption of continuous observations and research at the Kolyma station appears to be a critical task due to increased interest in the natural processes of the Arctic region. Present-day data, following the KWBS long-term observations series, could become a valuable indicator of climate change and a basis for studying its impact on the state of the permafrost and its associated hydrological regime. Currently, as the station infrastructure is still partly intact, and some of the specialists who worked at the KWBS are still active and willing to help, it is necessary to gain attention and support from the Russian and international scientific community regarding the renewal of the KWBS before it is too late.

8. Conclusions

The presented dataset describes water balance, hydrometeorological and permafrost related components at small research watershed in mountainous permafrost zone of North-East Russia, the Kolyma water-Balance Station (KWBS). It includes 50 years of continuous daily meteorological and streamflow data for main meteorological plot and runoff gauge of KWBS and daily data of shorter periods for another two meteorological sites and 9 runoff gauges. Meteorological data includes values of air temperature, water vapour pressure, vapour pressure deficit, atmospheric pressure, wind speed, low and total cloud amount, and surface temperature. The dataset also includes all-year daily, warm period daily, 5-, 10-days and monthly sums for 47 (in total) precipitation gauges within KWBS territory for different time spans over the period 1948-1997. It also contains soil evaporation data from different landscapes, snow evaporation series from two sites; snow surveys results for different watersheds within KWBS, as well as thaw/freeze depths at more than 30 observational sites.

Based on the observation data annual water balance of three micro-watersheds (0.27 - 0.69 km^2) was estimated for the whole period of observations. Estimated runoff coefficients varied from 51-56 % at to 95 % in rocky talus. Assessment of water balance at larger scale is complicated due to significant uncertainty of water balance estimation for rocky talus which occupies about the third of the KWBS area.

Analysis of flow and meteorological data revealed general warming and the changes of water balance components in 1948-1997. The increase of annual air temperature amounted to 1.1 °C, annual precipitation has grown by 21%. Annual flow increased by 24%, positive trends were also determined in May (92%), October (166%), November (252%).

The dataset is important because it characterizes the natural settings, which, on the one hand, are nearly ungauged, and on the other hand, are representative for the vast mountainous territory of Eastern Siberia and North-East Russia. It is unique because it combines water balance, hydrological and permafrost data which allow for studying permafrost hydrology interaction processes within the range of all scientific issues, from models development to climate change impacts research.

9. Author contribution

O. Makarieva and N. Nesterova digitized and prepared the dataset for publication with assistance from L. Lebedeva and S. Sushansky. The data were collected in 1948-1997 by Hydrometeorological Service of USSR and Russia and published in Observation Reports (1959-1997).

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Table 1 List of meteorological observation data

Station	Nizhnyaya	Verkhnyaya	Kulu	Kulu2
Latitude	61.85	61.86	61.88	61.88
Longitude	147.67	147.61	147.43	147.44
Elevation, m	850	1220	670	635
Air temperature	1948-1997	1948-1972	1981-1991 1992-1997	
Water vapour pressure				
Vapour pressure deficit	1974-1997	n/a		
Atmospheric pressure	1951-1997	1951-1972		
Low cloud amount	1948-1997	1948-1972		
Total cloud amount				
Wind speed				
Surface temperature				

Table 2 Number of snow routes, their total length and number of measurements points – maximum and minimum values within the whole period of observations

Watershed	Period	Amount of snow routes	Total length of the route, m	Amount of snow depth measurement points
Yuzhny	1960-1997	4	1400-1540	144-154
Severny	1950-1997	4/10	1950/2130	23/207
Morozova	1968-1997	2/5	960/2645	98/534
Ugroza	1983-1997	1	1200	120
Dozhdemerny	1959-1971	3	3240/5720	327/575
Vstrecha	1950-1997	1/17	2110/10850	119/1091
Kontaktovy	1960-1997	2/4	4830/13100	485/1314

Table 3 Mean, maximum and minimum observed snow water equivalent (SWE) (mm) before spring freshet at different landscapes of the Kontaktovy creek watershed, 1960-1997

Landscape	SWE		
	mean	max (1985)	min (1964)
Forest	144	265	79
Dwarf cedar tree bush	127	247	39
Rocky talus	100	182	46
Boulders	66	127 (1974)	2
Kontaktovy Creek	121	213	59

Table 4 Mean, maximum and minimum snow water equivalent (SWE) (mm) before spring freshet at different watersheds within KWBS

Watershed	Period	SWE		
		mean	max	min
Yuzhny	1960-1997	121	166	70
Severny	1950-1997	126	232	62
Morozova	1968-1997	161	298	71
Ugroza	1983-1994	133	200	93
Dozhdemerny	1959-1971	82	111	53
Vstrecha	1951-1997	123	213	60

