Polarforschung 87 (2), 177 – 194, 2017 (erschienen 2018)

Long-term Changes of River Water Inflow into the Seas of the Russian Arctic Sector

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Abstract: The annual runoff of rivers from the territory of Russia into the Arctic seas is approximately equal to 2922 km^3, or 55.6 % of the total inflow of river waters into the Arctic Ocean. Such an amount of fresh water and its long-term fluctuations, together with the sediments and heat transported by rivers, can have a significant impact on the regional marine hydrological processes and climate, on the hydro-meteorological conditions and ecosystems of river channels, valleys and estuaries, the abrasion-accumulation processes, safety and sustainability of nature management in the region. Almost the whole inflow of river waters (~84 %) is provided by 19 large Arctic rivers of Russia. The estimates of their runoff, as of 2015 and for the key cross sections in the lower reaches of rivers, were obtained for the first time. The new data allowed to clarify the values of seasonal runoff and to detail the features of its spatial variability. In multi-year flow fluctuations, the element of uncertainty is greater, and the patterns and trends are not so obvious. Nevertheless, the analysis of cyclicity and trends showed that the annual runoff of most major Arctic rivers has increased by 5-10 % compared to the runoff for the period from 1936 to 1970. The increase in the annual runoff of most rivers was provided by an increase in the water content in various hydrological seasons. Especially pronounced was the positive dynamics for the runoff of the winter low-water period, to the greatest extent in the mouths of the regulated rivers such as the Ob (by 20 %), Yenisei (68 %), Kolyma (174 %), and also Lena (47 %) that has a large regulated tributary (the Vilyui River). The results of the study show that the inter-annual and seasonal regulation of runoff performed by large reservoirs and their filling is the main factor of anthropogenic disturbances of the Arctic rivers runoff. The paper also assesses the role of full and irretrievable water consumption in the catchment areas of all the Arctic rivers (in the past, present and in the near future), its territorial and industrial structure. Its impact on the inflow of river waters to the Arctic Seas is not statistically significant, but it has signs of a crisis situation in some areas of the Arctic catchment area. In total, about 20.6 km^3 of river and subterranean waters are removed from the basins of the Arctic rivers on the territory of Russia per year. By the years of 2025-2030 this value is planned to be increased to 37.2 km^3 per year. The article also summarizes the existing predictions of a likely change in the river runoff in the Russian Arctic sector in the first half of the 21st century.

Zusammenfassung: Der jährliche Abfluss der Flüsse vom Territorium der Russischen Föderation in die arktischen Meere beträgt 2922 km^3 oder 55,6 % des gesamten Flusseintrags in den Arktischen Ozean. Solch eine gewaltige Menge an Süßwasser und seine langzeitlichen Schwankungen, zusammen mit den von den Flüssen transportierten Sedimenten und Wärme, kann einen großen Einfluss auf die regionalen hydrologischen Prozesse im Meer und auf das Klima haben, auf die hydrometeorologischen Bedingungen und Ökosysteme im Flusslauf, in den Tälern und Mündungen, auf Erosion und Ablagerung, auf Sicherheit und langfristige Pflege und Erhalt von Natur und Umwelt in der ganzen Region.

Fast die ganze Menge an Flusswasser (etwa 84 %) wird von 19 großen arktischen Flüssen Russlands bereitgestellt. Die Abflussschätzungen, Stand 2015 und von wichtigen Querschnitten in den Unterläufen der Flüsse erfolgten zum ersten Mal. Die neuen Daten erlauben eine gewisse Klärung des saisonalen Abflusses und Einblick in Kleinmuster der räumlichen Variabilität. Daraus lässt sich erkennen, dass der jährliche Abfluss der meisten größeren arktischen Flüsse heute im Vergleich zum Zeitraum 1936 bis 1970 um 5 bis 10 % zugenommen hat.

Der stärkere Jahresabfluss der meisten Flüsse wird bestimmt durch mehr Wasser in verschiedenen hydrologischen Jahreszeiten. Besonders deutlich war die positive Entwicklung des Abflusses für die winterliche niedrig-Wasserperiode: Am größten in den Mündungen der regulierten Flüsse Ob (20 %), Yenisei (68 %) und Kolyma (174 %), und auch der Lena (47 %), die mit dem Vilyiu Fluss einen großen regulierten Zufluss hat. Die Studie zeigt, dass die zwischenjährliche und jahreszeitliche Regulierung des Abflusses durch große Reservoire der Hauptfaktor der anthropogenen Veränderung in der Abflussmenge und dem Haushalt der arktischen Flüsse ist.

Die Arbeit betrachtet auch die Rolle des vollständigen und unwiederbringlichen Wasserverbrauchs in den Einzugsgebieten aller arktischen Flüsse (gestern–heute–morgen) in seiner territorialen und industriellen Struktur. Sein Einfluss auf den Zustrom von Flusswasser in den Arktischen Ozean ist statistisch nicht bedeutend hat aber Anzeichen einer kritischen Situation in einigen arktischen Einzugsgebieten. Insgesamt werden in Russland pro Jahr etwa 20,6 km^3 Fluss- und Grundwasser aus den Einzugsgebieten der arktischen Flüsse entnommen. Für die Jahre 2025–2030 wird dieser Wert – wie geplant – auf 37,2 km^3 pro Jahr steigen. Der Artikel fasst die bestehenden Aussagen zusammen, die einen möglichen Wechsel des Flusseintrags in den Russischen Sektor des Arktischen Ozeans in der ersten Hälfte des 21. Jahrhunderts beschreiben.

Keywords: runoff of the Russian Arctic Rivers, climatic and anthropogenic changes in the runoff, long-term and intra-annual runoff fluctuations, water consumption, forecast of runoff changes

doi:10.2312/polarforschung.87.2.177

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Manuscript received 18 May 2017; accepted in revised form 09 November 2017.

INTRODUCTION

The domestic hydrologists began to study the issues of assessing the runoff of the Arctic rivers for the first time at the beginning of the 20th century. At that time, the first results of stationary hydrological observations appeared, the relation of hydro-meteorological and ecological conditions in the Arctic with the amount and regime of runoff of the Arctic rivers, including the runoff of water, sediments, heat and dissolved substances were understood. An article by V. Shostakovich was the first work of this kind (SHOSTAKOVICH 1911). But the first more or less reliable estimates of this runoff (for the individual large rivers and parts of sea coasts) were obtained in the 1930s during numerous expeditionary studies (ANTONOV 1936, ZAIKOV 1936), the substantial expansion of the stationary hydrological observation network, the development of the Northern Sea Route and the beginning of the development of the first Arctic mineral deposits.

Monographs like "Water Resources and Water Balance of the Soviet Union Territory" (WATER RESOURCES 1967), "The Soviet Arctic" (GAKKEL & GOVORUKHA 1970), "Atlas of the Arctic" (GULYUK & SVIRSKY 1985) and "Water resources of the USSR and their use" (WATER RESOURCES 1987) should be mentioned among more recent and fundamental works with new, constantly updated estimates of river water runoffs into the Arctic seas of Russia. According to these sources, the total annual runoff into the White Sea and Barents Sea was in a range of 408-478 km^3/year (420-490 km^3/year together with the islands), into the Kara Sea of 1324-1347 km^3/year (1331-

1375 km^3/year together with the islands), into the Laptev Sea of 767-783 km^3/year, into East Siberian Sea of 213-268 km^3/year, and into Chukchi Sea of 24.2-78 km^3/year.

The monograph "Water resources of Russia and their use" (Shiklomanov 2008) was the last and the most fundamental work on this list. It contains updated estimates of the inflow of river waters into the six seas of the Russian Arctic (221, 210, 1391, 804, 267 and 29 km^3 per year, respectively), obtained by V.I. Babkin (State Hydrological Institute SHI, Saint-Petersburg) according to the data for the beginning of the 21st century. But like the results of earlier studies, it did not completely close the issue of a reliable estimate of river runoff in the key parts of the coast, including the estuary areas of rivers. In turn, the authors of the article have their own suggestions on the methods of such calculations (Alekseevskiy 2007, Magritskiy 2000, Mikhailov et al. 2006). Among other important works containing estimates of the inflow of river waters into the Arctic seas, the works by Ivanov (1976a, b), I.A. and A.I Shiklomanov (Shiklomanov & Shiklomanov 2003) and some foreign specialists should be mentioned (Serreze et al. 2003). There are much more works that concern the individual Arctic rivers, but, nevertheless, the results of them are taken into account in the above articles and monographs.

The issues of water regime of the Russian Arctic rivers were studied long ago and quite well, and the features of intra-annual fluctuations of river water discharges have been typified and mapped. The results of this large-scale and long-term work carried out by a lot of domestic hydrologists, including the authors of the article, are contained in several fundamental works and some articles also known to foreign specialists (Davydov 1955, Elshin & Kupriyanov 1970, Evstigneev et al. 1990, Kupriyanov 1969, Kuzin 1960, Muranova 1973, Protasieva 1972, Vodogretski 1973, Zhila & Alyushinskii 1972, Zaykov 1946). The new materials do not yet allow a serious revision of these results, but they initiate a constant refinement of the individual characteristics of water regime, taking into account the extension of the series of runoff observations and climate changes. This work has been carried out by the authors of the article; some of the results, including maps, were published earlier (Alekseevskiy 2007, Dzhamalov et al. 2016, Frolova et al. 2015).

The issue of climatic and anthropogenic long-term changes of the inflow of river waters into the seas of the Russian Arctic has not been studied sufficiently, using the example of only some (not more than 5 or 6) of the largest Arctic rivers and of a limited range of tasks. At the same time, the importance of this kind of studies is extremely high. At the present time, climatic changes in the main characteristics of the runoff of such rivers have been studied to a greater extent, with the identification and assessment of trends, periods of high and low water runoff (as well as cycles and latent periodicity), the assessment of the disturbance of stationarity of multi-year flow fluctuations, and their relation to climate warming and the changes in the moistening conditions in river catchment areas, macro-synoptic processes, frost degradation and even forest fires (Babkin et al. 2004, 2005, Dobrovolski 2007, Georgiadi & Kashutina 2016, McClelland et al. 2004, Pavelsky & Smith 2006, Roshydromet 2014, Savelieva et al. 2000, Semiletov et al. 1998, Shiklomanov 2008, Shiklomanov & Shiklomanov 2003, Shiklomanov et al. 2000, 2006, 2007, Simonov & Khristoforov 2005, White et.al. 2007, Yang et al. 2002, 2003, 2004). In general, they state a climatic increase in the runoff of the Arctic rivers for the present period. The disadvantage of these assessments and conclusions is that most of the results refer to rivers and river areas with hydrological gauges. In addition, the results obtained by different specialists are sometimes not quite comparable due to the use of rows different in length, the origin and quality of the initial data, different compared periods, and so on. The feature of the results presented in this article is the uniformity of periods and approaches in the analysis of data, the maximum possible number of rivers and gauges considered, not only large but also medium in size, throughout the Arctic zone of Russia and with the data on runoff in the mouths of rivers. Some preliminary results were published earlier (Alekseevskiy 2007, 2013, Alekseevskiy et al. 2004, 2015, Dzhamalov et al. 2015, 2016, Frolova et al. 2015, Magritsky 2015).

