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Anthropogenic Impact on the Runoff of Russian Rivers Emptying into the Arctic Ocean

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Abstract—The effect of water consumption and reservoirs on the regime and water resources of Russian rivers emptying into the Arctic Ocean is discussed. The impact of reservoirs on the annual and seasonal runoff of regulated rivers is estimated. The transformation of this impact along the rivers down to their outlet sections is analyzed. Possible variants of the development of water management measures in Arctic river basins in the first quarter of the 21st century are considered.

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INTRODUCTION

River water runoff is regarded as the most available resource that renews every year. This property of river water makes it most significant for practice as compared with water resources that renew more slowly or groundwater that renew annually. The hydropower potential of rivers is another factor of importance for humans. The simultaneous development of water and hydropower resources of rivers and the withdrawal of lake and subsurface waters that feed rivers constitute the maximum anthropogenic impact on river runoff and regime.

The resources of rivers emptying into the Azov, Caspian, and Baltic seas are best developed in Russia. The anthropogenic decline in the annual runoff of the Volga, Don, Kuban, Ural, and Terek (with the Sulak) in 1986–1990 amounted to 10, 28, 46, 31, and 30%, respectively [26]. The operation of reservoirs had a considerable effect on the water regime of the Svir, Narva, Ural, Volga, Sulak, Don, and Kuban rivers.

The effect of economic activity on the basins of rivers in North European and Asian parts of Russia is much weaker. This activity has almost no effect on many water bodies in the region, while in developed rivers, this effect is often shaded by the natural variations in the hydrological characteristics. In some cases, however, as for example, in regulated rivers of Siberia and Far East, the anthropogenic impact extends over large distances and reaches their mouths.

The materials available from the literature are not enough to identify the features and assess the extent of such impact. Until recently, the anthropogenic changes in the water regime and water resources were studied inadequately because of the poor development of northern territories, the small number of level gauges and the unfavorable conditions for hydrometric works.

The priority of this type of studies is now undeniable. Their significance is due to the lack of quantitative estimates of anthropogenic changes in the runoff of many northern rivers, the need to ensure the safety of production and the life of population under the conditions of changing nature development, the importance of studying the hydrological consequences of global climate warming, etc.

Because of the size of the Russian part of the Arctic Ocean drainage basin, the number of rivers, and the diversity of forms of anthropogenic impact on runoff, all issues that appear because of the economic activity cannot be discussed in a single paper. Therefore, the scope of this study was limited to

the assessment of the extent of water consumption in the watersheds of Arctic rivers, its long-term variations, and the assessment of its impact on the volume of water resources of these rivers;

the assessment of the number of regulated Russian rivers emptying into the Arctic Ocean and the boundaries of periods with the conventionally natural and regulated runoff;

the quantitative assessment of the effect of reservoirs on the annual runoff and water regime of rivers, the examination of its longitudinal transformation downstream of reservoir (down to the mouth reaches of regulated rivers);

the consideration of possible changes in the anthropogenic load in the future.

Other types of economic activity ant their hydrological effect were not considered because of the lack of reliable data. However, their impact on the runoff and water regime of some rivers is undeniable.

The source materials for this study included data collected during long-term observations at hydrologic gauges of Roshydromet (39 gauges in total), converted into the electronic form, processed, and analyzed by the author of this study. Additionally, data from reference publications of Soyuzvodproekt and State Water Cadaster, information from official sites of participants of water management complex in the areas under study, and some significant results of previous studies were used. The most important among the latter are [1–7, 9, 15, 18, 22–26, 28, 29, 31], etc.

BACKGROUND DATA ON THE REGION AND ITS RIVERS

The runoff of Russian rivers emptying into the Arctic Ocean forms within the territory of the Kola Peninsula and Karelia; the northern part of East European Plain; the Polar Urals; Western, Middle, and North-Eastern Siberia; Eastern Kazakhstan; China and Mongolia; Altai–Sayany highlands; Cisbaikalia and Transbaikalia; the northern slopes of Chukotka and Arctic islands.

The area of the drainage basins of the Barentz, White, Kara, Laptev, East-Siberian, and Chukcha seas totals 13.286 million km^2. The share of the Russian Federation in this area is 12.064 km^2 (90.8%), which accounts for 70.7% of the total territory of the country. The major portion of the drainage basin of the Russian part of the Arctic Ocean belongs to basins the Kara and Laptev seas, in which the basins of the largest rivers in the country, i.e., the Ob, Yenisei, and Lena are predominant. The drainage basins of the Chukcha Sea and the western part of the Barentz Sea are much less.

The area under study (within the RF territory) contains >1629 small, medium, and large rivers [13]. A small portion of these empties directly into Arctic seas. These can be conventionally divided into small (with the drainage area of < 2 thousands km^2), medium (2–50 thousands), large (50–200 thousands), very large (200–1000 thousands), and largest (> 1 million km^2) rivers.

The largest rivers in the region (and the country) are the Ob, Yenisei, and Lena. The very large are seven rivers: the Northern Dvina, Pechora, Khatanga, Olenek, Yana, Indigirka, and Kolyma; the large are nine rivers: the Onega, Mezen, Nadym, Pur, Taz, Pyasina, Lower Taimyra, Anabar, and Alazeya. About 110 rivers are medium.

According to V.I. babkin [20], the normal annual river runoff from the Russian part of the Arctic Ocean drainage basin is ~2900 km^3 (67% of the total runoff of Russian rivers) or 55% [30] of total river runoff into this ocean and Hudson Bay. According to the author's estimates, about 54.3% of this amount is accounted for by the runoff of the Yenisei (630), Lena (540), and Ob (408 km^3/year); 29.2% is accounted for by 16 large rivers; and 16.4%, by ~1500 medium and small rivers.

Intense economic activity is typical of the Kola Peninsula and Karelia, the basins of the Northern Dvina and Pechora, the southern parts of the Ob, Yenisei, and Lena basins, and the mining areas in the Pur and Kolyma rivers.

WATER CONSUMPTION

Water intake from water sources in river basins and the discharge of wastewater and return waters have an appreciable effect on the volume, regime, and quality of water resources. The structure of economic activity and the extent and regime of the use of water resources depend on the features of water bodies, the physico-geographic conditions, and the social–economic characteristics of river basins. The dynamics of water consumption and water disposal correspond to long-term changes in the scale and structure of the economic activity in the country.

Water consumption and disposal in RSFSR attained their maximum values in the late 1970s and in the 1980s. Until the mid-1970s, water consumption volume was found to rapidly grow because of the steadily increasing economic demand for water and the extensive economic development. From 1975 to 1991, the total normal annual water consumption volume in RSFSR amounted to 90–120, and the volume and the volumes of water disposal was 60–80 km^3 [2].

The majority of this volume was consumed in the river basins of the southern Russian seas and the Baltic Sea, where the main economic potential of the country is concentrated and the population density is very high. Water consumption in the basins of the western part of the White Sea drainage basin, and the basins of the Pechora, Lena, Indigirka, and Kolyma was low (0.13 km^3/year in 1990), and in many northern rivers it was close to zero (Table 1). Only 1.1, 17.7, and 5.1 km^3 of water per year were withdrawn in this time even from the most economically developed rivers—the Northern Dvina, Ob, and Yenisei (1, 4.3, and 0.8% of their normal runoff), respectively; the volume withdrawn from the rivers of Murmansk province was 2.3 km^3/year (1990) or 4.4%. Since these volumes are comparable with the errors in the calculation of normal annual river runoff, it can be assumed that no statistically significant changes took place in the water resources of northern rivers because of the industrial, agricultural, and municipal water consumption. However, in some regions, such as Ob–Irtysh basin, the economic load on water resources reached extreme values and freshwater was found to be deficient.