Table 5 Mean evapotranspiration (mm) in June – September at different landscapes of KWBS

# site	Landscape	Period	Elevation, m	Slope aspect	Jun	Jul	Aug	Sep	Total*
1	Larch forest	1962-1997	850	n/a	35	37	30	17	119
6	Swampy sparse growth forest	1969-1982	970	North	37	38	30	19	124
7	Dwarf cedar tree bush	1972-1997	1020	n/a	30	33	25	17	104

8	Dwarf cedar tree bush	1976-1997	900	South	47	40	30	14	131
9	Larch forest	1982-1992	669	West	36	39	37	24	136

*the sum for warm period

Table 6 Maximum depth of thawing at the different landscapes

# site	Watershed	Landscape	Period	Elevation, m	Maximum depth of thawing, cm
1	Kontaktovy	Forest	1954-1966	841	150
6	Dozdemerny	Rocky talus	1960-1965	1048	>240
9	Severny, Ugroza	Rocky talus	1954-1966; 1977-1978	986	168
12	Vstrecha, Severny	Dwarf cedar tree bush at rocky talus	1954-1962; 1966-1968; 1971-1997	866	157
15	Dozdemerny	Dwarf cedar tree bush at rocky talus	1958-1968; 1970-1982	952	>150
17	Vstrecha	Forest	1960-1965, 1969	914	>124
18 bh7	Kontaktovy	Peat bogs	1959-1960	835	69
18 bh8	Kontaktovy	Peat bogs	1959-1960	835	64

Table 7 The characteristics of KWBS watersheds

Code	Catchment (creek – outlet)	Period	Area, km^2	X	Y	Stream length, km	Mean watershed width, km	Mean stream slope, ‰	Mean basin slope, ‰	Catchment altitude (max-min, mean), m	Mean annual flow, mm	Maximum observed daily discharge, m^3s^{-1}
1104	Yuzhny	1960-1997	0.27	61.84	147.66	0.51	0.35	235	303	1110-917, 985	193	0.14
1107	Severny	1958-1997	0.38	61.85	147.66	0.74	0.38	175	388	1300-880, 1020	227	0.18
1103	Morozova	1968-1996	0.63	61.84	147.75	0.97	0.45	326	649	1700-1100, 1370	453	0.44
1624	Ugroza	1983-1991	0.67	61.86	147.67	0.9	0.74	218	461	1270-914, 1260	354	0.27
1106	Dozhdemerny	1952-1971	1.43	61.86	147.63	0.87	0.99	220	432	1450-950, 1180	208	0.31
1105	Vstrecha	1949-1997	5.35	61.85	147.66	3.4	1.5	92	346	1450-833, 1060	237	3.15
1100	Kontaktovy – Verkhny	1973-1980	5.53	61.84	147.70	2.8	2.1	185	473	1700-909, 1070	317	2.52
1625	Vstrecha – the mouth of Ugroza Cr.	1984-1996	6.57	61.84	147.66	3.6	1.8	76	406	1450-831, 1070	283	2.6
1101	Kontaktovy – Sredny	1948-1997	14.2	61.84	147.67	6.2	2.8	65.2	413	1700-842, 1120	289	7.02
1102	Kontaktovy – Nizhny	1948-1997	21.3	61.85	147.65	7.1	3.7	57.6	413	1700-823, 1070	281	8.15

Table 8 Water balance of three micro-watersheds of KWBS (mm, %)

Watershed	Severny			Yuzhny			Morozova	
Authors*	M	L	Z	M	L	Z	M	L
Period	1958-1997	1959-1990	1970-1985	1960-1997	1960-1990	1970-1985	1969-1997	1969-1990
SWE	126	-	-	121	-	-	161+36	-
P_{rain}	263	-		232	-	-	225	-
ΔP_{corr}	25	-	70	22	-	65	55	-
P_{total}	375	357	399	375	332	346	477	451
ET	113	120	-	124	132	-	73	73
E_{snow}	17	0	-	15	0	-	19	0
E_{total}	130	120	139	139	132	147	92	73
R	227	236	217	193	199	190	453	448
R (%)	56	66	54	51	60	55	95	99
η	57	1	43	43	1	9	-68	-70
η (%)	14	0,3	11	11	0,2	3	14	16

*M – current research (Makarieva et al.); L – Lebedeva et al. (2017); Z – Zhuravin (2004).