There are much fewer works devoted to the study of the anthropogenic factor of the long-term variability of the runoff of river waters into the Arctic seas. And if there are, they either date back to the period of 1970–1980, or the results of the studies are confined only to the downstreams of some large reservoirs and water intakes (Avakyan & Sharapov 1977, Chernyaev 2001*a*, 2001*b*, McClelland et al. 2004, Shiklomanov 1994, Veretennikova & Leonov 1982, Shiklomanov 2008, Zaitsev & Koronkevich 2003). One of the main reasons for this situation is the closure of the initial data for such studies until recently. The second important reason is the absence of a request from the society and the state in the USSR for such studies, except for the cases when an issue of transferring part of the runoff of the northern rivers to the south (to the basin of the Caspian Sea and Aral Sea, the construction of giant reservoirs (for example, Nizhnelensky Reservoir) and possible future hydrological consequences of these measures for the lower reaches and estuaries of the Arctic rivers and for the coastal zone of the seas and navigation was being solved. The authors of the article managed not only to collect all the necessary materials (as of 2014) and to process them, but also to analyze the impact of the creation and operation of reservoirs, the intake of river and ground waters on the runoff of the Arctic rivers, its current fluctuations, and to compile a specialized map for the first time.

Quite a large number of domestic and foreign publications are devoted to assessing possible changes in the runoff of the Arctic rivers. They use the estimates of climatic changes in the Arctic region as an input to the hydrological and water-balance models of diverse complexity (Alekseevskiy 2007, Arnell 2005, Aror & Boer 2001, Georgievsky et al. 1996, Gusev et al. 2016, Evstigneev & Akimenko 2005, Meleshko et al. 2008, Mokhov et al. 2003, Shiklomanov 2008). Some of the first who obtained a prediction of the change in the runoff on this basis were Miller & Russell (1992). The available estimates have been summarized and systematized in this article.

This article aims are to provide an objective and updated view of the processes related to runoff formation, transition and outflow into the Russian Arctic seas including those occurring in the present period, patterns of their spatio-temporal changes, and the role of large-scale economic activities in these processes. Conclusions are based on the results of extended and comprehensive hydrological studies being conducted at the Faculty of Geography of Moscow State University since 2002. The information framework for the authors' studies uses hydrological data from numerous gauging stations maintained by the Russian Hydrometeorological State service (ROSHYDROMET), averaged over the months, hydrological seasons and years. The earliest observations date back to 1881 (Ust-Pinega post, and Severnaya Dvina River). The prevalent part of hydrological monitoring stations considered in this study was established in the late 1920s to 1930s. The latest observations refer to 2014-2015. Data were published in the relevant special-purpose hydrological reference books, the so-called Hydrological Yearbooks, or, in recent years, were acquired by the authors from ROSHYDROMET's departments. Information on water management activities within the catchment areas of the Arctic rivers – previously of restricted access to national and, particularly, to foreign experts – was collected from various sources: reference books of the State Water Cadastre System (State water cadastre 1982-2014), Schemes for Integrated Use and Protection of Water Objects (open access, <http://www.dpbvu.ru>, <http://skiovo.enbvu.ru>, <http:// nobwu.ru>, <http://www.amurbvu.ru>), as well as official websites of stakeholders of the water management complex. Standard statistical and graphic processing of hydro-meteorological information was used.

WATER RESOURCES OF RIVERS IN THE RUSSIAN SECTOR OF THE ARCTIC OCEAN BASIN

They are formed across the area of 13.3 million km^2, which amounts to 70.7 % of the total country area (Alekseevskiy 2013). Over 1.63 million rivers are located on this territory (Tab. 1, Fig. 1). Coastal sites of the Russian Arctic seas differ by value of discharges of the rivers and river network density (drainage density, defined as the ratio of the total river network length (km) to the area of the territory (km^2)). On the Kola Peninsula, it amounts to 0.4-0.9 km/km^2, increasing up to 0.7-1.0 km/km^2 in the north of the Yamal and Gydansky peninsulas, 0.7-1.25 km/km^2 on the Taimyr Peninsula, 0.8-1.08 km/km^2 in the polar part of the Verkhoyansk Range, 0.8-1.2 km/km^2 within the Chukotka Autonomous Region, and 1.0-1.78 km/km^2 on the Novosibirsk Islands. The river network is significantly less dense in the northern part of the West Siberian Lowland (0.3-0.5 km/km^2), the Yana-Indigirka and Kolyma lowlands (0.12-0.5 km/km^2), which is associated with a small amount of precipitation, insignificant surface slopes, swampiness, and a large number of lakes.

Only a small proportion of rivers run directly into the Arctic seas. They can be subdivided conventionally by watershed area into small rivers (catchment area <2,000 km^2), medium rivers (2,000-50,000 km^2), large rivers (50,000-200,000 km^2), very large (200,000-1•10^9 km^2) and the largest (>1•10^9 km^2). The largest rivers of the region (and in the country) are the Ob, Yenisei and Lena. Seven rivers are considered as very large: the Severnaya Dvina, Pechora, Khatanga, Olenek, Yana, Indigirka and Kolyma, and nine rivers are large: the Onega, Mezen, Nadym, Pur, Taz, Pyasina, Nizhnyaya Taymyra, Anabar and Alazeya. According to the estimates in Alekseevskiy (2007), approximately 110 streams can be attributed to the medium-size rivers.

The long-term average inflow to the Arctic Ocean approximately equals to 2,922 km^3/year (Shiklomanov 2008). The runoff distribution along the Arctic coastline is greatly uneven. According to the estimates of authors, about 55 % of water resources contribute to the runoff of the three largest rivers of the country – the Yenisei, Lena and Ob – 30 % on 16 large rivers, and 15 % on ca. 1,500 medium-size and small rivers. Thus, almost the entire water inflow (~84 %) into the Russian Arctic Seas is provided by 19 major rivers. Most of the river waters (about 48 %) come from the Kara Sea catchment (Tab. 2).

HYDROLOGICAL REGIME OF THE RUSSIAN ARCTIC RIVERS

The largest portion of the runoff to the seas of the Russian Arctic is formed during melting of the snow cover on the plains. Thawed snow water in some rivers is enriched with melt water from the highland snow patches, glaciers and precipitation. Therefore, the main water regime phase of most of the Arctic

Ocean	Total area of basin (10^3 km^2) (1) (2)	Ratio of basin area to sea area	Area of the basin within the Russian EEZ		Number of rivers (5)
			total (3)	excluding islands (3) (4)	
Barents Sea	668.4	0.47	525.7	–	61348
White Sea	717.6	7.97	709.8	–	109534
Kara Sea	6649.65	7.53	5739.5	5688.1	475187
Laptev Sea	3692.9	5.58	3692.9	3673	421786
East Siberian Sea	1295.5	1.42	1295.5	1271.2	483672
Chukchi Sea	261.5	0.44	101	94.8	41830
Total	13285.55	2.91	12064.4	–	1593357 1629121 (6)

Tab. 1: Hydrographic characteristics of catchments of the Russian Arctic seas. Data (1): from Ivanov (1976); (2): from Water Resources of the USSR (1987); (3): from Mikhailov et al. (2006); (4): from Water Resources (1967); (5): from Domanitsky et al. (1971); (6): rivers of Arctic islands included.

Tab. 1: Hydrogaphische Charakteristika der Einzugsgebiete der Russischen Arktischen Seegebiete. Daten (1): Ivanov (1976); (2): Water Resources of the USSR (1987); (3): Mikhailov et al. (2006); (4): Water Resources (1967); (5): Domanitsky et al. (1971); (6): Einschließlich der Flüsse der Arktischen Inseln.

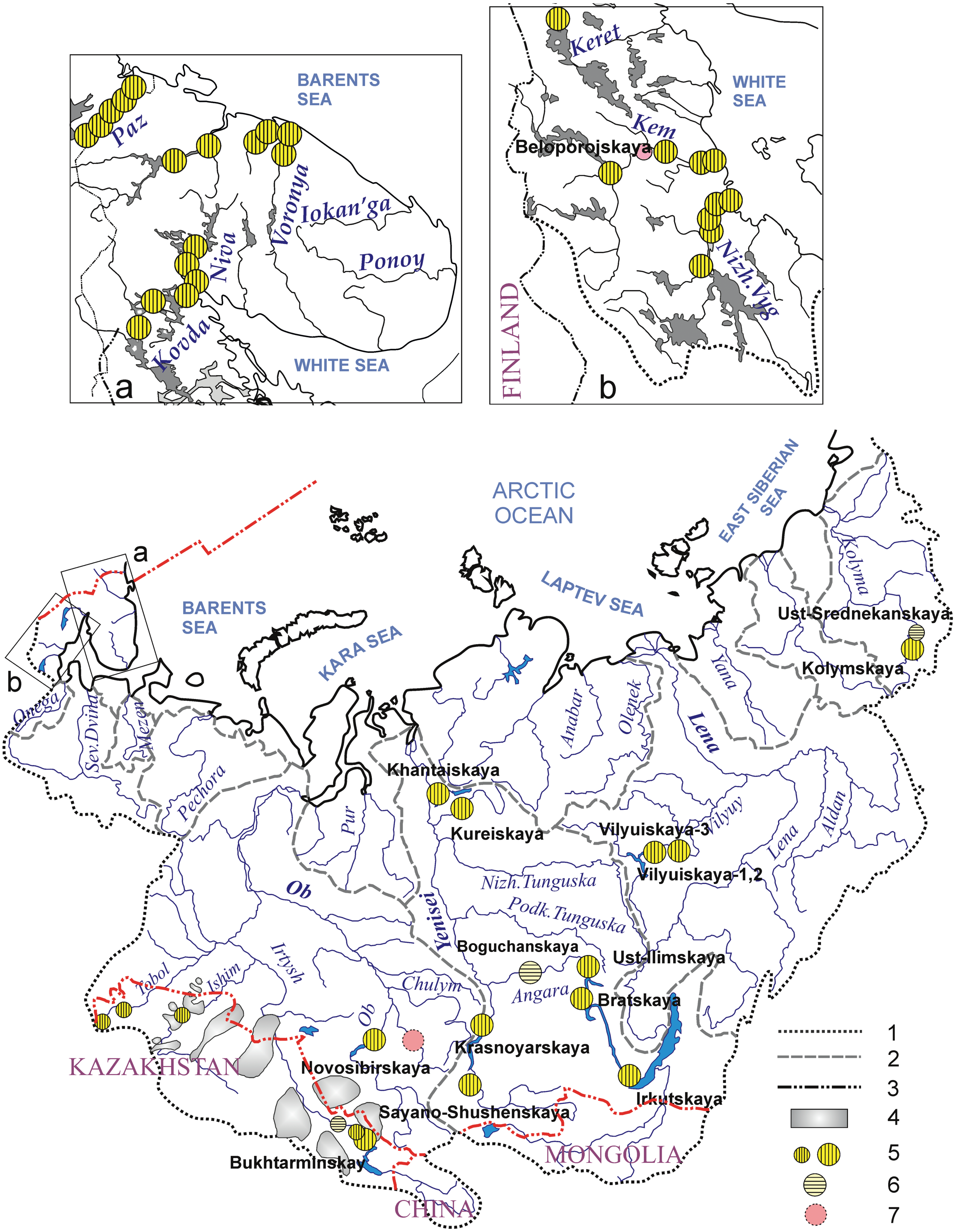

Fig. 1: Rivers and catchment areas of the Russian Arctic Seas. Legend 1: boundary of the Arctic Ocean river basin; 2: boundaries of large river basins; 3: state borders; 4: drainless areas; 5: functioning hydroelectric station (HES); 6: functioning HES, but not fully completed; 7: HES under construction.

Abb. 1: Flusssysteme und Einzugsgebiete der in die russischen Arktischen Meere mündenden Flüsse. Legende: 1: Südgrenze des arktischen Einzugsgebietes. 2: Grenze der großen Flusssysteme. 3: rot Staatsgrenzen. 4: Abflusslose Gebiete. 5: Wasserkraftwerke in Betrieb. 6: Wasserkraftwerk in Betrieb, nicht voll ausgebaut. 7: Wasserkraftwerk im Bau.