Unlike the rivers of southern Russian seas, the major portion of water taken from the basins of the rivers under consideration is returned into the water bodies. The difference between these values characterizes the so-called consumptive use, which results in a systematic drop in river runoff. In the 1980s, the largest consumptive water use was recorded in the Ob–Irtysh basin (7.5 km^3/year) because of the arid conditions of water supply, the developed agriculture, and the interbasin water transfer in the Ob and Irtysh basins (Fig. 1).

Table 1. Relationship between (the top number) the volume of water withdrawal and (the bottom number) water disposal (the difference between them is given in parentheses), km^3/year, for Russian rivers in the Arctic basin [12]

River	Runoff in the mouth, km^3/year	Years									
		1981–1985		1986–1990		1992–1995		1996–2000		2001–2004	
Onega	16.2	$\frac{0.038}{0.030}$	(0.008)	$\frac{0.043}{0.035}$	(0.007)	$\frac{0.032}{0.024}$	(0.008)	$\frac{0.025}{0.018}$	(0.007)	$\frac{0.018}{0.013}$	(0.005)
Northern Dvina	108	$\frac{1.166}{1.050}$	(0.115)	$\frac{1.201}{1.074}$	(0.127)	$\frac{1.119}{0.989}$	(0.129)	$\frac{0.909}{0.791}$	(0.118)	$\frac{0.857}{0.751}$	(0.106)
Mezen	27.4	$\frac{0.005}{0.004}$	(0.001)	$\frac{0.006}{0.005}$	(0.001)	$\frac{0.005}{0.003}$	(0.002)	$\frac{0.003}{0.002}$	(0.001)	$\frac{0.002}{0.001}$	(0.001)
Pechora	130	$\frac{0.484}{0.375}$	(0.109)	$\frac{0.596}{0.491}$	(0.106)	$\frac{0.566}{0.476}$	(0.091)	$\frac{0.522}{0.438}$	(0.084)	$\frac{0.458}{0.375}$	(0.084)
Ob*	408	$\frac{17.818}{10.518}$	(7.300)	$\frac{17.675}{10.063}$	(7.612)	$\frac{9.843}{7.142}$	(2.701)	$\frac{9.324}{7.265}$	(2.059)	$\frac{9.267}{7.314}$	(1.953)
Yenisei	630	$\frac{5.034}{4.221}$	(0.813)	$\frac{5.204}{4.253}$	(0.951)	$\frac{4.403}{3.457}$	(0.946)	$\frac{3.613}{2.828}$	(0.785)	$\frac{3.260}{2.711}$	(0.549)
Lena	540	$\frac{0.447}{0.360}$	(0.086)	$\frac{0.422}{0.294}$	(0.128)	$\frac{0.316}{0.212}$	(0.105)	$\frac{0.317}{0.221}$	(0.095)	$\frac{0.319}{0.224}$	(0.095)
Kolyma	121	$\frac{0.138}{0.108}$	(0.030)	$\frac{0.108}{0.036}$	(0.071)	$\frac{0.106}{0.062}$	(0.043)	$\frac{0.082}{0.070}$	(0.012)	$\frac{0.066}{0.052}$	(0.014)

* Until 1992, data on water use for USSR territory; after 1992, data on RF.

The period of relatively stable anthropogenic impact on water resources of the country, which was due to the slower economic growth and the introduction of water-saving technologies, was replaced by a period of economic crisis, leading to a considerable drop in the volumes of economic water use. In 1995, these volumes decreased in the country by 20% as compared with 1989 [2]. In 1996, the volumes of water withdrawal and disposal in Russia amounted to 92.3 and 61.0 and in 2000, 85.9 and 57.3 km^3, respectively.

The decrease in the water withdrawal in the river basins of Arctic seas was 20–40% (Table 1). The least decrease was recorded in Pechora basin (15%). In the Russian part of the Ob Basin, water consumption dropped by 23% as compared with 1983–1986. Similar drops were found to take place in water disposal volumes in all river basins except the Kolyma. The result of this was a decrease in consumptive water losses by ~25–30%.

Since the late 1990s, the effect of economic activity on the water resources in the rivers of the region became relatively stable. The volume of water consumption in the Lena basin somewhat increased as compared with the mid-1990s. However, they still remain near zero in some northern rivers. For example, in the Indigirka basin, water intake in 1997 was as small as 0.008 [7], and the volume of wastewater discharge into water bodies was 0.004 km^3.

THE HYDROPOWER DEVELOPMENT OF RIVERS AND RUNOFF REGULATION

The hydropower development of Russian rivers emptying into the drainage basin of the Arctic Ocean started in the late 19th century, though it reached a significant level only in the 1950s–1970s. By the 21st century, large hydraulic structures were constructed on rivers of the Kola Peninsula and Karelia and in the basins of the Ob, Yenisei, Lena, and Kolyma. Long reaches of river channels were transformed into chains of reservoirs. This caused significant changes in the runoff of regulated rivers. In some cases, such changes extend down to river mouths and affect the hydrological conditions of the coastal zone.

Background Data

Water resources, contained in numerous rivers, lakes, and swamps, play a large role among the natural resources of the Kola Peninsula and Karelia. The specific hydrography of the region favored the construction of regulating reservoirs on lakes. Now almost all large lakes here are dammed and transformed into reservoirs of the lake or mixed type.

The mass construction of reservoirs and hydropower stations was carried out here in the 1950s–1970s. Before World War II, only Nizhnetulomskaya HPP was operated on the Tuloma River; Niva HPP, on the Niva