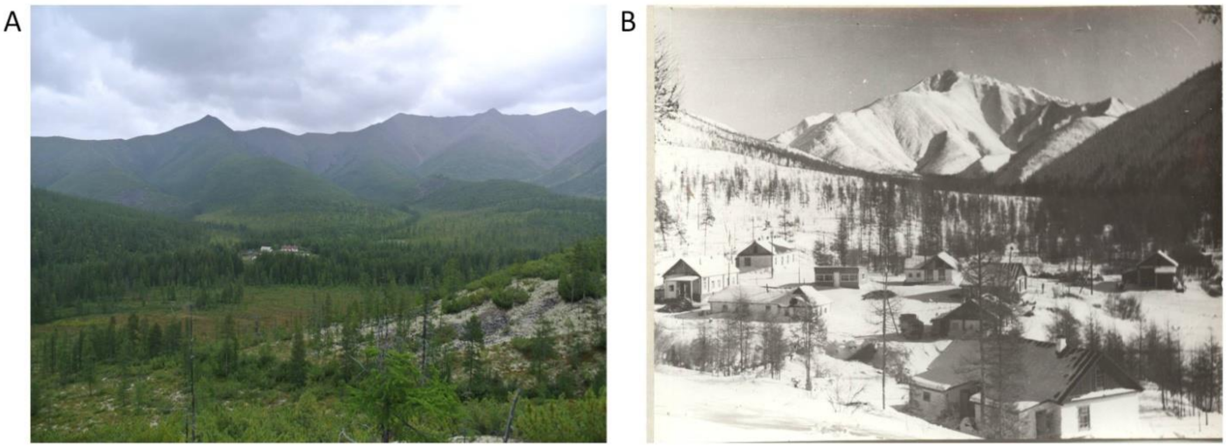

Fig. 1 The view of the Kolyma Water Balance Station, A – August 2016 (the photo by O. Makarieva), B – historical photo from Sushansky (1989)

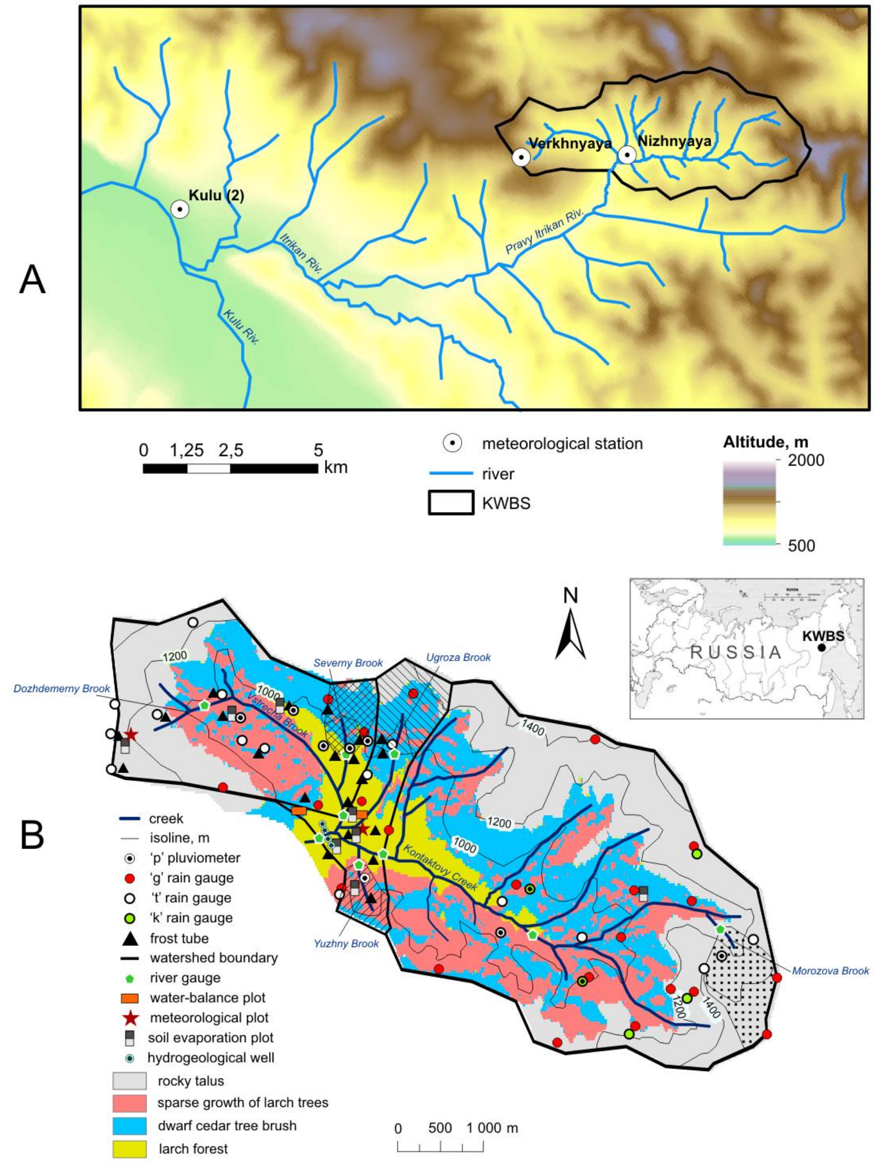

Fig. 2 Scheme of the Kolyma Water Balance Station (KWBS) indicating the location of observation sites