River	Observation period	Lowest hydrometrical station					Marine boundary of the delta	
		area of river basin (10^3 km^2)	discharge, (m^3/s)	water runoff, (km^3/yr)	specific discharge, ($l/s{\cdot}km^2$)	runoff depth, (mm)	area of river basin (10^3 km^2)	water runoff (5) (km^3/yr)
1	2	3	4	5	6	7	8	9
Rivers of White Sea								
Ponoy (1)	1935–2015	15.3	175	5.51	11.4	360	15.5	5.56
Niva (1)	1935–2015	12.8	165	5.21	12.9	407	12.8	5.21
Kovda	1935–2015	26.0	278	8.78	10.7	338	26.1	8.83
Kem'	1935–2015	27.6	276	8.72	9.98	315	27.7	8.74
Nizny Vyg (1)	1935–2015	26.5	262	8.25	9.87	311	27.1	8.43
Onega	1935–2015 (1)	55.7	497	15.7	8.9	282	56.9	16.1
Severnaya Dvina	1935–2015	348	3170	100	9.1	287	357	103
Mezen	1935–2015	56.4	636	20.1	11.3	356	78.0	27.3
Rivers of Barents Sea								
Pechora	1935–2015	248	3490	110	14.1	444	322	147
Rivers of Kara Sea								
Ob	1935–2015	2430 (2) 2953	12700	401	5.2 4.3	165 136	2470 2990	411
Nadym	1955–1991 2000–2004 2011–2015	48.0	452	14.3	9.4	297	64.0	18.2
Pur	1936–2015 (1)	95.1	895	28.2	9.4	297	112	32.7
Taz	1952–1996 (1)	100	1040	32.8	10.4	328	150	45.1
Yenisei	1936–2015	2440	18700	590	7.7	242	2580	635
Pyasina (3)	–	166	–	–	–	–	182	71.2
Nizhnya Taymyra (4)	1944–1994	123	1050	33.2	8.5	270	124	33.5
Rivers of Laptev Sea								
Khatanga	1961–1994	275	(2310)	(73.0)	(8.4)	(265)	364	(87.1)
Anabar (1)	1936–2015	78.8	466	14.7	5.9	187	100	18.0
Olenek (1)	1936–2015	198	1120	35.3	5.7	179	219	38.8
Lena	1935–2015	2430	17200	543	7.1	223	2490	553
Yana (1)	1935–2015	224	1065	33.6	4.8	150	238	35.1
Rivers of East Siberian Sea								
Indigirka (1)	1935–2015	305	1640	51.8	5.4	170	360	55.4
Alazeya (1)	1940–2015	29.0	51.8	1.63	1.8	56	64.7	3.3
Kolyma (1)	1935–2015	526	3300	104	6.3	198	647	124
Rivers of Chukchi Sea								
Amguema (1)	1944–1998	26.7	273	8.60	10.2	322	28.1	9.13

Tab. 2: Basic characteristics of the annual runoff of major rivers in the Arctic Ocean catchment, Russian sector. Notes (1): Data incomplete, average runoff is reduced to the long-term period value; (2) top: catchment area; below: basin area including drainless areas; (3): according to Water Resources (1987); (4): according to Zimichev (2004); (5): values of changes in runoff from the basin outlet station to the sea calculated by Magritsky in (Alekseevskiy 2007) and Magritskiy et al. (2015).

Tab. 2: Grunddaten des jährlichen Eintrags der größeren Flüsse in den Russischen Sektor des Arktischen Ozeans. Beachte: (1) Daten sind unvollständig, der jährliche Eintrag bezieht sich auf den langzeitlichen Wert; (2) oben: Einzugsgebiet, (2) unten: Einzugsgebiet einschließlich der abflusslosen Gebiete; (3): entsprechend Water Resources (1987); (4): entsprechend Zimichev (2004); (5): Werte für Beckenabfluss in die See nach Magritsky in Alekseevskiy (2007) und Magritskiy et al. (2015).

rivers is a seasonal flood wave, which is observed in the spring (rivers of the European part of Russia and Western Siberia), or in spring–summer (the Ob, Yenisei, Olenek, Lena, and other) period. Occasional rainfall flood waves occur persistently during the warm season. They are characterized by a brief and intensive rise in flow rates and water levels. Rainfall floods of the summer–autumn period are the most important for flood formation for the rivers in the Yana-Kolyma area. In this case, the flood wave has multiple peaks. The flood period ends the earliest (in June and early July) in the rivers located of the northern slope of the East European plain (except for the Pechora) and in small and medium-size rivers in other parts of the Russian Arctic. Seasonal flood waves on the large transit rivers – the Ob, Yenisei, Lena and Kolyma –, as well as in the northernmost rivers regulated by lakes – the Pyasina and Nizhnyaya Taymyra – end in August and September.

The summer low-water season is well expressed for the rivers flowing in the north of European Russia, Western Siberia and the western part of the Laptev Sea basin. Other rivers mostly display the gradual decrease of their discharges, which starts after the completion of spring-summer flood wave and lasts until the beginning of the winter season. The steady winter low-water period starts with the end of autumn (with or without floods), in October to November, when rivers get covered with ice. The winter low-flow characteristics have relatively high values in North European Russia and the Kara Sea rivers in comparison with low values in the catchments of the Laptev, East-Siberian and Chukchi seas, due to severe environmental conditions. A number of medium-size or even large northern rivers (the Anabar, Olenek, Yana, Alazeya, etc.) during winter can become completely frozen up.

In general, the contribution of spring and summer months to the annual total freshwater runoff is very high for all Russian Arctic seas (Fig. 2). This value ranges from 50 to 75 % in the basins of the White, Barents and Kara seas (Tab. 3). During this period, the Laptev Sea (except for the Lena estuary as it has an intrazonal water regime), the East-Siberian and Chukchi seas receive ca. 70-90 % of the annual total. For the majority of rivers, the maximum runoff is observed usually in May (rivers of the White Sea), June (most of the rivers), and July (rivers of the north-eastern part of the Kara Sea basin and

Region	Runoff for individual seasons (% of annual volume)			
	IV–VI	VII–VIII	IX–XI	XII–III
Watershed of western sector of Barents Sea (Kola Peninsula) **	48.6 38.6	17.7 17.1	22.8 23.9	10.8 20.4
Watershed of western sector of White Sea (Kola Peninsula Karelia) **	39.4 36.5	19.8 16.7	24.7 24.5	16.2 22.3
Watershed of eastern sector of White Sea	57.9	12.6	19.3	10.2
Watershed of Eastern sector of Barents Sea	53.9	19.2	19.7	7.2
Watershed of Kara Sea **	42.3 42.2	28.8 26.4	19.9 19.0	9.0 12.4
Watershed of Laptev Sea	42.5	33.7	19.4	4.4
Watershed of East Siberian Sea	40.6	39.4	18.2	1.9
Watershed of Chukchi Sea	45.2	43.3	11.3	0.1

Tab. 3: Relative distribution of river inflow into the Arctic Seas from the territory of Russia for the entire period of hydrometric observations (ALEKSEEVSKIY 2007). **: outlets of rivers under study; top: natural flow; bottom: regulated flow.

Tab. 3: Durchschnittlicher Flusseintrag in die Arktischen Meere aus den Russischen Gebieten im gesamten hydrometrischen Beobachtungszeitraums (ALEKSEEVSKIY 2007). **: Flussmündungen in Beobachtung; oberer Wert: ursprünglicher Fluss; unterer Wert: regulierter Fluss.

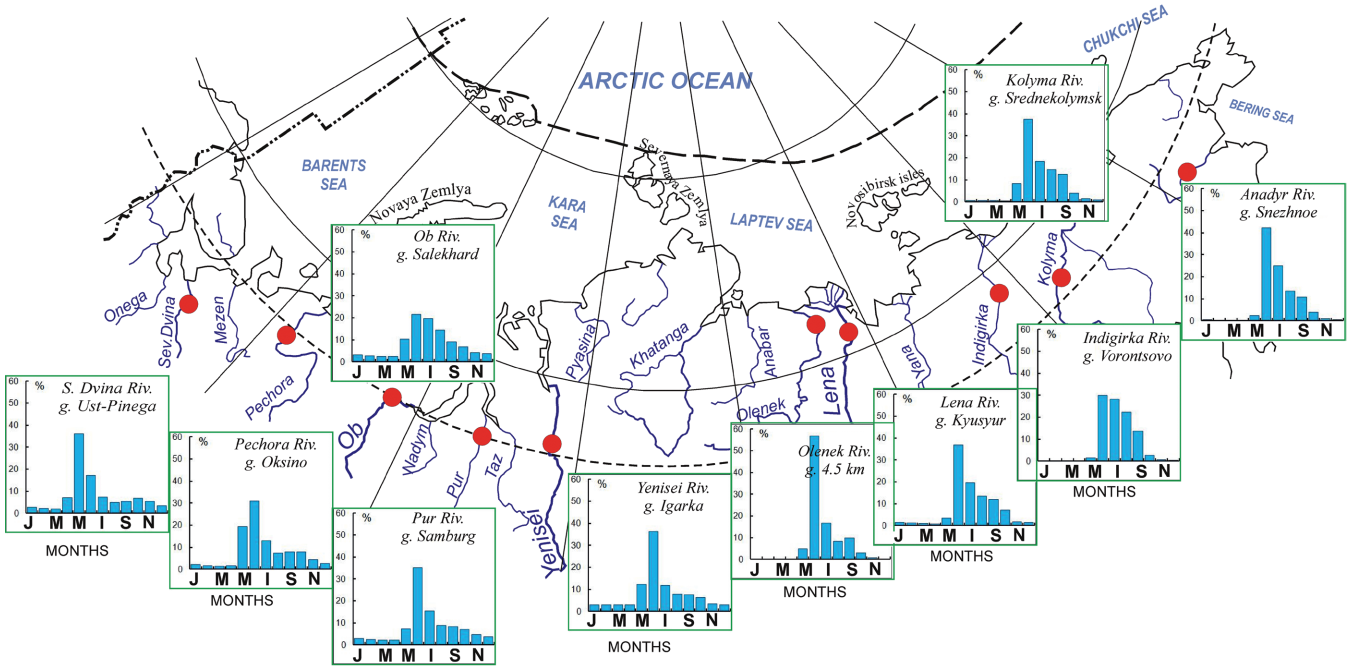

Fig. 2: Intra-annual distribution of the monthly runoff in rivers of the Arctic Ocean basin, expressed as a proportion (%) of its annual value.

Abb. 2: Veränderung des jährlichen Fluss-Transports in den Arktischen Ozean dargestellt als monatlicher Anteil der Jahresmenge in Prozent.

the Alazeya). The river runoff in autumn (months IX–XI) does not exceed 25 %. The share of runoff produced during the steady winter low-water period ranges from 1.5-4 % (rivers of the Yana-Kolyma area) to 10-18 % (rivers of the northern slope of the Russian Plain, the Ob and Yenisei).