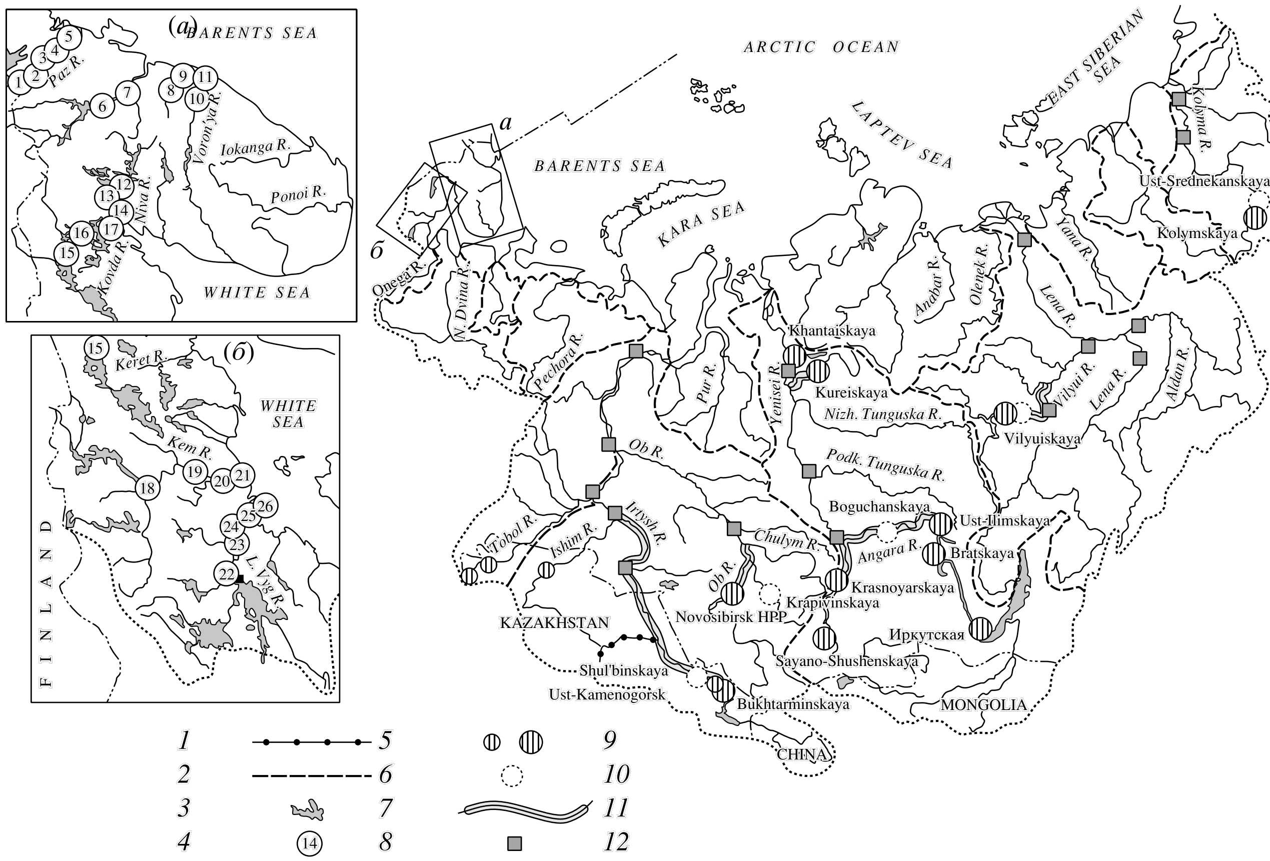

Fig. 1. Scheme of water management development of rivers flowing into the seas of the Arctic Ocean. (a) Kola Peninsula, (b) Karelia. Borders: (*1*) state, (*2*) Arctic Ocean drainage basin, (*3*) large-river drainage basins; (*4*) rivers; (*5*) "Irtysh–Karaganda" channel; (*6*) "Siberia–Aral" channel project; (*7*) water bodies; (*8*) HPPs of Kola Peninsula and Karelia (according to the numbering in Table 1); (*9*) Siberian HPPs; (*10*) HPPs under construction; (*11*) lower pools of Siberian reservoirs; (*12*) hydrological gauges.

River; and Nadvoitskaya Dam, on Vygozero Lake. By the end of the 20th century, hydropower stations were constructed on the Paz River (a chain of seven HPP, including Skugfoss and Melkefoss in Norway), the Tuloma R. (2 HPPs), the Teriberka R. (2), the Voron'a R. (2), the Niva R. (3), the Kovda R. (3), the Kem R. (4), and the Lower Vyg R. (5) (Table 2, Figs. 1a, 1b).

The runoff regulation of the Paz, Tuloma, Teriberka, Voron'ya, and Niva started in 1950, 1937, 1984, 1970, and 1934, respectively. The development of the hydropower resources of the Kovda River took place in the 1950s–1960s (since 1955). Three power stations and five reservoirs are in operation on this river. The hydropower development of the Kem River basin started in 1966–1977 by the commissioning of the Putkinskaya HPP. Prior to that, the Kem runoff was regulated only by the cutaway Yushkozerskoe Reservoir constructed in 1955 in a basin of Kuito Lake [15]. Nowadays, a chain consisting of the Yushkozerskii (1980), Krivoporozhskii (1991), Poduzhemskii (1971), and Putkinskii (1967) hydropower stations is in operation on this river. The development of the water resources of the Lower Vyg R. started as long ago as the 1930s during the construction of the White Sea–Baltic Sea Channel and gradually changed its type. By the character of the effect on the water regime of the river, three periods can be identified: the period of unregulated runoff (before 1931, inclusive), the period of partially regulated runoff for navigation (1932–1952), and the period of regulated runoff (since 1953). Now, three lake-type reservoirs (Segozero (1957), Vygozero (1932–1933), Ondozero (1955)), four valley-type reservoirs, and five hydropower stations (all in all, ~50 hydraulic structures) are in operation on the Lower Vyg River.

The scheme of the power-oriented development of the lake–river systems in the Kola Peninsula and Karelia is such that one or several dammed lakes regulate the runoff in an entire chain of HPPs. Lake Inari plays such role for the HPPs on the Paz River, Verkhnetulomskoe Reservoir serves for the Tuloma River, Lovozero Lake, serves for the Voron'ya River, Lake Imandra and Pirengskoe Reservoir serve for the Niva River, the Kumskoe Reservoir (Topozero and Pyaozero lakes) serves for the Kovda River, and Vygozero, Segozero, and Ondozero lakes serve for the Lower Vyg River. The downstream hydraulic structures form channel or valley near-dam reservoirs that effect weekly, diurnal, or (rarely) seasonal regulation of water runoff.

Table 2. Basic data on the hydropower facilities in the Kola Peninsula and Karelia within the White Sea's basin according to [1, 6, 8, 15, 35] (here and in Tables 3 and 4, dash means no data available; V_{tot} and V_{eff} are the total and effective capacity, respectively)

River	HPP	No.	Distance from the sea, km	Com-mission-ing data	Reservoir	Character of regulation	Area at normal operation level, km^2	V_{tot}, km^3	V_{eff}, km^3
Paz	Kaitakoski	1	130	1959	Kaitakoski (Lake Inariyarvi)	Long-term	1100	4.955	2.455
	Yaniskoski	2	121	1950	Yaniskoski	Daily	5.0	0.030	0.004
	Rayakoski	3	110	1955	Rayakoski	The same	8.0	0.051	0.008
	Khevakoski	4	96	1970	Khevakoski	The same	16.0	0.082	0.006
	Borisoglebskaya	5	4	1963	Borisoglebskoe	Weakly, Daily	56.0	0.330	0.027
Tuloma	Verkhnetulomskaya	6	74	1963	Verkhnetulom-skoe (Lake No-tozero)	Long-term	745	11.520	3.860
	Nizhnetulomskaya	7	0.0	1937	Nizhnetulomskoe	Weakly, Daily	38.0	0.390	0.037
Teriberka	Verkhneteriberskaya	8	12.4	1984	Verkhneteriber-skoe (Lake Venchjaver)	Seasonal	31.1	0.452	0.290
	Nizhneteriberskaya	9	0.2	1987	Nizhneteriber-skoe	Daily	1.42	0.011	0.003
Voron'ya	Serebryanskaya-1	10	51	1970	Serebryanskoe-1 (Lake Lovozero)	Long-term	236	2.860	1.570
	Serebryanskaya-2	11	26	1972	Serebryanskoe-2	Seasonal, Weakly	25.5	0.428	0.005
Niva	Niva-1	12	27.9	1952	Imandra	Long-term	876	11.200	2.330
					Pirengskoe	The same	227	3.000	0.877
	Niva-2	13	15.4	1934	Pinozero	Weakly	17.6	0.079	0.043
	Niva-3	14	6.2	1949	Plesozero	Daily	1.6	0.010	0.002
Kovda	Kumskaya	15	146	1962	Kumskoe (Topoz-ero, Pyaozero, Kundozero)	Long-term	1910	9.830	8.630
	Iovskay	16	79.0	1960	Iovskoe (Sushoz-ero, Ruvozero, Sokolozero)	Seasonal	294	2.060	0.545
	Knyazhegubskaya	17	1.2	1955	Knyazhegubskoe (Notozero, Kov-dozero, Sennoe, Bab'e, Belich'e, Nerpozero)	The same	610	3.436	1.928
Kem	Yushkozerskaya	18	189	1980	Yushkozerskoe (Lake Kuito)	Long-term, Seasonal	657	4.748	1.254
	Krivoporozhskaya	19	–	1991	Krivoporozhskoe	Weakly	70.4	0.566	0.067
	Poduzhemskaya	20	20.0	1971	Poduzhemskoe	Daily	12.0	0.024	0.011
	Putkinskaya	21	5.7	1967	Putkinskoe	The same	6.4	0.049	0.003
Lower Vyg (WSBC)	Ondskaya	22	–	1956	Vygozero	Long-term, Seasonal	1250	6.440	1.140
					Segozero		815	4.700	4.020
					Ondozero		199	0.600	0.370
					Ondskoe Res.		21.2	0.068	0.037
	Palokorgskaya	23	44.0	1967	Palakogorskoe	Daily	85.0	0.299	0.074
	Matkozhnevskaya	24	21.0	1953	Matkozhnenskoe	The same	19.0	0.082	0.017
	Vygostrovskaya	25	11.0	1961	Vygostrovskoe	The same	4.6	0.018	0.002
	Belomorskoe	26	5.5	1962	Belomorskoe	The same	2.24	0.007	0.001