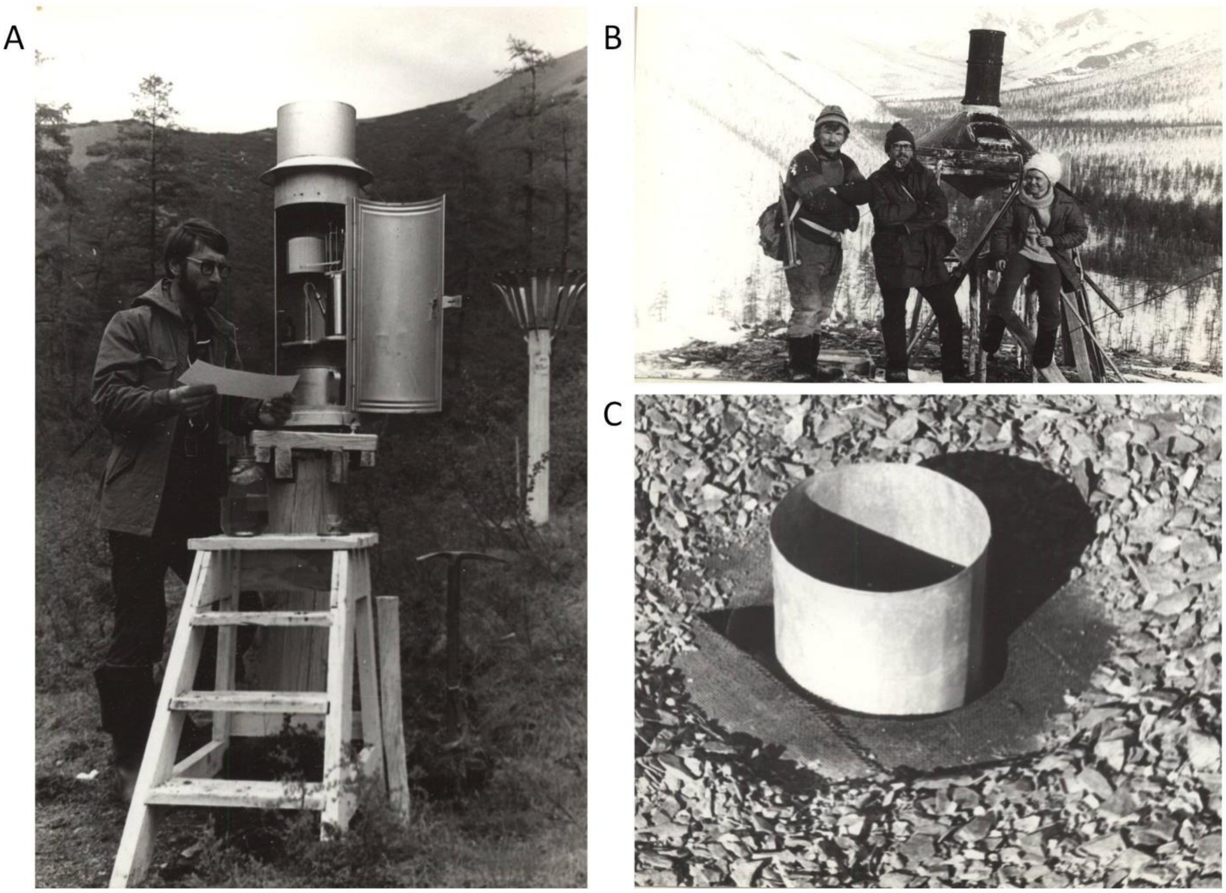

Fig. 3 A – Pluviometer, Tretyakov gauge, B – Kosarev gauge, C – remaining of ground gauge GR-28 (Sushansky, 1988, 1989)

Fig. 4 A, B – Snow survey at the Kontaktovy creek catchment; C – measurement of snow density, 1960 (the photos from the KWBS archive, provided by S.I. Sushansky).