NATURAL LONG-TERM CHANGES IN WATER RUNOFF OF THE ARCTIC RIVERS

The annual and seasonal runoff of Arctic rivers is highly variable. This fact mostly is associated with the influence of natural (climatic) factors (ALEKSEEVSKY 2007, ALEKSEEVSKY et al. 2015, SHIKLOMANOV 2008). Long-term fluctuations of the annual runoff are characterized as cyclic processes, distinguished by recurrence of low and high flow multi-year periods of different duration and value. Simultaneous periods (chronological coincidence of periods with equal unit discharges) in runoff fluctuations is inherent to the Onega and Severnaya Dvina, Pur, Taz and Nadyrn rivers, the Yenisei, Khatanga, Anabar and Olenek rivers, the Yana, Indigirka and Kolyma rivers. Phase asynchronism is observed in the Severnaya Dvina and Ob rivers, the Mezen and Yenisei rivers. Synchronism in fluctuations of the annual runoff was found in the Arctic rivers

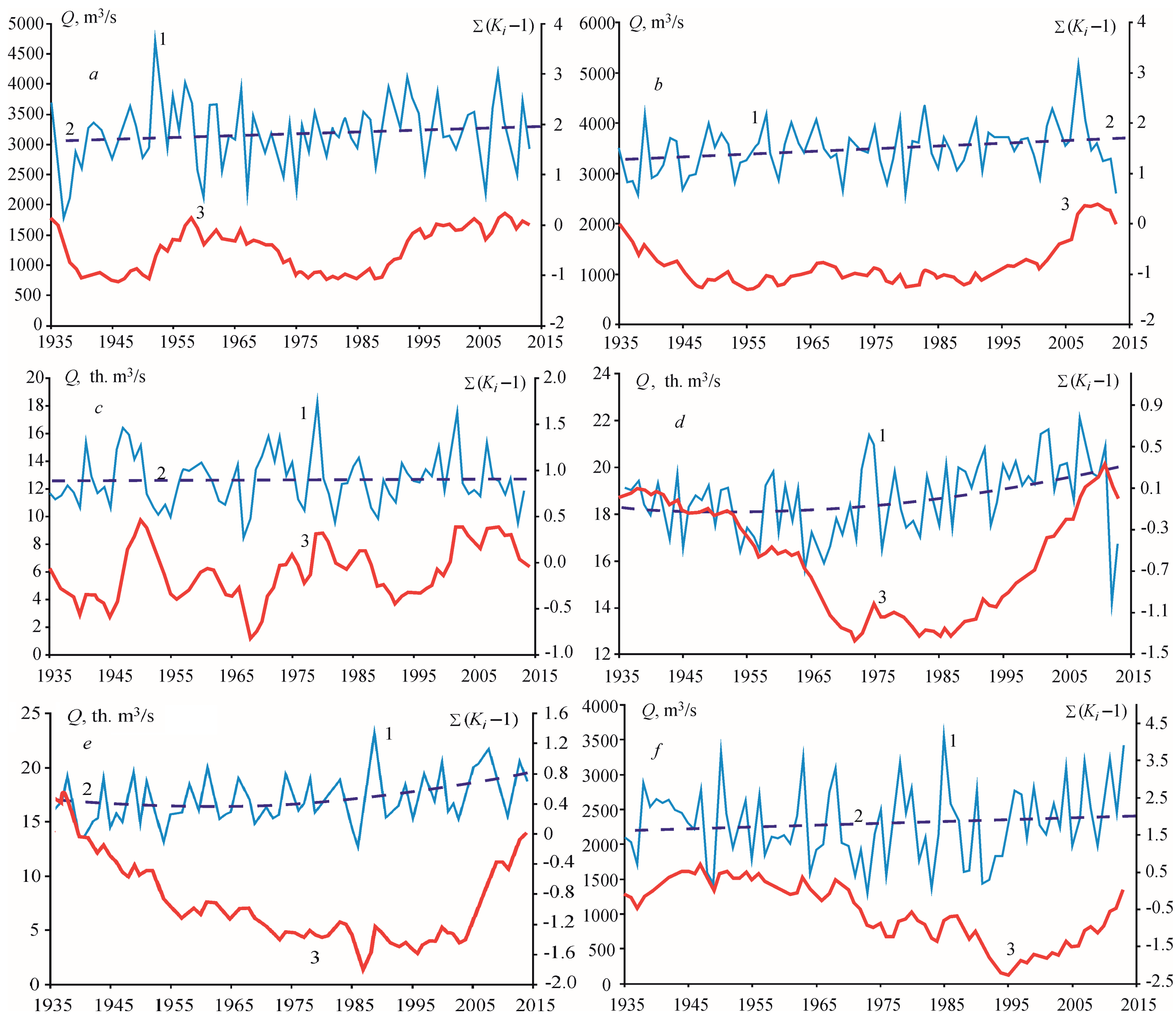

Fig. 3: Changes in the annual runoff of rivers of the Arctic Ocean basin for the period 1935-2013 (data: Magritskiy unpubl.). (a): Severnaya Dvina (Ust-Pinega gauge); (b): Pechora (Ust-Tsilma gauge); (c): Ob (Salekhard gauge); (d:) Yenisei (Igarka gauge); (e): Lena (Kyusyur gauge); (f): Kolyma (Srednekolymsk gauge). Legend: (blue line) 1: average annual water flow (m³/s); (broken line) 2: annual runoff trend; (red line) 3: residual mass curve for the annual flow rates. To approximate the long-term average annual flow rates in the lower Yenisei River, we have selected a polynomial trend, which most clearly reflects the anthropogenic decrease in the annual runoff during the 1950s to 1970s caused by filling of a large number of huge reservoirs.

Abb. 3: Wechsel des jährlichen Abflusses in den Arktischen Ozean für den Zeitraum 1935–2012 (Magritsky, nicht publ.). (a): Severnaya Dvina (Ust-Pinega Pegel). (b): Pechora (Ust-Tsilma Pegel. (c): Ob (Salekhard Pegel). (d): Yenisei (Igarka Pegel). (e): Lena (Kyusyur Pegel). (f): Kolyma (Srednekolymsk Pegel. Legende: Blaue Linie 1: durchschnittlicher Jahresverlauf (m³/s). Gebrochene Linie 2: Langfristige Veränderung des jährlichen Abflusses. Rote Linie 3: Verbleibende Restmenge für den jährlichen Abfluss. Zur Beurteilung der langfristigen Abflussraten im Unterlauf des Yenisei wurde ein Polynom-Trend entwickelt, der sehr deutlich die anthropogen beeinflusste Abnahme des jährlichen Abflusses in der Zeit 1950 bis 1970 beschreibt, verursacht durch das Füllen einer Vielzahl von großen Staudämmen.

of European part of Russia, the northern part of the Ob catchment, the northwest of the Republic of Sakha (Yakutia), and the Yana-Kolyma region.

The primary feature of long-term runoff variation is its trend to increase on the most number of Arctic rivers starting from the second half of the 1980s, and for the rivers of the North-east – from the mid-1990s onwards (Fig. 3). This phenomenon is caused by changing climatic conditions of the runoff origin since the late 1970s, and especially the late 1980s, when a significant rise in the average air temperature in the north of European Russia and Siberia was observed (Fig. 4). Concurrently the other climatic characteristics (the amount and pattern of precipitation, evaporation, snow cover changes etc.) were changing (ROSHYDROMET 2014). An opposite trend – quite stable or even with a decreasing tendency in the average annual flow rates – was observed in the last few years. However, it is seen that the runoff into the Russian Arctic seas since the second half of 1980s has grown and continues to maintain at very large values (Fig. 5).

The majority of rivers situated on the Arctic slope of European Russia display a clear trend of increasing annual runoff depth in the range from 20 to 40 mm, as compared with the period 1936–1975. The runoff depth increased mostly in the rivers of the Kola Peninsula, Karelia and the Onega River (by

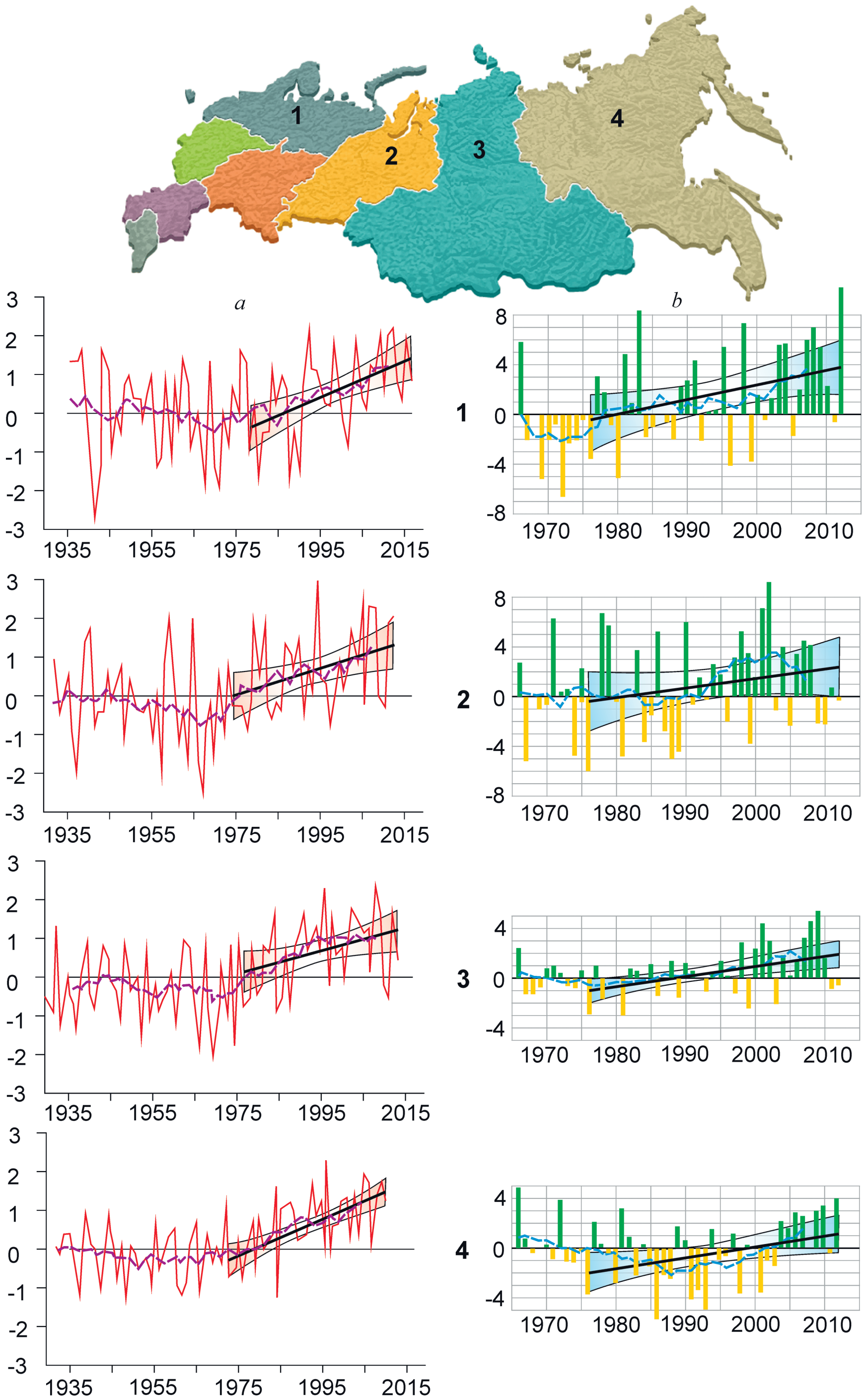

Fig. 4: Spatially averaged annual mean anomalies of the surface air temperature, 1935 – 2012 (a) and precipitation, 1966 – 2012 (b), in Federal Districts of the Russian Federation (ROSHYDROMET 2014). 1: North-West of European Russia; 2: Western Siberia; 3: Central Siberia; 4: Eastern Siberia. Anomalies are calculated as deviations from the mean value for the years 1961–1990. Dashed curves correspond to the 11-year smoothing spline. The linear trend for the period 1976–2012 and its 95 % confidence interval are indicated.