Table 3. Basic data on reservoirs in the basins of Siberian rivers according to [1, 6, 8, 35]

River	Reservoir	Distance from the sea, km	Years of filling	Area at normal operation level, km^2	V_{tot}, km^3	V_{eff}, km^3	Dam height, m	Water exchange		
								W_{ann}/W_{tot}	V_{eff}/W_{eff}	V_{eff}/W_{ann}
								year		
Ob	Novosibirskoe	2987	1956–1959	1070	8.80	4.40	28.2	5.88	0.135	0.080
Irtysh	Bukhtarminskoe	3165	1960–1967	5490	49.62	30.81	90.0	0.38	2.330	1.640
	Ust-Kamenogorskoe	3086	1952–1959	37.0	0.66	0.04	65.0	29.80	0.003	0.002
Tom	Krapivinskoe	–	Under construction	670	11.70	9.70	–	2.55	–	0.330
Yenisei	Shushenskoe	3013	1978–1983	621	31.34	15.30	234	1.49	0.430	0.330
	Mainskoe	2992	1984	11.5	0.12	0.07	17.0	388.70	–	0.002
	Krasnoyarskoe	2378	1967–1970	2000	73.29	30.42	128	1.21	0.430	0.340
Angara	Irkutskoe/with L. Baikal	1714	1956–1959	154/1466	2.1/48.1	0.45/46.5	44.0	28.70	0.010	0.007
	Bratsk	1116	1961–1967	5478	169.3	48.20	125	0.54	0.790	0.530
	Ust-Ilimskoe	928	1974–1977	1922	58.93	2.74	102	1.71	–	0.030
	Boguchanskoe	444	Under construction	2326	58.20	2.30	–	1.88	0.090	0.020
Kureika	Kureiskoe	101	1988	558	9.96	7.30	81.5	1.96	–	0.370
Khantaika	Khantaiskoe	63	1970–1975	2120	23.52	12.81	65.0	0.75	–	0.720
Vilyui	Vilyuiskoe-1,2	1345	1967–1974	2176	35.88	17.83	75.0	0.55	1.140	0.910
	Vilyuiskoe-3	1204	Under construction	104	1.08	0.19	50.0	19.90	–	0.010
Kolyma	Kolymskoe	1893	1980–1989	443.4	14.40	6.56	130	0.99	0.900	0.460
	Ust-Srednekanskoe	1677	Under construction	264	5.40	2.60	66.0	4.37	–	0.110

The limited reserves of water resources in the Ob Basin's steppe and forest–steppe regions, which feature highly developed industry and agriculture and numerous populated municipalities, made it necessary to construct reservoirs and runoff-diversion systems. The largest reservoir in the Russian part of the basin is the Novosibirsk Reservoir, which effects seasonal runoff regulation (Table 3). It was commissioned in the autumn of 1956 and filled up to the maximum operating level in the summer of 1959. The largest in the Ob Basin is the Bukhtarminskoe Reservoir in Eastern Kazakhstan. Since 1960–1966, it effects the long-term regulation of Itysh runoff by changing the water volume in dammed Lake Zaisan (1800 km^2) in area. Ust-Kamenogorskoe and Shul'binskoe (with the effective storage of 1.8 km^3 and the area of 255 km^2) reservoirs were constructed further downstream.

Large reservoirs in Ob–Irtysh basin are the Verkhnetobol'skoe (846 km^3 in volume), Karatomarskoe (586), Sergeevskoe (690), and Petropavlovskoe reservoirs in the Kazakhstan part of Tobol and Ishim basins; the Argazinskoe (980) and Shershnevskoe (176) reservoirs on the Miass River; the Gilevskoe (471) on the Alei River in Altai Territory; Bol'shoi Uvat (231) in Tyumen province; the Ayatskoe (110), Reftinskoe (142), Lenevskoe (141), and Chernoistochinskoe (111 million m^3) reservoirs in Tura basin in Sverdlovsk province. Overall, ~270 artificial water bodies with the total water volume of ~70 km^3 are located in this basin. As such, the total capacity of the Novosibirsk, Bukhnarminskoe, and Shulbinskoe reservoirs is 61, and their effective capacity is 36.7 km^3 or 9% of the mean Ob runoff in its mouth.

Out of the rivers in the Asian part of Russia, the hydropower resources of the Yenisei and its tributaries are best developed. The river basin contains 39 reservoirs. Seven largest reservoirs have the total capacity of 368.44 km^3 and the total area of 12850 km^2 (Table 3, Fig. 1). The effective capacity of the reservoirs V_{eff} accounts for ~19% of runoff in the mouth of the Yenisei. The valley Sayano-Shushenskoe, Mainskoe, and Krasnoyarsk reservoirs were constructed in the upper and middle reaches of the Yenisei. The lake-type Irkutsk (with Lake Baikal) and Ust-Ilimsk reservoirs transformed the upper reaches of the Angara River. The lake-type Khantaiskoe (on the Khantaika River) and valley Kureiskoe (on the Kureika River) reservoirs are located on the right-hand tributaries of the lower Yenisei north of the polar circle.

The drainage basin of the Yenisei reservoirs occupies 44% of the Yenisei's basin. About 36% of water resources of the river form here. The character of their effect on river runoff varied with time. The period of natural runoff ended in 1956. The years when the Irkutsk, Bratsk, Ust-Ilimsk, Krasnoyarks, and Khantaiskoe reservoirs were filled (1956–1976) reflected an increase in the regulating effect of artificial water bodies. The period of Yenisei runoff regulation and the further development of its hydropower resources started in 1977.

Lena runoff is not regulated. However, the Vilyui Reservoir was constructed on its tributary, the Vilyui River. This reservoir is among the largest in the country and the largest in the continuous permafrost zone. This reservoir was filled in 1967–1973. The last unit at its hydropower plant was commissioned in 1976. The reservoir has a significant effect on all characteristics of water regime in the middle and lower Vilyui and, in some cases, in the lower Lena, as well. Overall, the Lena Basin has 12 artificial water bodies with a total volume of 36.201 km^3 and a total area of 2214 km^2 [8].

The Kolyma River was dammed in late 1980; however, several years were required for the characteristics of the Kolyma HPP to reach their design values. The Kolyma HPP started generating electric power in 1982. Operations aimed to extend the dam body were finished in September 1988, and by 1990, the Kolyma Reservoir was filled to its design capacity with a maximum operating level of 450 m. Since 1980 to 1988, this level was 390 m. It corresponded to the total and effective capacity of 0.844 and 0.5 km^3, respectively; the reservoir area was 59.2 km^2. In 1944, the maximum operating level was raised to 451.5 m and its capacity increased to 15.031 km^3. Thus, the intense regulation of the Upper Kolyma's runoff started in 1989.