Fig. 5 A - Rykachev evaporimeter, B - weighing the GGI-500-30 evaporimeter (Sushansky, 1989)

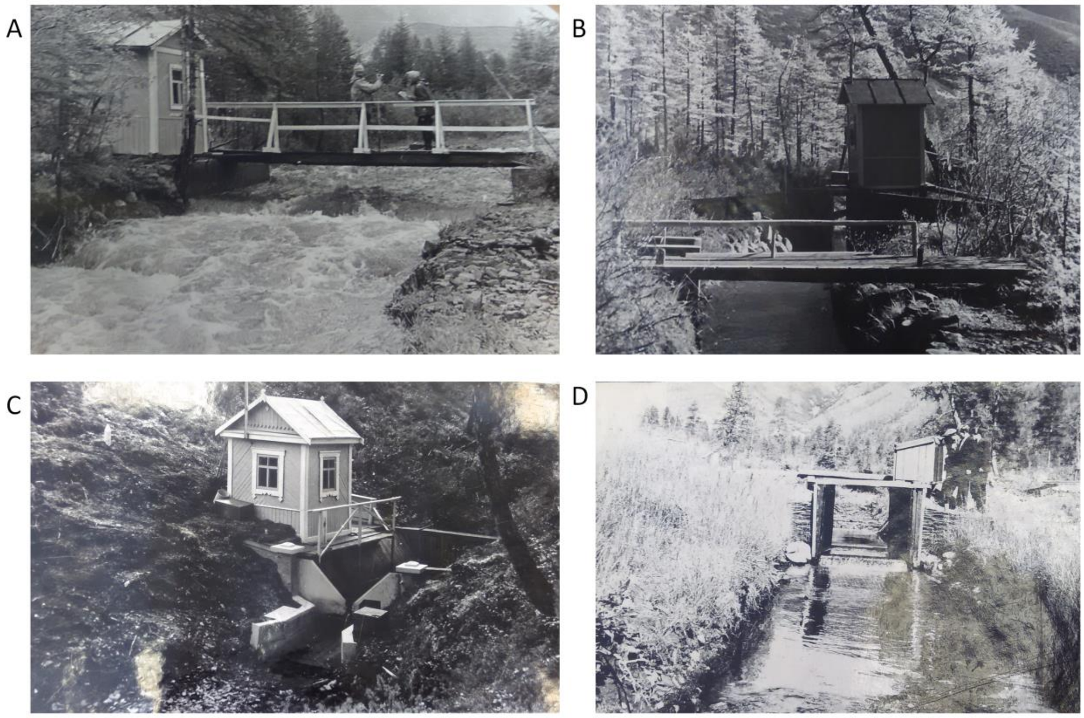

Fig. 6 Runoff observations: A – runoff gauge at the Kontaktovy creek, 1979; B – runoff gauge at the Dozhdemerny creek, 1959; C – runoff gauge at the Yuzhniy creek, 1960; D – runoff gauge at the Vstrecha creek, 1953 (the photos from the KWBS archive, provided by S.I. Sushansky)

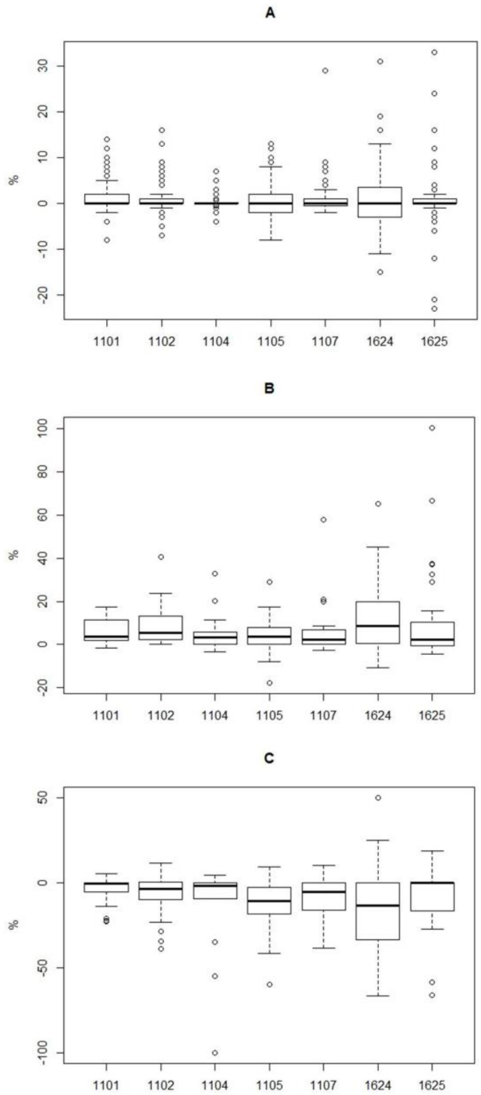

Fig. 7 Characteristics of discharge accuracy, 1984-1997. A – the percentage of extrapolation of stage curves, B, C – the difference between measured and estimated maximum and minimum instant discharges respectively