Abb. 4: Regionale jährliche Anomalien der (a) Oberflächentemperatur (1935–2012) und (b) Niederschlag (1966–2012) in den Bundesdistrikten der Russischen Föderation (ROSHYDROMET 2014). 1: Nordwest-Europäisches Russland. 2: Westliches Sibirien. 3: Zentrales Sibirien. 4: Östliches Sibirien. Die Anomalien beschreiben die Abweichung vom Mittelwert der Jahre 1961 bis 1990. Die gebrochene Kurve beschreibt die 11-Jahres Glättungs-Spline. Der lineare Trend für den Zeitraum 1976 bis 2012 ist dargestellt.

12 %), due to the increased flow of both spring floods and other hydrological seasons. A non-typical picture is observed in the Mezen River; its runoff depth has practically remained the same and even slightly decreased, despite the upward trend since 1975 (at a rate of 5.2 mm/10 years). The same situation is seen in the Ob River and rivers of the northern part of the Western Siberia (the Pur, Taz and Nadyrn catchments). If we consider the Mezen River case as a rare exception, such trend in the Ob basin can be explained by the fact that its greater part is located in the southern arid latitudes and hence the runoff losses from evaporation increase (under the influence of air warming), as well as by higher water consumption in China, Kazakhstan and Southern Siberia of Russia.

Further eastward the annual runoff again increases. This trend persists throughout the territory westward of the Kolyma River basin. The increase in runoff is 10-15 mm (~5 %) for the Yenisei and Khatanga rivers, 16 mm (9 %) for the Anabar River. In the Olenek River basin, it reaches a maximum of 20-30 mm, or 18 % of the runoff value recorded prior to 1975. Runoff changes in the Lena, Yana, Indigirka, Alazeya and other rivers are placed within the positive range, 10 to 20 mm (8-11 %). Here, the most significant trends in the annual runoff increase, 9-14 mm/10 years, are shown throughout the period from 1975 to 2013. Starting from the Kolyma River, the “growth wave” again subsides to 8 mm (4.5 %) and goes below 5 mm (and possibly up to the negative values) eastward of the Kolyma River basin.

Long-term changes in the annual runoff of the Arctic rivers are followed by transformation in the intra-annual distribution of water resources (Tab. 4, Fig. 6). In the North-European rivers, except for the Mezen River, and in the Yakutian rivers, except for the Kolyma River, the annual runoff increase was accompanied by increased discharge during almost all seasons. The volume of spring-summer flood increased by 1.5-7.5 %, on average. The seasonal flood runoff was least changed in the Mezen River (0.7 %). A decline in the runoff volume was recorded in the Ob and Yenisei rivers (regulated by the reservoirs) over the entire open water period, in the Kolyma River

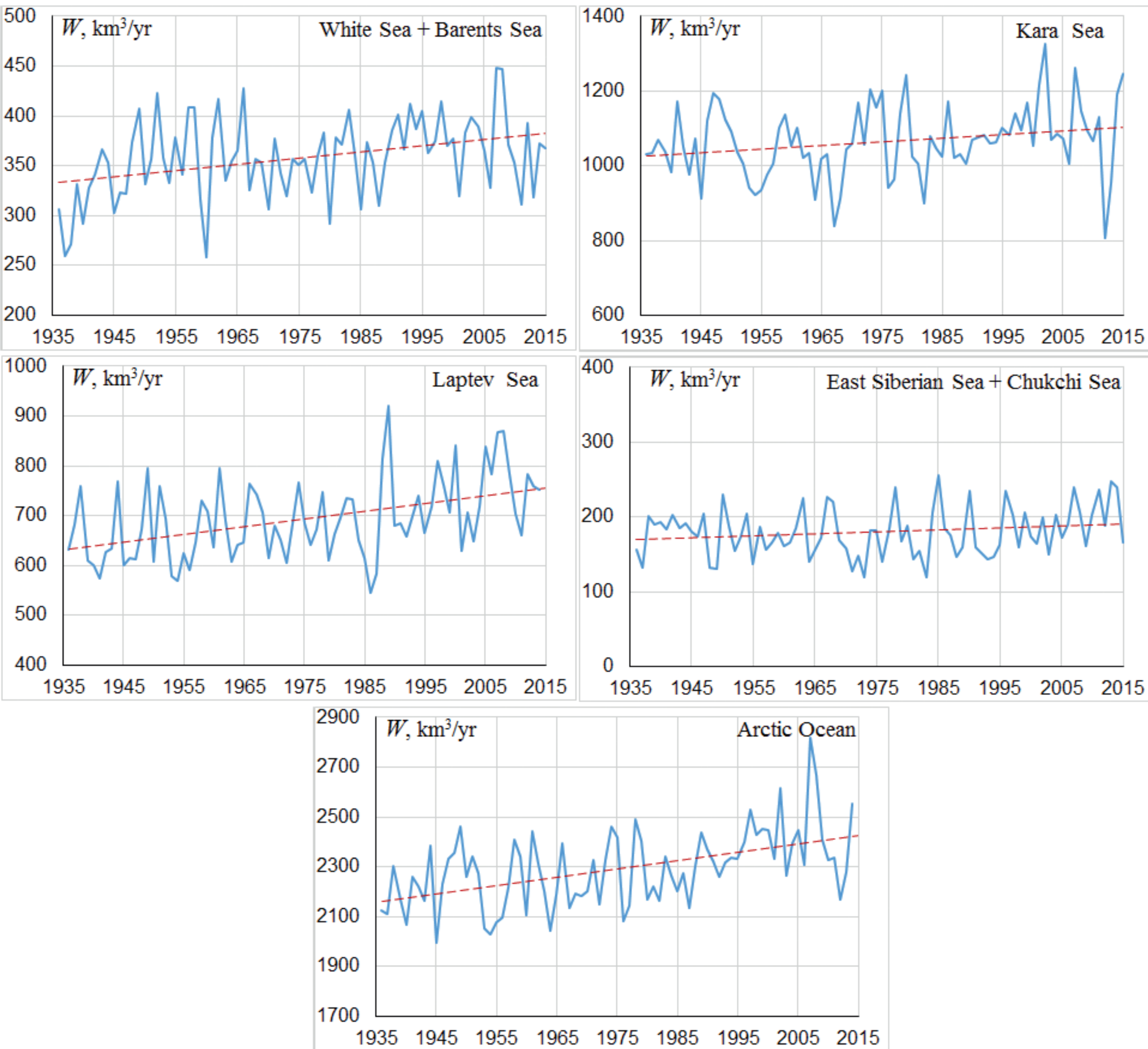

Fig. 5: Long-term changes of river runoff into the Russian Arctic seas, 1936–2014/2015 (Magritsky unpublished). According to the observation data at the hydrological stations covering approximately 80 % of the total river runoff into the Russian Arctic seas and watershed area.

Abb. 5: Langfristige (1936–2014/2015) Änderung der Flussschüttung in die russischen Arktismeere (Magritsky unpubliziert).

– during the flood season only, resulting from the seasonal runoff redistribution by the reservoirs. The magnitude of runoff changes in the summer-autumn period is much greater, as compared with the spring, from 3 % in the Lena River, up to 40-45 % in the Yana and Indigirka rivers. In the latter case, this could be contributed not only by precipitation, but also by the waste of water accumulated in numerous glaciers, snow patches, permafrost and buried ice, under conditions of accelerated warming (Alekseev et al. 2012, Magritsky et al. 2013). The flow of the Mezen River decreased. Of undoubted interest is the dynamics of winter runoff, which is clearly positive in almost all rivers. For the Yana and Indigirka rivers, negative or around zero deviations between the values characterizing winter runoff in 1976 to 2015 and in 1936 to 1975, respectively, are explained by very small winter flow rates in these rivers and low accuracy of the input data. A noticeable increase in the water discharges during the winter low water period was observed in the Onega, Severnaya Dvina, Pechora, Ob, the rivers in the northern part of the Western Siberia and in the western part of the Laptev Sea catchment (15-40 %), particularly, in the Yenisei, Lena and Kolyma – 68 %, 47 % and 174 %, respectively, – a consequence of regulating the seasonal runoff of these rivers and their large tributaries by huge reservoirs.

ANTHROPOGENIC CHANGES IN THE RUNOFF VOLUME AND REGIME OF THE ARCTIC RIVERS

Human-induced changes of the runoff and the hydrological regime of the rivers draining into the Russian Arctic seas are caused by the exploitation of hydropower plants on these rivers and their tributaries, as well as water withdrawal from rivers and associated with them lakes and underground water reservoirs (Avakyan & Sharapov 1977, Chernyaev 2001b, Vuglinsky 1991, Shiklomanov 1989, Shiklomanov 2008, Magritsky 2008).

The degree of water use in the basins of the Russian Arctic is relatively low, which results from poor natural resource use and low population density. Many of the rivers and their

River	Catchment area	Period	Runoff depth (mm)				Changes in the annual runoff depth
			flood	summer-autumn period	winter low-water period	year	
Onega	55 700	1936–1975	148	85	31	265	
		1976–2013	153	100	43	299	34.1
Severnaja Dvina	348 000	1936–1975	169	83	27	280	
		1976–2013	174	90	32	296	16.4
Mezen	56 400	1936–1975	207	119	31	358	
		1976–2013	209	110	34	354	-4.2
catchment between Mezen and Pechora	–	1936–1975	187	91	52	329	
		1976–2013	195	98	62	354	25.1
Pechora	312 000	1936–1975	288	95	57	437	
		1976–2013	302	99	61	459	21.9
Ob	2 430 000	1936–1975	110	27	28	165	
		1976–2013	106	25	33	164	-1.0
Yenisei	2 440 000	1936–1975	148	55	33	235	
		1976–2013	141	51	56	247	12.6
Anabar	78 800	1936–1975	138	36	1	175	
		1976–2013	146	46	0	191	15.7
Olenek	198 000	1936–1975	127	35	2	163	
		1976–2013	147	44	2	192	28.9
Lena	2 430 000	1936–1975	129	71	14	213	
		1976–2013	136	74	20	230	16.9
Yana	216 000	1936–1975	118	17	1	134	
		1976–2013	126	24	1	148	14.0
Indigirka	305 000	1936–1975	136	24	3	161	
		1976–2013	143	35	3	179	17.6
Kolyma	361 000	1936–1975	131	61	6	196	
		1976–2013	121	69	16	205	8.7

Tab. 4: Intra-annual runoff distribution in the lower reaches of the major rivers and in the inter-basin catchments of the Russian Arctic during typical periods (unpublished data).

Tab. 4: Jahreszeitliche Abflussmengen im Unterlauf der größeren Flüsse in Beziehung zu den Einzugsgebieten in der Russischen Arktis (unpublizierte Daten).