Reservoirs and Rivers

The hydropower construction causes changes in the hydrographic characteristics of rivers and the transformation of river runoff. The transformed reaches of rivers include reservoirs (the upper pools), the upstream channel reaches affected by backwater, and the lower pools of the hydropower plants. The length of the lower pool is equal to the length of the channel reach within which the total normal annual volume of lateral inflow equals the normal annual flow through the reservoir dam [6]. In the case of the Irtysh, Ob, Yenisei, Angara, Vilyui, and Kolyma, this length, according to the author's estimates, is ~2075, 450, 363, 928, 800, and 300 km, respectively (Fig. 1). Within these limits, the flood and freshet peaks are notably reduced, because of which the floodplain is rarely inundated, water abundance during low-water periods is increased, the diurnal and weekly regulation can be distinctly seen, channel processes are more active, and the share of the reservoir water exceeds that of the river water. However, the effect of reservoir on the runoff and its regime does not disappear beyond the lower pool. This takes place at a much larger distance from the dam. Sometimes this effect can be seen near river mouths. Therefore, it is more reasonable to determine the length of a lower pool by the position of the section where the water masses of the reservoir and a lateral tributary mix completely, or water flow increases twofold as compared with that at the HPP dam [32]. In such case, the length of the lower pool is not a constant value and depends on the hydrological season. It reaches its minimum values when the lateral inflow is large and is maximal in low-water periods, when groundwater recharge declines and water discharge into the lower pool is large.

The extent and the character of changes in water runoff and regime in the dam section depends on the position, characteristics, and the operation regime of the reservoir. The further longitudinal transformation of the technogenic impact is determined by the climatic and geological–morphological conditions, the length, the hydrographic structure, and the hydrological regime of the downstream part of the river and its particular watershed.

The construction of reservoirs has its effect on river water resources and regime. Changes in water resources are commonly regarded for the river as a whole, while the disturbance of water regime can be associated with individual parts of the channel. Diurnal variations in the discharge, level, and flow velocity are the first to disappear. Observations carried out in 1959 on the Ob showed that water level variations under the effect of daily regulation at the Novosibirsk HPP extend downstream the channel over 100–110 km [10]. The effect of weekly regulation on water level almost disappears at about 500 km from the dam [3], i.e., within the lower pool of the Novosibirsk Reservoir. The seasonal and year-to-year runoff regulation can be traced over a longer distance. Thus, three characteristic segments can be identified in the river, i.e., those subject to the effect of (i) daily, (ii) weekly, and (iii) seasonal and year-to-year regulation of water flow [1].

Variations in the Normal Annual River Runoff

Variations in the normal annual runoff of rivers are due, primarily, to the filling of the dead storage capacity of reservoirs and the initial saturation of soil on its bed. These are the so-called one-time losses, which increase the natural stationary water resources of the basin. To fill the dead storage capacity of the majority of large river-type lowland reservoirs requires 5–10% of the normal annual runoff of a river, while the respective value for mountain and piedmont reservoirs can be 100% and more [9]. Therefore, the process of filling of the unregulated volume of reservoirs extends over several years. The losses due to soil saturation on the res-

Table 4. Variations in annual runoff, km^3, in rivers of the Arctic Ocean's basin under the effect of reservoirs (considering data [9, 12])

Basin and reservoirs	Runoff withdrawal for dead storage filling, km^3	Runoff losses for evaporation (km^3/year)			Long-term runoff regulation***	
		total	additional			
			from water surface	from waterlogged zone	max. accumulation	max. drawdown
Karelia and Kola Peninsula	38.75	–/2.50**	–	–	–	–
Ob Basin	24.8	(5.25)	–	–	–	–
Novosibirskoe	4.40(0.13)*	0.59	0.16	0.02	1.98 (45)	–1.60 (36)
Bukhtarminskoe	18.81	3.65	–	–	4.36 (14)	–11.8 (38)
Yenisei's basin	251.40	18.00	1.45	0.48	–	–
Sayano-Shushenskoe	16.04	0.31	0.19	0.02	7.85 (51)	–0.78 (5)
Krasnoyarsk	42.87	1.24	0.61	0.32	16.30 (54)	–15.1 (50)
Irkutsk	1.65(0.15)*	0.02/13.2**	–	–	0.15 (33)	–0.10 (22)
Bratsk	121.1 (7.35)*	1.94	0.29	0.03	26.00 (54)	–21.3 (44)
Ust-Ilim	56.19	0.60	0.18	0.01	1.78 (65)	–1.12 (41)
Kureiskoe	2.66	0.17	0.04	0.03	–	–
Khantaiskoe	10.71	–/0.53**	0.14	0.07	–	–
Lena's basin	18.20	0.79	–	–	8.52	–5.63
Vilyui	18.05	0.78	0.17	0.10	8.52 (48)	–5.63 (32)
Kolyma's basin						
Kolyma	7.84	0.13	0.03	0.02	–	–

Notes: * Figures in parentheses are for saturation of shores and banks by water.
** The bottom number includes the evaporation from lakes.
*** Figures in parentheses are relative the effective capacity of reservoir, %.

ervoir bed are much smaller (Table 4). However, this type of losses can be significant in the case of a large water body (e.g., the Bratsk Reservoir) and the appropriate hydrogeological conditions.

The volume of water consumed for the filling of the dead storage volume of reservoirs by late 1985 was 251 km^3 in Yenisei basin, 24.8 in Ob Basin, and 18.2 km^3 in Lena basin. The greatest changes were recorded in Yenisei runoff, where ~40% of water resources were consumed during this process. The major reduction of runoff took place in the 1960s–1970s and especially, during the active filling of the Bratsk Reservoir (1964). The character of long-term variations in the annual runoff in the Vilyui and the lower Lena was notably disturbed in 1967–1973 and 1969–1973, respectively.

A near constant amount of river runoff is evaporated from the reservoir surface. This amount is maximum in rivers where chains of large reservoirs were constructed (e.g., the Yenisei and Angara), as well as in territories with a large concentration of water bodies (Karelia and the Kola Peninsula) and in the case of their concentration in arid parts of the basin (Ob) (Table 4). The total evaporation from the surface of water bodies in the Russian part of the Arctic Ocean's basin is ~26.7 km^3 per year. The exclusion of data on lake-type reservoirs containing natural water bodies reduces this value more than twice.

Evaporation always has its effect on river runoff. Therefore, when estimating the real effect of reservoirs on river runoff, one should take into account the losses for additional evaporation because of the higher evaporation from the water area of an artificial water body and the underflooded zone as compared with the evaporation under natural conditions. It amounts to 16–75% of the potential value given in Table 4.

Reservoirs not always reduce the volume of annual river runoff. The reduction of floods decreases the inundated floodplain area shortens the inundation period in the lower pools of hydraulic structures, thus reducing the losses of water for evaporation and infiltration into soil. According to G.V. Pryakhina [25], this decrease in the lower pool of the Novosibirsk Reservoir in 1964–1987 was 2.6 and that downstream of the Krasnoyarsk Reservoir in 1972–1977 was 1.8 km^3/year. These volumes are comparable with or greater than the total runoff losses for additional evaporation from the surface of these reservoirs (Table 4).