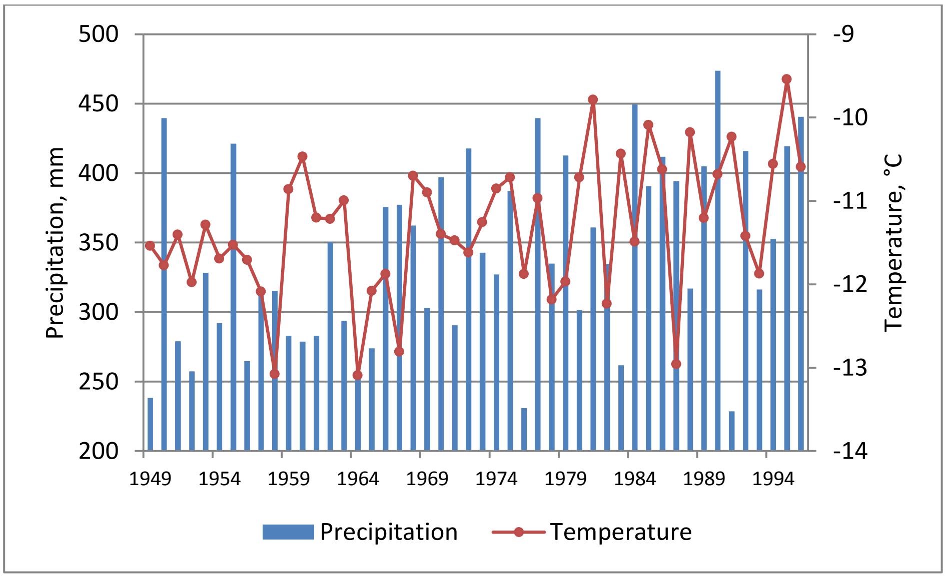

Fig. 8 Annual precipitation (mm) and air temperature (°C) at Nizhnyaya weather station, 1949-1996

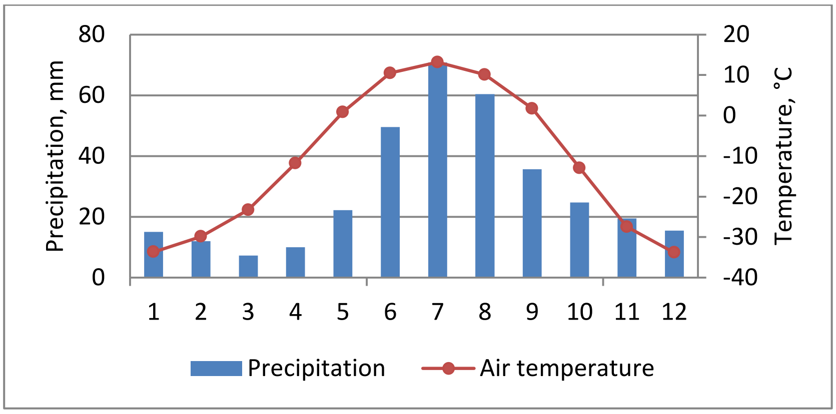

Fig. 9 Mean monthly precipitation (mm) and air temperature (°C) at Nizhnyaya weather station, 1949-1996

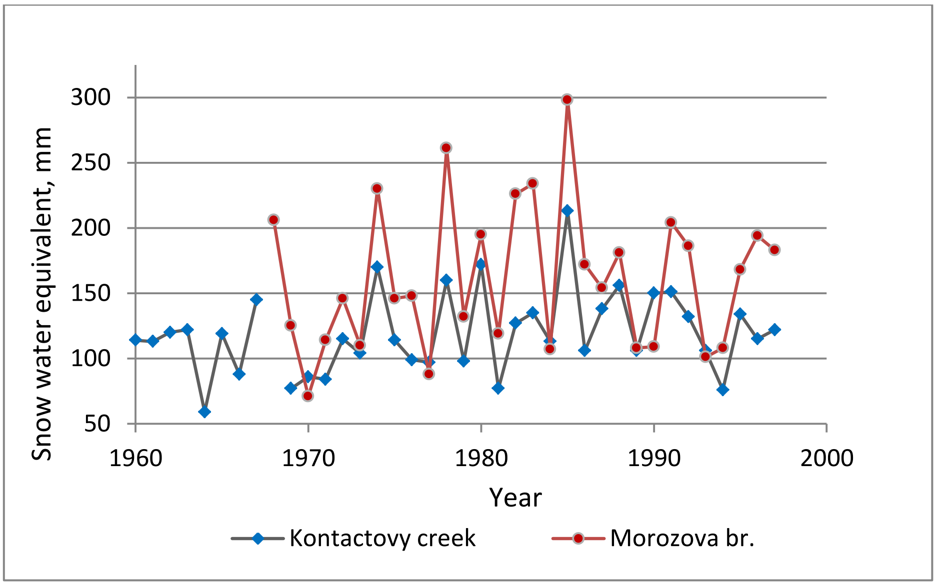

Fig. 10 Snow water equivalent at the Kontaktovy creek and Morozova br.