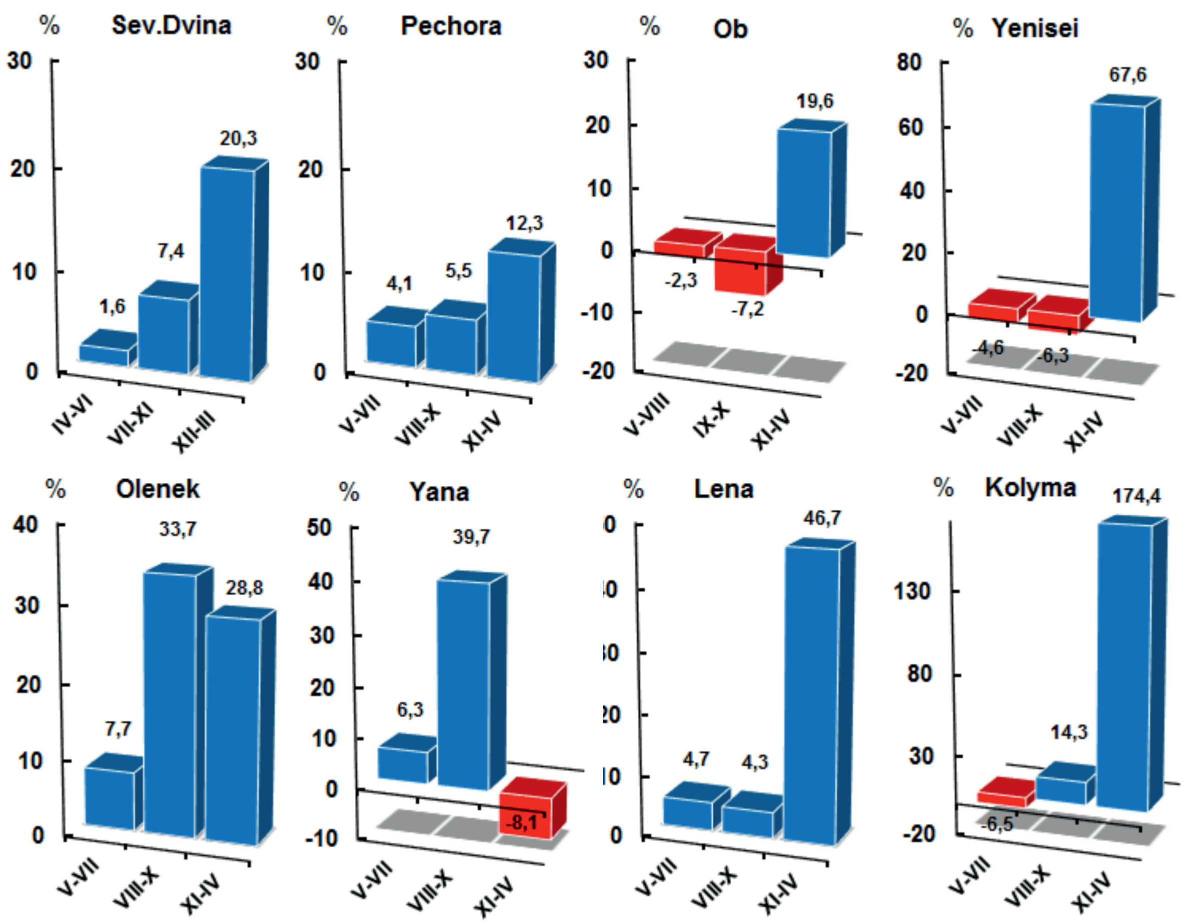

Fig. 6: Changes in the seasonal runoff pattern, 1976–2015 vs. 1936–1975 (authors' original materials). Three hydrological seasons with respective months are indicated on the X-axis. They refer to flood, summer-autumn low water and winter low water periods, but for different rivers within the huge Arctic basin the seasons have different chronological boundaries.

Abb. 6: Vergleich des saisonalen Abflussmusters für den Zeitraum 1976–2015 *versus* 1936–1975. Dargestellt sind die Monate dreier hydrologischer Perioden: – Flut – sommer-herbstliches Niedrigwasser – winterliches Niedrigwasser; für die verschiedenen Flüsse in dem riesigen arktischen Becken haben die Perioden unterschiedliche chronologische Grenzen.

basins are hardly affected by economic activities involving water use. However, in some cases the economic pressure on water resources is high. These are the regulated rivers of the Kola Peninsula and Karelia, the Severnaya Dvina mouth, the Norilsk industrial area, southern parts of the Yenisei and the Ob basin in particular, the Ural region and the regulated Siberian rivers, and mining districts in the Lena River basin, etc.

Water consumption and sewage discharges peaked in the late 1970s and 1980s, which resulted from increased economic needs during the extensive development of the Soviet economy (Tab. 5). However, in many rivers water withdrawal was relatively small or almost lacking. Even in the most economically developed areas – the basins of Severnaya Dvina, the Ob and the Yenisei rivers – withdrawal amounted to 1.2, 15.7 and 5.12 km^3/year (or 1.1 %, 3.9 % and 0.8 % of the long-term average runoff value, respectively). Water withdrawal from the Murmansk Region rivers amounted to 2.3 km^3/year (4.4 %). In certain rivers located in the south of the Ob-Irtysh basin and the Ural economic region, decline in the runoff from economic activities reached threshold values that corresponded to the emerging freshwater deficit. The major water consumers were industry, heat power plants and municipal services. These accounted for 80-90 % of withdrawn waters from the Ob and Yenisei basins, and almost 100 % in the North European Russia and Siberia. Irrigation and water supply to agricultural sector (in the steppe and forest-steppe areas of the Ob, Yenisei and Lena basins) consumed up to 10-20 % of the withdrawn water. Most of water was taken from the river drainage system (80-95 %) and the rest from underground aquifers. The difference between the withdrawal of riverine waters and wastewater discharges forms the anthropogenic reduction of the river flow. It reached peak values in the Ob-Irtysh basin (5.4 km^3/year), due to the arid conditions of water supply, developed agriculture and the inter-basin water runoff distribution between the upper Ob and Irtysh.

In the 1990s, the volume of withdrawn waters decreased. The reduction amounted to 20-35 % for industry and agriculture, on average. This overall situation persisted until the beginning of the 21st century. By 2004 to 2013, the greatest water consumption was characteristic of the Murmansk region rivers (1.8 km^3/year), river basins of the Severnaya Dvina (0.7), Pechora (0.4), Ob (13.8 km^3/year excluding water withdrawal in China and Kazakhstan), Yenisei (3.0 km^3) and Lena (0.3 km^3/year). At the same time, water consumption increased in the north of the Western Siberia basin, due to the developing oil and gas production industry. Currently, many areas and rivers are yet

River basin	1981–1990		2004–2013		2025–2030	
	water withdrawal *	water disposal into the river network	water withdrawal *	water disposal into the river network	water withdrawal *	water disposal into the river network
Murmansk region	(2300)	no data	1794	1739	no data	no data
Onega	33	33	10.4	8.8	17.3	15.1
Severnaja Dvina	1152	1062	697	610	2121	1997
Mezen	4	5	1.0	0.7	2.8	1.7
Pechora	458	433	420	352	745	618
Ob	15927	10291	13762 **	8748 **	16300 **	no data
Pur	No data	No data	97.2	35.9	129	40.4
Taz	No data	No data	1.9	1.2	2.7	0.6
Yenisei	4909	4237	3009	2633	10060	8818
Lena	370	327	298	295	408	320
Yana	No data	No data	6.6	4.3	9.9	6.6
Indigirka	(5)	(2.9)	7.5	4.0	12.5	9.8
Alazeya	No data	No data	0.11	No data	0.11	no data
Kolyma	114	72	56.4	38.8	148.3	86.1

Tab. 5: Volume of water consumption (10^6 m^3/year) in the basins of rivers draining into the Russian Arctic seas (according to data from State Water Cadastre (1982-2014) and Schemes for integrated use and protection of water objects). Note *: from surface and underground sources (damage to runoff - irreversible water losses); **: data on water consumption in the territory of Kazakhstan and PRC were unavailable; in parentheses: rough data.

Tab. 5: Genutzte Wassermenge (10^6 m^3/J.) aus den Einzugsgebieten der in die Russischen Arktischen Schelfmeere mündenden Flüsse. Daten aus State Water Cadastre (1982-2014) und Schemes for Integrated Use and Protection of Water Objects. Beachte *: aus Oberflächen- und Tiefen-Entnahme (Störung im Abfluss oder Verlust); **: keine Angaben aus dem Gebiet Kasachstan und VR China; in Klammern: geschätzte Mengen.

unaffected by water use. The total water withdrawal from the Arctic rivers and associated underground sources amounts to ca. 20.6 km^3/year, which is comparable with the annual runoff of the Nadym River, and is less than the withdrawal within the Volga River basin. By the years 2025 to 2030 withdrawal may increase to 37.2 km^3/year. Industry is the leading water consumer in the Murmansk Region and river basins of the Severnaya Dvina, Yenisei, Nizhnyaya Taymyra, Lena and Anadyr. The share of the heat power plant sector is significant in the Ob, Yenisei, Yana, Indigirka and Kolyma basins. Municipal services are heavy water users in the Severnaya Dvina, Mezen, Pur, Taz, Khatanga, Olenek, Lena and Anadyr basins.

The volume of wastewater discharge into the rivers (14.3 km^3/year) is comparable to that of water withdrawal. Currently, water consumption hubs in the Russian Arctic region are as follows. In the North of European Russia: enterprises and settlements of the Murmansk Region and Karelia, cities of Arkhangelsk and Severodvinsk (with suburbs), Vorkuta and Naryan-Mar; in Siberia: Salekhard and Labytnangi cities, industrial areas – the North Ob oil and gas production and Norilsk, mining enterprises in northeastern Yakutia (Republic of Sakha) and Chukotka Autonomous Region.

The second largest source of anthropogenic impact on the Arctic river runoff volume and its regime are water reservoirs and their regulation influence. Development of the water power potential of the Arctic rivers was started in the late 19th century and HPS (Hydroelectric Power Stations) construction was at its maximum in the second half of the 20th century. Large hydropower systems are now operating on a number of rivers of the Kola Peninsula and Karelia (Fig. 1). Hydropower stations have been constructed on the rivers Paz (a series of 7 HPS including Skugfoss and Melkefoss in Norway), Tuloma (2 HPS), Teriberka (2), Voronya (2), Niva (3), Kovda (3), Kem (4) and Nizhny Vyg (5). They produce 8.4×10^9 kWh electric energy annually. The total area and volume of reservoirs amount to 9,340 km^2 and 68.3 km^3, respectively. There are no important water reservoirs and HPS on the North European rivers; their stream is not regulated. In Siberia and the Far East, 17 large and about 300 medium-capacity hydraulic structures are located within the Arctic catchment, mainly on the Yenisei and Angara rivers. Large, but single reservoirs have been constructed on the Ob, Khantaika, Kureika and Kolyma rivers. The largest reservoirs and hydropower stations are located on the Siberian Arctic rivers (Tab. 6).

The impact of the reservoirs on the flow of the Arctic rivers and the rivers themselves can be twofold. On the one hand, it is the single or non-recurrent impact represented by the withdrawal of the river runoff for filling reservoirs and saturating their bottoms and thus changing the hydrological characteristics of the rivers. On the other hand, it has an impact recurring annually or permanently. This is the inter-annual or intra-annual flow regulation, annual evaporation losses from the surface of the reservoirs and the flooding area, and the reduction of evaporation losses at the downstream, due to reduced floodplain flooding. The maximum one-time losses, almost 50 % of the river resources, were recorded in the Yenisei basin. It could not but affect the long-term fluctuations of the annual river runoff, which reduced gradually in 1960 to 1970s, and particularly in the year of the active filling the Bratsk Reservoir (1964). The Boguchany HPS operates since November 2012. Filling its reservoir led to the reduction of the Yenisei

River	Reservoir	distance from sea (km)	years of filling	Area at normal operation level (km^2)	V_{total} (km^3)	V_{eff} (km)^3	Dam height (m)	Water exchange		
								W_{annual}/V_{total} year^{-1}	$V_{eff}/V_{total.}$ year	V_{eff}/W_{annual} year
Ob	Novosibirskoe	2987	1956–1959	1070	8.80	4.40	28.2	5.88	0.135	0.08
Irtysh	Bukhtarminskoe	3165	1960–1967	5490	49.62	30.81	90.0	0.38	2.33	1.64
	Ust-Kamenogorskoe	3086	1952–1959	37.0	0.66	0.04	65.0	29.8	0.003	0.002
Tom’	Krapivinskoe	–	under construction	670	11.7	9.7	–	2.55	–	0.33
Yenisei	Shushenskoe	3013	1978–1983	621	31.34	15.3	234	1.49	0.43	0.33
	Mainskoe	2992	1984	11.5	0.12	0.07	17.0	388.7	–	0.002
	Krasnoyarskoe	2378	1967–1970	2000	73.29	30.42	128	1.21	0.43	0.34
Angara	Irkutskoe / Lake Baikal	1714	1956–1959	154/1466	2.1/48.1	0.45/46.5	44.0	28.7	0.01	0.007
	Bratsk	1116	1961–1967	5478	169.3	48.2	125	0.54	0.79	0.53
	Ust-Ilimskoe	928	1974–1977	1922	58.93	2.74	102	1.71	–	0.03
	Boguchanskoe	444	2012–2015	2326	58.2	2.31	96	1.88	0.09	0.02
Kureika	Kureiskoe	101	1988	558	9.96	7.3	81.5	1.96	–	0.37
Khantaika	Khantaiskoe	63	1970–1975	2120	23.52	12.81	65.0	0.75	–	0.72
Vilyui	Vilyuiskoe -1,2	1345	1967–1974	2176	35.88	17.83	75.0	0.55	1.14	0.91
	Vilyuiskoe -3	1204	2004–2005	104	1.08	0.19	50	19.9	–	0.01
Kolyma	Kolymskoe	1893	1980–1989	443.4	14.4	6.56	130	0.99	0.90	0.46
	Ust-Srednekanskoe	1677	2013–2018	265	5.4	2.6	66	4.37	–	0.11

Tab. 6: Parameters of the major reservoirs in the Asian part of the catchment area of the Russian Arctic seas.