The long-term regulation of river runoff by reservoirs has almost no effect on the normal annual runoff. It affects the mean annual runoff and its year-to-year variations. These variations can be very wide and depend on long-term variations in water reserves in reservoirs (Fig. 2, Table 3). This is especially true for rivers with chains of reservoirs (Yenisei and Angara) or rivers with very large reservoirs (Irtysh, Vilyui, and Kolyma). The value of long-term runoff regulation is limited by the effective capacity of the reservoir, though it commonly does not exceed 50–60% of this volume. The maximum volume of water accumulation in most reservoirs does not exceed their maximum drawdown volume.

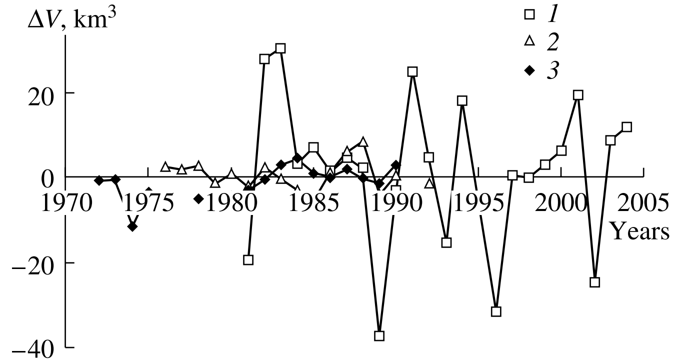

Fig. 2. Variations in water reserves in reservoirs on the (*1–3*) Yenisei, Vilyui, and Ob rivers, respectively.

Seasonal Regulation of River Runoff

Seasonal regulation of river runoff results in the redistribution of runoff within year and its leveling in time. The specific features of this process depend on the water management objectives and the technical parameters of each structure, as well as on the hydrological and climatic factors. The extent of such redistribution increases with increasing reservoir volume V_{des} and its regulating capacity V_{eff} as compared with the flood and annual runoff volumes W_{fl} and W_{an}, respectively. Commonly, water abundance during floods and freshets decreases and that during low-water period increases.

The Krasnoyarsk, Vilyui, and Kolyma reservoirs effect the most significant transformation of seasonal runoff (Table 5). The flood runoff in the lower pools of the respective hydraulic structures decreased by 27–51% relative to its natural values. Water abundance in the summer–autumn period changed insignificantly. The greatest increase was recorded in the winter base flow (28–44%). The Angara reservoirs, which can retain >50% of its runoff (Ult-Ilimskaya HPP section), caused insignificant changes in the Angara regime because of its high natural regulation by Lake Baikal. The low regulating role of the Novosibirsk Reservoir was due to the small V_{eff} as compared with the spring flood runoff volume in the Upper Ob, especially in high-water years.

The regulating effect of reservoirs on river runoff extends over hundreds of kilometers. Most often it attenuates far from river mouths. However, there are some exceptions. In the Kola Peninsula and Karelia, reservoirs are very close to the sea coast. Therefore, they have a strong effect on the hydrological regime in the mouth areas of regulated rivers. The operation of reservoirs caused a decrease in the spring runoff along with an increase in the winter runoff in the mouths of the Paz, Tuloma, Voron'ya, Niva, Kovda, and Lower Vyg rivers. The monthly share of the annual river runoff discharged into the sea shows almost no variations (7–9%). Only the share in June (May) is 1–2% higher. The regime of the Kem River featured no significant variations, although an appreciable increase was recorded in the winter base flow.

In Siberian rivers (where reservoirs are far from the Arctic coast), the along-channel transformation of the impact distorts the initial anthropogenic changes in water regime, reduces the effect, and, under certain conditions, return its characteristics to the natural values. Changes in the regime of the winter low-water period extend over the largest distance (Fig. 3). Under the conditions of an abrupt drop in water reserves in a river network and a decrease in groundwater discharge in winter, along with a decline in the regulating effect of the floodplain and a possible increase in winter runoff because of current climate changes [30], the anthropogenic increase in water flow can extend down to river mouths. This effect can be somewhat shadowed by increased ice and frazil formation and the lateral inflow, which persists in large rivers in winter. The effect of reservoirs can be observed in winter even when an artificial water body has a small regulating capacity (Ob) or is located in the basin of a tributary (Ob, Lena) (Fig. 3b). During other stages of water regime, the effect of reservoirs on it is typical only of rivers with a considerable runoff regulation. An important factor of the longitudinal transformation of disturbed water regime of a river is the water abundance of the year.

The significant changes in Ob water regime recorded between the Novosibirsk HPP dam and Novosibirsk City are much less evident at Kolpashevo town (564 km from the dam). The runoff near this town amounted to 124–92% (on the average, 96%), 99–102 (100), and 104–154 (119) of the natural runoff in April–June, August–October, and November–March 1957–2000, respectively. At Belogor'e village (1834 km from the dam), the influence of all reservoirs in the Ob–Irtysh basin and climatic factors caused a decrease in water flow in August–October down to 92–96% (on the average, 94%) of their values in 1932–1956, an increase in winter up to 98–128 (115), and almost no changes on the average during spring–summer flood. However, they amounted to 116% in April and 93% in July. Near Salekhard (2699 km), a decrease in the summer–autumn (on the average 93%) and an increase in winter (111%) still persist. An increase in runoff (up to

Table 5. Characteristics of river water regime in the lower pools of HPPs

River, section	Period	Runoff distribution over seasons, % of the annual			W, km^3/year	The coefficient of intra-annual runoff nonuniformity	Normal annual characteristic water flow, m^3/s	
		spring flood	summer–autumn season	winter low-water period			Q_{max}	Q_{min}
Niva, HPP-3	1925–1934	43.1	27.5	29.4	5.11	6.0	–	–
	1956–1988	23.2	23.4	53.4	5.05	1.3	230	75
Kovda, Knyazhegubskii channel	1925–1954	41.5	35.6	22.9	8.49	5.5	714	106
	1955–1988	27.9	32.7	39.4	8.74	1.4	560	47
Kem, Putkinskaya HPP	1925–1966	48.2	34.0	17.8	8.11	5.1	700	78
	1967–1988	45.5	33.7	20.8	8.80	3.9	755	82
Lower Vyg, Matkozhnenskaya HPP	1913–1931	46.2	32.9	21.0	8.54	3.7	647	113
	1956–1988	33.7	34.4	31.9	8.20	1.3	572	133
Irtysh, Ust-Kamenogorsk HPP	1903–1960	55.6	25.5	18.9	19.8	5.7	2310	134**
	1961–1987	39.0	25.8	35.1	16.7	2.0	1780	236
Ob, Novosibirsk HPP	1894–1956	67.6	22.0	10.4	55.0	16.2	7270	272
	1958–2003	57.9	23.7	18.4	49.7	5.8	4640	381
Yenisei, Krasnoyarsk HPP	1955–1966	63.3	27.4	9.3	90.8	17.5	13100	347
	1967–2001	35.9	26.6	37.5	83.5	1.4	4850	1700
Angara, Boguchany vil.	1931–1961	26.6	43.2	30.2	118	3.5	16400	1330
	1962–1999	22.3	33.8	43.9	109	2.4	11300*	1270*
Vilyui, Chernyshevskii vil.	1926–1964	69.7	29.3	1.0	20.0	1007	–	–
	1959–1966	67.9	31.1	1.0	21.2	1017	7230	2.35
	1968–1994	18.4	36.9	44.7	19.7	2.6	2030	154
Kolyma, Sinegor'e vil.	1933–1951 1968–1980	45.8	52.8	1.4	14.4	724	4510	1.64
	1981–1987	36.2	58.3	5.5	14.8	167	5670	1.61
	1992–2001	18.5**	44.1**	37.4**	14.4**	2.6**	–	–

Notes: * Up to 1988, inclusive.
** Very approximately.