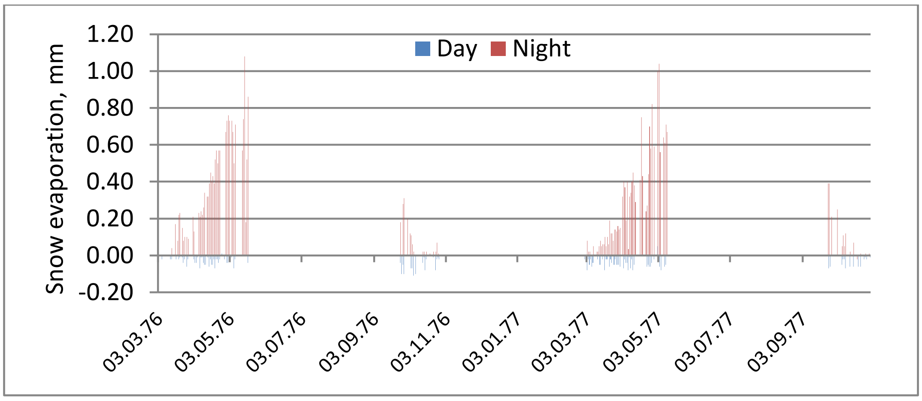

Fig. 11 Snow evaporation (mm) during day and night period, 1976-1977

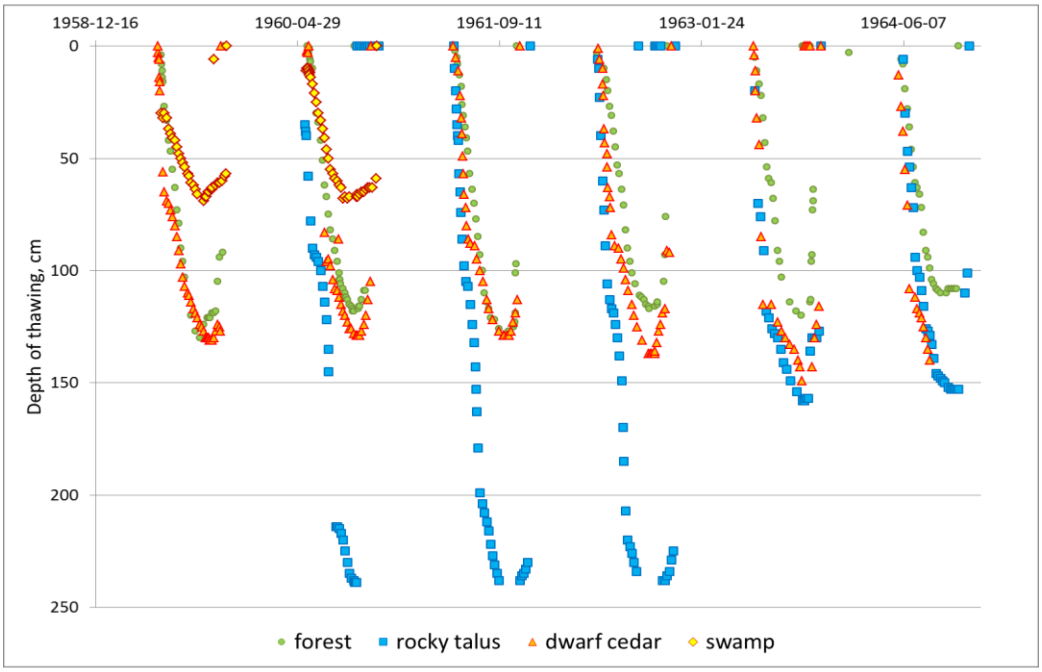

Fig. 12 Depth of ground thawing at the different landscapes of KWBS

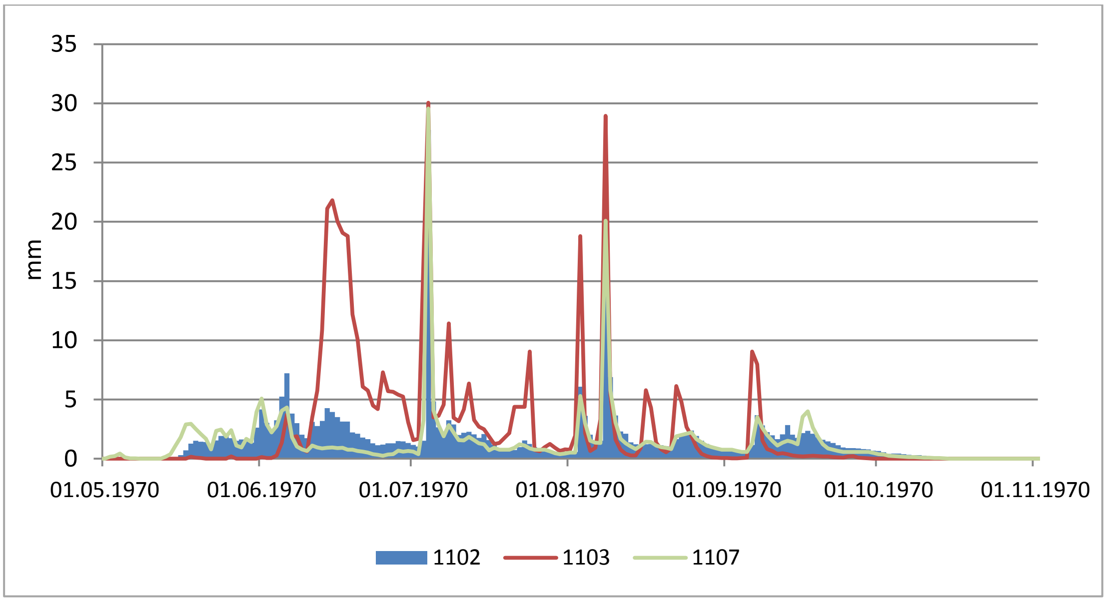

Fig. 13 Flow depth (mm) at the Kontaktovy creek – Nizhny (1102), Severny br. (1107) – south-facing slope with cedar dwarf bush