Tab. 6: Übersicht über die größeren Wasserreservoire im asiatischen Einzugsgebiet der Russischen Arktis.

runoff starting from 2012 and the low water period in the Selenga River basin.

Water evaporation from the reservoir surface is a factor contributing to a persistent reduction of river flow. It has maximum values in the rivers with a series of large reservoirs (the Yenisei and Angara cascades), in the areas with high density of water bodies (Karelia and the Kola Peninsula) and if located in arid areas of the basin (the Ob and Irtysh rivers). It was calculated that about 27.5 km^3 of water can evaporate from the surface of the Arctic artificial water bodies (Magritskiy 2008). Taking into account the losses for additional evaporation (which makes 16-75 % of the total evaporation), we can assume that the evaporation from the reservoir surface does not affect the volume of the Arctic rivers runoff. Long-term flow regulation, as well as the initial filling of reservoirs, can affect the parameters of the river inflow into the sea, but it almost does not change long-term mean values of runoff, modifying its variation only (Fig. 7). Changes can be very significant for the rivers with cascades of reservoirs (Yenisei, Angara) or rivers with huge reservoirs (Irtysh, Vilyui, Kolyma), but the distortion of the stationary by variation, become statistically insignificant for river estuaries. The threshold value of long-term flow regulation is limited by the effective reservoir capacity; as a rule, it usually does not exceed 50-60 % of this volume for the reservoirs in the Arctic rivers.

Specific features of seasonal river flow regulation by reservoirs depend on the economic designation and technical parameters of each structure, as well as on hydrological and climatic factors. Water re-distribution value increases with the increase in the total volume of reservoirs and their regulating capacity, as compared with the flow volume during the flood period and for the whole year (Tab. 6). The most pronounced transformation of the seasonal flow is observed downstream of Krasnoyarsk, Vilyuisk and Kolyma reservoirs. The seasonal flood runoff has dropped by 27-51 % in the downstream of the hydropower stations, mentioned above, as compared to the natural volume. The discharges of rivers in the summer-autumn period have changed very slightly. The part of the winter low-water period has shown the greatest increase (by 28-44 %). The Angara reservoirs which can receive >50 % of the river flow (the Ust-Ilimsk HPS outlet) have insignificantly modified the Angara River regime, due to its high natural regulation by Lake Baikal. These changes can probably become more significant as soon as the Boguchany HPS is put into operation and as a result of the severely low water content in the catchment of the lake. The low regulating function of the Novosibirsk reservoir is due to the low effective capacity, as compared with the flow volume of the upper Ob during the spring flood, especially in high-water years. On the contrary, the Bukhtarminsk HPS completely regulates the Irtysh river runoff.

The regulatory impact of reservoirs on the river flow can be tracked along several hundreds of kilometers. More often, it fades far from the river mouth. However, there are exceptions. The reservoirs in the Kola Peninsula and Karelia almost adjoin

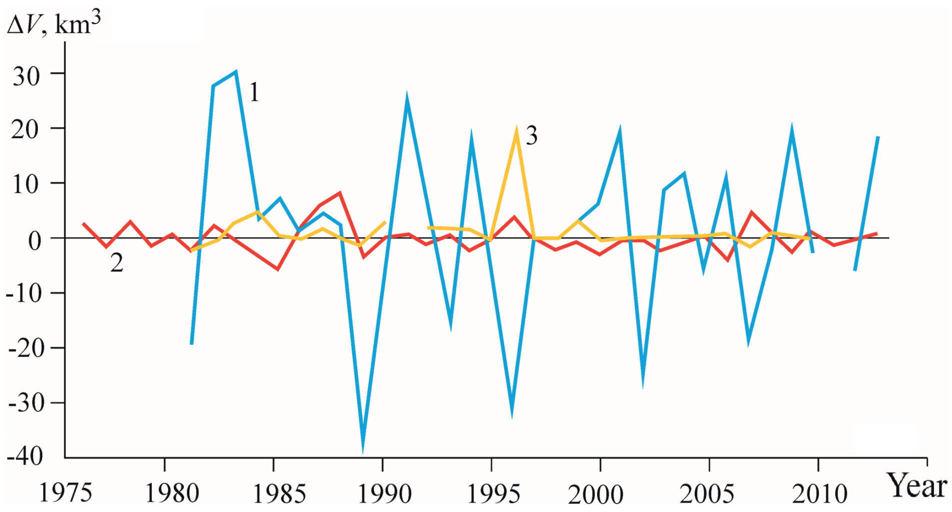

Fig. 7: Intra-annual fluctuations of water reserves in reservoirs of the Yenisei (1), Vilyuy (2) and Ob (3) rivers (Magritsky unpubl.). Water reserves increase reduces annual runoff in the mouth of the river by approximately the same value and, conversely, decrease of water volumes in reservoirs increases the flow of rivers in this year. The gap in the line graph is the missing data.

Abb. 7: Jahreszeitliche Schwankung der Wassermengen in den Reservoiren der Flüsse Yenisei (1, blau), Vilyuy (2, rot) und Ob (3, ocker) (Magritsky unpubl. Daten). Zunahme in den Reservoiren verringert den jährlichen Abfluss an der Mündung um etwa den gleichen Betrag, umgekehrt, steigt mit der Abnahme des Wasservolumens in den Reservoiren in dieser Zeit der Flussabfluss. Lücken im Kurvenverlauf: keine Daten.

the seacoast; therefore, they produce the maximum impact on the current hydrological regime in the mouths of regulated rivers. The along-channel impact transformation in the Siberian rivers (there, reservoirs are located far from the Arctic coast) distorts the initial pattern of anthropogenic changes in the water regime, decreases the reservoir's impact on the flow and under certain conditions brings its characteristics back to natural values (Magritsky 2008, 2015). The regime of the winter low-water period incurs the most far-reaching changes. As a result, the operation of reservoirs has become an important factor in the reduction of discharges on the Kolyma and Yenisei in the spring-summer and the autumn seasons. Starting from 1970, the Yenisei water flow rates at the outlet were 158 % (November through March), 213 % (April), 92 % (May through July) and 86% (August through October) of the respective values for 1936 to 1961 (Alekseevskiy et al. 2015). In the Lower Kolyma, the flow rates after 1992 amounted to 334 % (November through April), 92 % (May to June, July through October) compared with the prior-regulation period 1948 to 1980, before launching the 1st phase of the Kolyma HPS (Fig. 8). Climate changes in the Lena River basin and operation of the Vilyuisk reservoir (which generates additional flow in winter, up to ~700 m^3/s) have significantly improved the hydrological conditions of the winter low-water period in the lower river reaches: the runoff volume of the Lena River has increased by 15.7 km^3/year (November through April, as compared to 1936 to 1975), i.e., by 47 %. The first period of rapid growth started in 1978-1979 and the second in 2004. The contribution of natural and anthropogenic factors to this process was almost equal.

Ultimately, in addition to the increased water runoff in the winter period, due to climatic conditions, seasonal regulation leads to the enormously large winter flow rates in river mouths of the major and regulated rivers of the Asian part of the Russian Arctic catchment basin, and conversely, the distorted flow reduction in other hydrological seasons. This process has both positive and negative aspects. Probably, the activation of certain hydrological processes observed in the Arctic at present could be explained by anthropogenic changes in the seasonal flow pattern, in addition to climate changes in the river catchments. The impact of reservoirs on other stages of the water regime is evident only in rivers with considerable flow regulation. In this case, the annual water content is an important factor of along river transformation of the disrupted water regime.

FORECASTS OF CHANGES IN WATER RESOURCES IN THE RUSSIAN ARCTIC

Obviously, changes in water resources and the water regime of the Arctic rivers are likely to continue in the 21st century, in consequence of global and regional warming (Meleshko et al. 2008, Mokhov et al. 2003, etc.). According to the available scenarios, the annual river runoff in North European Russia and Siberia is expected to increase in the 21st century. The multi-year increase in renewable water resources will spread more intensively north- and northeastward to the northern and northeastern regions of Siberia, as well as in those rivers with a greater proportion of their watersheds located in high latitudes. By the end of the first quarter of the 21st century, the relative increase in runoff will be less than 8-11 % (in comparison with the runoff in 1961 to 1990). In absolute terms, the greatest increase in renewable resources will be characteristic of the lower Ob (up to 20-30), Yenisei (40-50) and Lena (30-60 km^3/year) rivers. By the mid-21st century, the relative increase in water resources of the Severnaya Dvina, Pechora, Ob, Yenisei and Lena rivers can reach 4-14 % or more. For the rivers of the northern slope of the East European Plain, as well as for the Ob River, forecasts of the future runoff are ambiguous. This can be explained by a minor change in precipitation and a substantial increase in evaporation expected in the steppe and forest-steppe parts of the Ob River basin in the 21st century. The greatest relative increase in runoff is predicted to occur by the mid-21st century in the Lena (up to a maximum of 35 %) and Kolyma (43 %) rivers and in absolute terms in the Yenisei and especially in the Lena rivers. In general, a decrease or stability of renewable water resources is expected for certain Arctic rivers.