101–118%) was recorded in April, June, and July, while in May, it was found to drop (to 98%). The time lag between the beginning of a decrease in spring–summer and an increase in winter runoff was found to appear and increase with the distance from the dam. These were found to take place in April and August in Novosibirsk, in May and October–November in Kolpashevo, in June–July and December in Belogor'e, and in August and December in Salekhard, respectively.

The regime of the Irtysh forms largely under the effect of the operation of the Irtysh reservoir chain. The author's analysis of variations in the river water regime showed that in 1966–1999 river runoff at Omsk (1266 km from Ust-Kamenogorsk dam) in November–March and April increased up to 158 and 147% relative its values in 1936–1960, respectively. Contrary to that, the runoff during the spring–autumn flood (except for April) and the spring–summer period (August–October) decreased to 83 and 89%, respectively. Downstream of the mouths of the Ishim (Ust-Ishim village, 2076 km) and Tobol (Tobol'sk town, 2453 km), the anthropogenic changes in runoff also manifest themselves, including those caused by water management operations in the basins of these tributaries. Winter water flow in these sites increased by 44 and 31%, respectively. Water flow dropped by 9 and 5% in May–July and by 18 and 19% in August–October, respectively. The moments when Irtysh flow starts decreasing in spring–summer and starts increasing in winter shift with the distance from the Ust-Kamenoglrsk HPP from May and September to June and October at Omsk city and to May and November at Ust-Ishim village and Tobol'sk town, respectively.

Significant runoff variations are also typical of the Yenisei. At Bazaikha village (34 km from Krasnoyarsk HPP, water flow was 398 and 188% of its values in 1936–1961 in November–March and April 1970–2001, 47% in May–July, and 96% in August–October. Downstream of the Angara mouth at Yeniseisk town (448 km from the dam), the degree of runoff changes decreases in November–March (198%), April (184%) and May–July (70%) and increases in August–October (86%) under the effect of Angara reservoirs. The emptying of large tributaries into the river along with channel and floodplain flow regulation in the Lower Yenisei facilitate the further decrease in the regulating effect of the Angara–Yenisei reservoir chain. However, this decrease is not as significant as that in the reach between the HPP dam an Yeniseisk town, although the lateral inflow into the Lower Yenisei is greater than Angara flow by a factor of 2.5 (down to Igarka). Downstream of Podkamennaya Tunguska River mouth (934 km from the dam), the seasonal runoff amounts to 177, 194, 82, and 84% and at Igarka town (1805 km from the dam), to 158, 213, 92, and 86%, respectively. In the reaches near Yenisei mouth, water releases into the lower pool of the Khantaiskoe Reservoir facilitate even greater increase in winter flow. Thus, water abundance in the Yenisei under the conditions of its regulation increased in winter and decreased in the warm season. The largest relative increase in water flow was recorded in March (570–220%), whereas the largest such increase in the outlet section (Igarka town) was recorded in April (213%). The maximum decrease in runoff was recorded in June (35% at Bazaikha settlement and 61% at Yeniseisk town), July (69% at Podkamennaya Tunguska village), and August (79% at Igarka gauge).

The monthly Angara runoff downstream of Irkutsk HPP dam under regulation amounts to 8–9% of the annual value. The runoff increased in December–June (105–152% relative to its values in 1928–1956), and decreased in July–November (74–94%). Insignificant variations in monthly runoff within year were recorded at Bratsk (7.2–9.2% of the annual value) and downstream of the Ust-Ilim HPP (7–10%). Variations in normal monthly flow values are somewhat greater in the water-abundant years and lower in dry years. Water flow increased in November–April (up to 117–183% at the Bratsk HPP) and decreased in May–October (62–87%). The runoff peak shifted to autumn. The share of the spring–summer flood increases significantly toward Boguchany village (612 km from Ust-Ilim HPP dam) and, especially, Tatarka village (900 km), though it does not reach the natural values. Water flow at Boguchany village in May–June and July–October 1962–1999 was 80–87 and 73–79% of the natural values, respectively; in November–April, this flow reached 103–177%.

The operation of the Vilyui Reservoir resulted in an increase in the winter runoff (November–April) in the Vilyui runoff by a factor of 44 and a decrease in the spring flood (May–June) by a factor of 3.5–4. The significant increase in the water abundance in July (up to 150%) and October (196%) is compensated, to an extent, by its drop in September (84%). The effect of runoff regulation gradually decreases with the distance

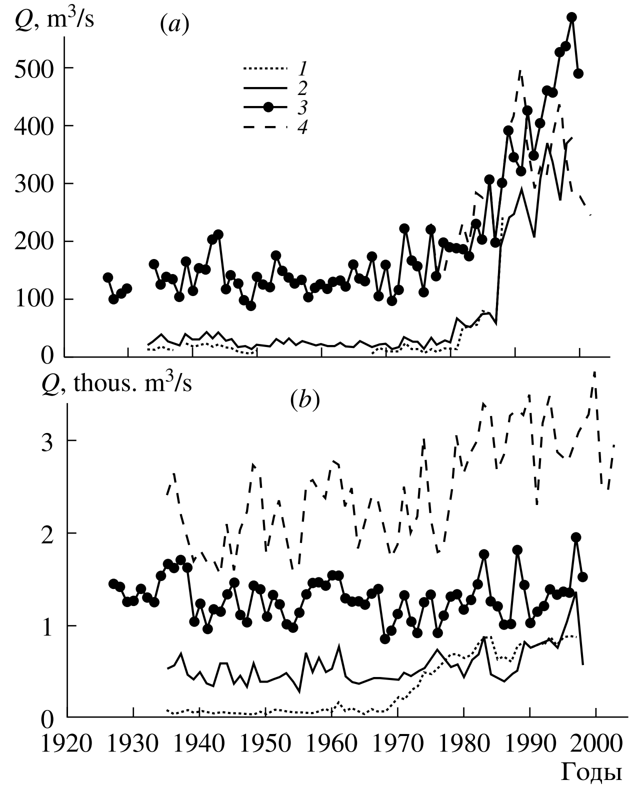

Fig. 3. Variations in the mean winter water flows. (a) Kolyma R. (*1*) at the section of Kolyma HPP dam, (*2*) at Ust-Srednekan settlement, (^{3}) at Srednekolymsk town, and (*4*) Kolymskoe gauge; in (*1*) the lower and (*2*) middle reaches of the Lena River and the lower reaches of (^{3}) the Aldan and (*4*) Vilyui rivers.

from the HPP, although the increase in the winter runoff is still high [16, 33]. In 1968–1998, its value at Suntar village (605 km from the dam) increased by a factor of 25 as compared with that in 1935–1966; the respective increase factors were 9.2 at Khatyryk-Khomo settlement (1223 km) and 1.2 at Kyusyur settlement, the Lena river (2240 km). The increase in the winter flow in the lower reaches of the Lena coincided with the beginning of the operation of the Vioyui HPP, an increase in the winter runoff of the Vilyui and, to a lesser extent, the Aldan (Fig 3b). The significant year-to-year variations in the winter flow in the Lower Lena is due to runoff variations in the Middle Lena and the Aldan. Variations in the spring and summer–autumn flow in the Vilyui under the effect of the reservoir do not reach the Lena's mouth. The volume of spring flood in the Vilyui's mouth decreased by 1.3 times. The mean water abundance in July–October changed insignificantly. Water flow in July and August increased (up to 103 and 111% of their values in 1935–1966) and those in September and October decreased (to 77 and 95%).