landscape and Morozova br. (1103) – rocky talus landscape at watershed divides, 1970

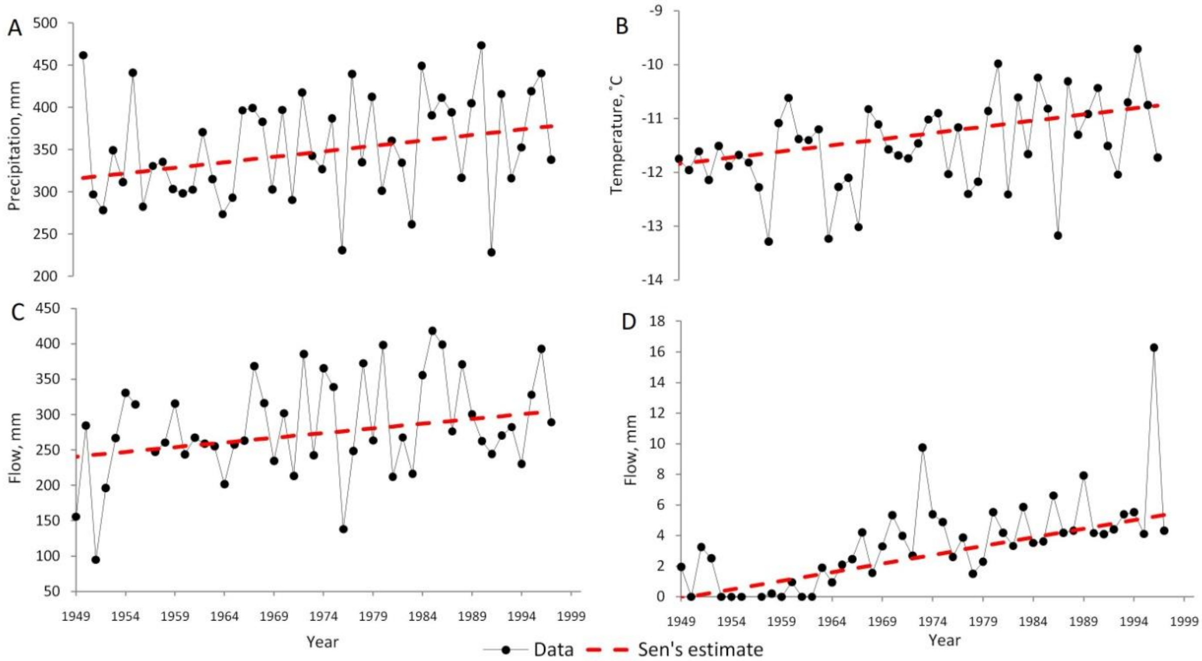

Fig. 14 The trends of hydrometeorological elements, 1949-1997. A - annual precipitation at the Nizhnyaya station; B - annual air temperatures at the Nizhnyaya station; C - annual flow at the Kontaktovy creek – Nizhny; D - flow in October at the Kontaktovy creek – Nizhny