An increase in the annual runoff is also projected for medium-sized rivers that flow into the Russian Arctic seas. The intensity of this process varies greatly across the territory, depending on the forecast method used and the selected scenario for the future development of the global economy and society. The projected increase in the average runoff will be accompanied by an increase in the maximum flow rates and

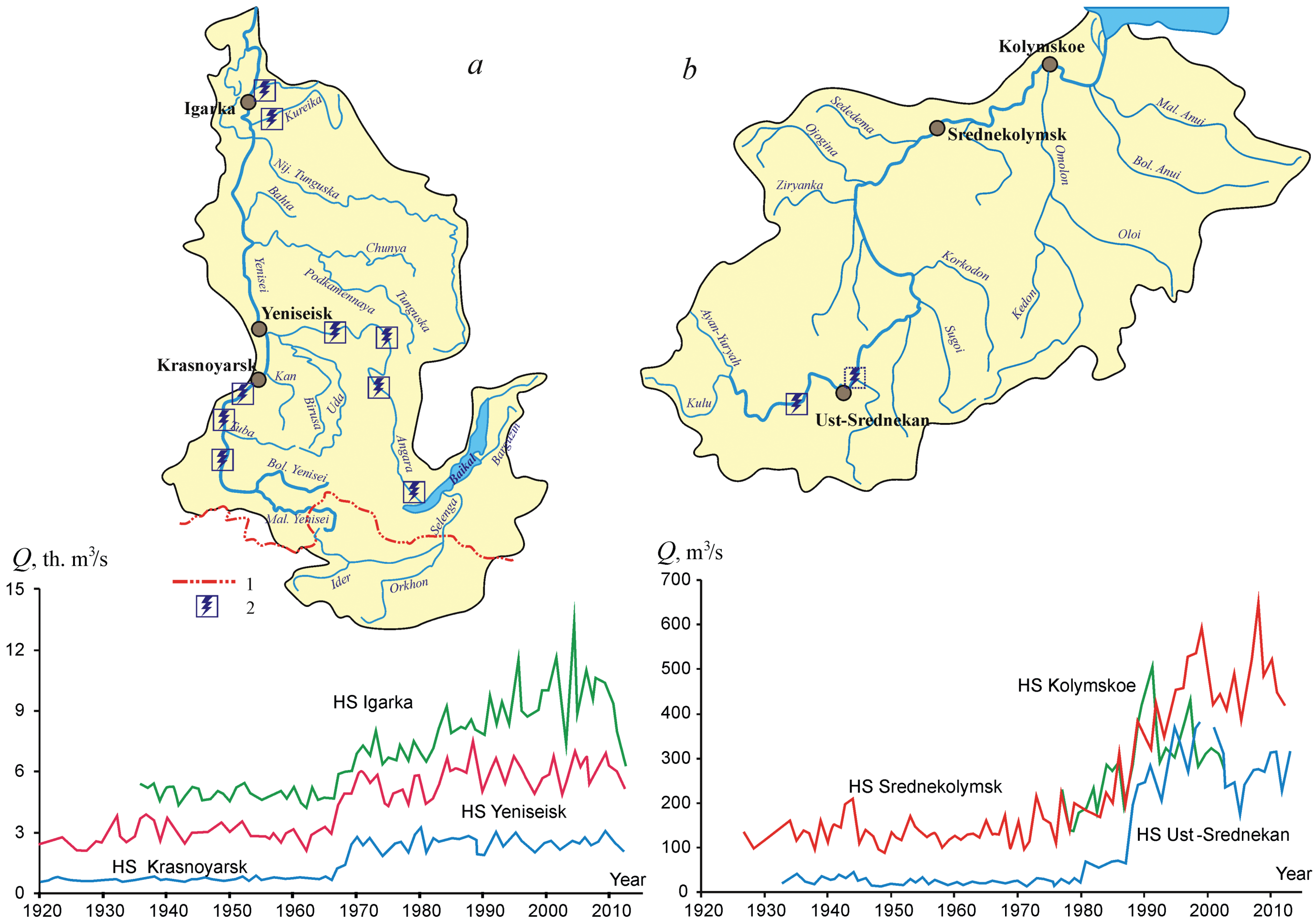

Fig. 8: Increase in the winter runoff caused by the seasonal regulatory role of reservoirs at the Yenisei (a) and Kolyma (b) rivers, since the 1980s (Magritsky unpubl.). 1: state border of the Russian Federation, 2 – hydroelectric power stations. The gap in the line graph is the missing data.

Abb. 8: Zunahme des winterlichen Abflusses verursacht durch die regulierende Rolle der Staudämme am (a) Yenisei und (b) Kolyma (Magritsky unpubl. Daten). 1: Staatsgrenze Russische Föderation, 2: Wasserkraftwerke HS.

water levels, which can create security risks to the population, social and industrial objects. As regards the intra-annual distribution, the winter river runoff will play the more important role. Its change will be the greatest for rivers flowing in the North European Russia and the smallest for rivers east of the Yenisei River. Reduced runoff in the warm period of the year can be expected by the end of the first quarter of the 21st century in the Ob and the Yenisei rivers, while its increase is likely to develop in the Lena River and, to a large extent, in the Pechora and the Severnaya Dvina rivers. By the mid-21st century, an increase in water resources during the warm period is projected for all five rivers discussed above and primarily for the North European rivers and the Lena. However, the pattern of the intra-annual runoff distribution will not undergo fundamental changes, as compared with current conditions (ALEKSEEVSKIY 2013).

The expected increase in the volume of regional domestic water consumption, as a whole, will not lead to critical runoff changes in rivers draining into the seas of the Russian Arctic sector, because they will be compensated by the increase in their water content due to climatic changes. A strained water situation is expected to emerge in the southern areas of Western Siberia (steppes of the Ob-Irtysh basin). Recovering former volumes of industrial, agricultural and domestic water consumption, as well as increased water withdrawal (planned and already partway realized) in China and Kazakhstan can eventually lead to increasing of the water storage capacities (ALEKSEEVSKIY 2013).

CONCLUSION

The annual runoff of rivers from the territory of Russia into the Arctic seas is approximately equal to 2,922 km^3 (SHIKLOMANOV 2008), or 55.6 % of the total inflow of river waters into the Arctic Ocean, including the river runoff of Hudson Bay and Hudson Strait (SHIKLOMANOV & SHIKLOMANOV, 2003). Such a huge fresh water runoff and its long-term variability can not only form a fresh water layer 22 cm thick in the seas of the Arctic sector of Russia, but also, together with the sediments, dissolved substances and heat transported by the rivers, have a significant impact on the marine hydrological processes and, probably, the regional climate (SEMILETOV et al. 1998), on the hydro-meteorological conditions and ecosystems of river channels, valleys and estuaries, the processes of reformation of river and sea shores, river channels and estuaries, etc.

The distribution of river runoff along the length of the Arctic coast of Russia is characterized by high non-uniformity. Almost the whole inflow of river waters (~84 %) is provided by the three largest and 16 large Arctic rivers of Russia. The rest is removed by 1,500 medium and small rivers. Most of river waters (~48 %) flow into the Kara Sea. The estimates are refined due not only to the new data (up to 2014–2015), but also to the correct prolongation of long-term rows with the water consumption measured at river gauging sections and the calculation of runoff at the heads and at the marine edge of river deltas. For some rivers, the difference between the new and old estimates turned out to be significant, for example, this value is 12.2 % higher for the Pechora River (Shiklomanov 2008) and 11.8 % higher for the Yana River. In addition, the list of the considered rivers has expanded.

The uneven distribution of river runoff along the length of the Arctic coast is supplemented by its uneven distribution throughout the year. The patterns of intra-annual fluctuations in the water content and the nature of the water regime of the rivers flowing into the Arctic seas have been relatively well known to domestic and foreign experts for a long time. The new data allowed the authors of the article to refine, to a certain degree, the values of seasonal runoff, to detail the features of their spatial variability.

The main results of the study reveal the causes, features and patterns of long-term fluctuations in the annual and seasonal runoff of large and medium-sized Arctic rivers (within the Arctic zone of Russia) related to the current large-scale changes in the climate and water management in river catchment areas.

Analyzing of the inter-annual component, cyclicity and trends in the long-term runoff fluctuations, since the 1920s to1930s, a number of important and interesting conclusions has been obtained. The average runoff of most major Arctic rivers has increased by 5-10 %, compared to the runoff for the period from 1936 to 1975. It mainly took place since the second half of the 1980s and due to climatic reasons. The rivers of the northeastern sector showed a marked increase in the middle and the second half of the 1990s. The annual runoff increased most of all for the rivers of the Kola Peninsula and Karelia, the Onega River (up to 11-13 %) and the Republic of Yakutia (up to 8-18 %). Moreover, the runoff continued to increase throughout the current period, as evidenced by some positive and often significant linear trends. The total decrease or "stable behavior" of the runoff for the same period was found in the Mezen River and the rivers of the Ob North and the Far North-East. The features of spatial variability of all these trends have been demonstrated on the designed map.

In the last few years, the observation materials at hydrologic gauges indicate the prevalence of the opposite trend – the stabilization or even a decrease in the annual runoff of water of the considered Arctic rivers.

The inter-annual variability of annual runoff value is comparatively low (the value Cv does not exceed 0.15 for the largest rivers, and it is less than 0.25-0.30 for large rivers), whereas the in-row connectivity coefficient is, on the contrary, high (up to 0.31-0.38) and statistically significant. This is an objective consequence of the large sizes and regulating capacity of catchment areas of rivers, as well as of the high value of water runoff.

The cyclic and directed changes in the annual runoff of the Arctic rivers have not led to the statistically significant disturbances of stationarity of the rows with rare exception yet. The Onega River and the Severnaya Dvina River showed disturbances in stationarity in terms of dispersion, and the Yenisei River – on average.

The increase in the annual runoff on most rivers was provided by an increase in the water content of various hydrological seasons. The amount of spring–summer flood increased on average by 1.5-7 %. The Mezen River has the lowest value (0.7 %). The rivers Ob and Yenisei, regulated by reservoirs, showed a decrease in the runoff over the entire free channel period, the Kolyma River – only during the high-water season. Especially pronounced was the positive dynamics for the runoff of the winter low-water period, to the greatest extent in the mouths of the regulated rivers Ob (by 20 %), Yenisei (68 %) and Kolyma (174 %), and also Lena (47 %) that has a large regulated tributary (Vilyui River). The similar situation is on the regulated rivers of the Kola Peninsula and Karelia. The results of the study show that it is the inter-annual and seasonal regulation of runoff performed by large reservoirs and their filling that is the main factor of anthropogenic disturbances in the amount of runoff of the Arctic rivers into the seas and their water regime. It can be traced for hundreds of kilometers along the channels of the regulated Siberian rivers. The annual evaporation of water from reservoirs, especially the additional losses for evaporation from valley reservoirs, does not have any impact on the water resources of the Arctic rivers. Up to ~27.5 km^3 of water per year can be evaporated from the reservoirs in the catchment areas of the Arctic rivers (Magritskiy 2008). Little is also affected by inter-annual regulation, with the exception of the rivers of the Kola Peninsula and Karelia.

The paper also assesses the role of full and irretrievable water consumption in the catchment areas of all the Arctic rivers – in the past, present and in the near future, its territorial and industry structure. Its impact on the inflow of river waters into the Arctic seas is not statistically significant, but has signs of a crisis situation in some areas of the Arctic catchment area, for example, in the south and in the Ural sector of the Ob-Irtysh basin, in the Norilsk and Murmansk Arctic sectors. Total of about 20.6 km^3 per year is removed from the Arctic rivers and the related underground water sources. By the years of 2025 to 2030, this value may increase to 37.2 km^3 per year. For a lot of river basins, the water consumption is almost zero.

The increase in the water resources usage of the Arctic rivers in the 21st century will likely take place due to global and regional climate warming (Alekseevskiy 2007, Arnell 2005, Aror & Boer 2001, Gusev et al. 2016, Georgievsky et al. 1996, Evstigneev & Akimenko 2005, Meleshko et al. 2008, Mokhov et al. 2003, Shiklomanov 2008). By the middle of the 21st century the relative increase in the water resources of the Ob, the Yenisei and the Lena is likely to range from 4-14 % or more. But for the Ob, the forecasts are ambiguous. This is due to the expected slight change in precipitation and a significant increase in evaporation in the steppe and forest-steppe parts of its basin. The greatest relative increase in runoff is predicted to be by the middle of the 21st century for the Lena (up to 35 %) and the Kolyma (up to 43 %), or for the Yenisei and especially the Lena in absolute terms. As for the intra-annual distribution, the role of winter river runoff will increase.

ACKNOWLEDGMENTS

This study was supported by Russian Science Foundation grant No. 14-37-00038 (creation of databases, study of the impact of economic activity) and Russian Foundation for Basic Research 18-05-60021 (statistical analysis and analysis of climate induced changes or river runoff).

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