Major changes in the Kolyma's water regime took place after 1988–1990 (Fig. 3a) [33]. The relative changes in the winter flow at the Kolyma HPP dam in 1992–1998, 2001 amounted to 2690% of the natural values (1933–1951, 1968–1980), those for May, June were 40%, and for July–October 84%. At Ust-Srednekan settlement (227 km downstream of the Kolyma HPP), winter flow in 1992–2001 averaged 1395% of the respective values in 1948–1980, while it amounted to 61% in May, June and 100% in July–October. At Srednekolymsk town (1209 km from the dam), they were 334, 92, and 92%, while at Kolymskoe–I gauge, they were 260, 100, and 94%, respectively. Thus, amount of water reaching the Kolyma's mouth area between September and May increased: 118% (Sep.), 145 (Oct.), 162 (Nov.), 172 (Dec.), 297 (Jan.), 460 (Feb.), 594 (Mar.), 628 (Apr.), and 238 (May). The flow in summer months decreased (to 74–91%). The steady increase in winter water flow from year to year is due to the gradual raising of the parameters and capacity of the Kolyma HPP, and, perhaps, to climate-induced changes in the water regime of tributaries.

POSSIBLE ANTHROPOGENIC CHANGES IN RUNOFF IN THE 21ST CENTURY

Water consumption in the drainage basins of most rivers of the region is expected to increase in the first quarter of the 21st century, and the water management characteristics of the 1980s are likely to be attained (Table 1). Most probably this will not cause a decrease in the river runoff into the Arctic seas, because of its anticipated increase due to climate changes [14, 19, 21, 30, 34]. In all likelihood, it will be much greater than the possible anthropogenic decrease in the runoff of Arctic rivers, notwithstanding the ambiguous character of climate-induced changes in river runoff in the first half of the 21st century. This increment will increase eastward and will be larger in the rivers with a higher share of their drainage area in high latitudes.

Notwithstanding the anticipated increase in river runoff, the situation with water management can become stressed in some regions in the Russian part of the Arctic Ocean's drainage basin. These regions include the southern and Ural parts of the Ob–Irtysh basin, where climate changes are expected to cause a decrease in the first half of the 21st century [21], and the increase in water consumption is expected to be the largest among other rivers in the region. Apart from the restoration of the past volumes of industrial, agricultural, and municipal water consumption, the increase in water withdrawal here will be also caused by the large-scale diversion of river runoff between river basins that is planned in the territories of three states. First, Chine plans to withdraw from 0.5–1 to 2–4 km^3 of water from the Chernyi Irtysh into the channel Chernyi Irtysh–Karamai town with a length of >300 km [36]. Second, the transfer of part of the Irtysh's water toward Astana, the new and rapidly developing capital of Kazakhstan [17]. Third, because of the steadily aggravating water crisis in Kazakhstan and Central Asia, the issue of possible partial diversion of the runoff of the Ob, Tobol, and Irtysh into the Aral region is still discussed (Fig. 1). Several options of such diversion are known to exist, but the priority in 1970 was given to the Turgai option, which was developed in Soyuzgiprovodkhoz Institute. According to this project, it was planned to withdraw water in the volume of 25–27 km^3/year at the first phase and up to 60 km^3/year at the second phase [27]. The implementation of these plans requires 15–25 years. Fourth, the Governor of Omsk province made a decision to construct a dam on the Irtysh with the aim to maintain its water level meeting the water management requirements under the conditions of its anthropogenic and natural drop [11].

The overwhelming majority of water resources in Russia (>80%) are concentrated in Siberia [26]. Therefore, the major hydropower construction is planned for this area (Fig. 1, Table 3). The facilities being constructed now include the large Krapivinskoe Reservoir on the Tom (120 km upstream of Keverovo), the 2nd phase of the Shul'binskoe Reservoir on the Irtysh (with the effective capacity of 7.1 km^3), the Boguchanskii HPS in the Lower Angara, the Vilyui–3 HPP in the Middle Vilyui, and the Ust-Srednekanskii HPS in the Middle Kolyma. The completion of the construction of the Boguchanskaya HPP is planned for 2011, and that of Ust-Srednekanskaya HPP will be completed in 2010–2016. The first unit in the Vilyui–3 HPP was commissioned on September 8, 2004. In Karelia and the Kola Peninsula, the use of the hydraulic power of the rivers of Ponoi, Iokanga, Keret, etc. is anticipated, and the construction of the Beloporozhskaya and Morskaya HPPs on the Kem river will be completed.

CONCLUSIONS

The studies carried out by the authors allowed him to consider and assess (based on up-to-date data) the major anthropogenic impact on the runoff and water regime of Russian rivers emptying into the seas of the Arctic Ocean and the hydrological consequences of water management.

The regime and water resources of the rivers under consideration are subject to an appreciable impact of water consumption on watersheds and the operation of reservoirs. Water consumption in river basins causes a decrease in their annual runoff. Unlike the rivers of the Azov and Caspian seas, the consumptive water losses for the region under consideration are comparable and often much less than the errors in the assessment of water runoff in the mouths of Arctic rivers. However, in some regions, such as Ob–Irtysh basin, fresh water is already deficient. The considerable anthropogenic changes in the runoff and water regime of rivers flowing into the Russian Arctic seas are largely due to the operation of large reservoirs. The character of these changes is many-sided, although it can reflect some individual features of the river.

The decrease in the annual runoff in regulated rivers is due to the initial filling of reservoirs and the saturation of soils in its bed. These are one-time losses, which disturb the natural character of long-time variations in the annual runoff until the reservoir reaches the design level. Since such one-time losses depend on the capacity and number of reservoirs, the most pronounced drop in water abundance was recorded during the filling of reservoirs on the Angara and Yenisei, as well as the Vilyui Reservoir.

Changes in the annual runoff of rivers are due to the increase in evaporation from the inundated and waterlogged zone as compared with its value under natural conditions, as well as due to a decrease in water losses in the lower pools of hydropower systems caused by the evaporation from floodplains and infiltration into soils. The values of the increase and decrease in runoff in Siberian rivers are on the average comparable and lie within the accuracy limits of runoff calculations. The effect of the second factor is virtually absent in the rivers in Karelia and the Kola Peninsula.

The long-term regulation of river runoff by reservoirs has almost no effect on their normal values, though its influence on the mean annual flow and runoff variations from year to year can be appreciable. These can be quite large in this region, especially in the Yenisei's basin.

The seasonal regulation of river runoff causes its annual redistribution and leveling. The reservoirs in the Kola Peninsula and Karelia lie near the sea coast. Therefore, they exert a maximum effect on the present-day hydrological regime of the mouth areas of these rivers. In the Asian part of the drainage basin, the Krasnoyarsk, Vilyui, and Kolyma reservoirs cause the deepest transformation of river water regime. With increasing distance from the hydropower system, the along-channel transformation of the impact disturbs the initial (at the dam) character of anthropogenic changes in water regime, reduces the impact of the reservoir on the runoff, and, under certain conditions, restores the natural values of its characteristics. The largest propagation distance in Siberian rivers is typical of anthropogenic increase in winter water abundance. In other hydrological seasons, notable changes in water flow were recorded only in the mouths of the Yenisei and Kolyma.

As the volume of water consumption increases and the construction of more reservoirs is completed, the anthropogenic impact on the runoff and water regime of rivers in the region increases. The heaviest water management situation can form in Ob–Irtysh basin. A significant increase in the consumption of water can be expected to take place in the southern and Ural regions of the basin against the background of the anticipated natural drop in water flow in the first quarter of the 21st century.

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