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Influence of river flow regulation in the Angara-Yenisei region on the hydrochemical regime of the cascade of hydroelectric power plant reservoirs and their downstream sections

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Abstract. The paper gives an analysis of the influence of river regulation on the chemical composition of surface waters in cascades of HPP reservoirs and downstream sections on the example of the largest rivers of Eastern Siberia. After regulation changes in the temperature regime of watercourses occur, which leads to a change in the timing of the onset of the main ice formations and the emergence of non-freezing sections of rivers. There is a local oxygen deficiency in the summer in the bays and the near-bottom horizon. According to the ionic composition surface waters belong to the hydrocarbonate class of the calcium group. A change in the morphometric parameters of water bodies causes a chain of subsequent hydrochemical reactions. In surface waters, there is a violation of fishery standards for the content of Al, Fe, Zn, Mn, Al¸Cu, phenols and oil products. The integral assessment of water quality by the value of the specific value of the combinatorial index of water pollution shows a high fluctuation along the rivers. The risk of negative impact on the watercourse increases with increasing concentrations of pollutants relative to natural conditions.

1 Introduction

Half of Russia's economically efficient hydropower potential is concentrated in Siberia, and mainly in the Angara and Yenisei river basins. This is a confirmation of the prospects for the development of the energy sector of the Angara-Yenisei macroregion due to hydrogeneration in the territory in order to ensure the development of energy-intensive industries of priority investment projects in the Yenisei Siberia [1].

On the other hand, the creation of a cascade of reservoirs is a negative intrusion into the existing ecological conditions. The erection of dams often has a significant negative impact on the hydrological, biological and chemical processes above and below the dams [1–5].

In recent decades, the problems of the impact of hydroelectric power plants and reservoirs on the environment in Eastern Siberia have become the subject of in-depth study, while complex hydrobiological work to study and assess the consequences of their creation and water quality is of paramount importance [6-16].

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There is little information about changes in the hydrochemical composition of water in the cascade of reservoirs in the Angara-Yenisei region and their downstream after regulation. Basically, researchers within the framework of the EIA describe the change in the chemical composition of the water body during the construction of the HPP and the first years after its completion [6; 18-20].

Thus, the purpose of the work is to identify the role of hydropower construction on the Angara and Yenisei rivers in shaping the quality of the aquatic environment in terms of the content of chemicals in reservoirs and their downstreams. To achieve this goal, it was necessary to solve the following tasks: a) describe the hydrographic characteristics of water bodies; b) on the basis of literature data, consider trends in changes in the hydrochemical characteristics of reservoirs and watercourses after regulation; c) give an integral spatial assessment of changes in water quality using State reports on the state and protection of the environment.

2 Hydrographic characteristics of rivers and their cascades

In hydrographic terms, the object of this work is the basins of the region's largest rivers, the Yenisei and Angara (Table 1; Fig. 1). According to the scheme of natural zoning, r. The Yenisei flows in a meridional direction to the north on the territory of three geographical regions - the West Siberian Plain, Taimyr and the Central Siberian Plateau. The Angara basin is elongated from the southeast and northwest, located on the southwestern margin of the Central Siberian Plateau and in a significant part of the East Sayan mountain system [21].

Table 1. Hydrographic characteristics of rivers.

Characteristics	Yenisei	Angara
River source	confluence of the rivers: Big Yenisei and Small Yenisei	Baikal lake
The main type of river feeding	snow	Baikal lake, snowy
Length, km	3 487	1 779
Water basin area, thousand km^2	2 580	1 040
Drop from source to mouth, m	620	380
Average long-term water consumption in the lower reaches, m^3/s	17 700	4 200
Hydrographic network development factor, km/km^2	0.40	0.47

In addition to natural factors, the hydrographic features of the rivers are due to the construction of a cascade of hydroelectric power plants (Table 2) both on the Yenisei itself (Sayano-Shushenskaya, Mainskaya, Krasnoyarskaya) and on its tributary - the Angara (Irkutskaya, Bratskaya, Ust-Ilimskaya and Boguchanskaya) (Fig. 1). The construction of a cascade of reservoirs led to the reconstruction of these watercourses and a radical change not only in the hydrological, but also in the hydrochemical regime.

Fig. 1. Map of the location of the hydroelectric power station of the Angara-Yenisei region.

Table 2. Technological parameters of hydroelectric power plants and reservoirs of the Angaro-Yenisei region.

River	HPP			Reservoir		
	Name	Dam site, km from the mouth	Total power, MW	Years of filling	Volume at FSL, km^3	Water exchange, per year
Yenisei	Sayano-Shushenskaya	3013	6 400	1978-1985	29.1	1.22
	Mainskaya	2991	340	1984-1985	$1.6 \cdot 10^{-7}$	-
	Krasnoyarsk	2502	6 000	1967-1972	73.3	1.56
Angara	Irkutsk	1714	660	1956-1959	2.1	24-32
	Fraternal	1120	4 600	1961-1967	169.7	0.55
	Ust-Ilimskaya	818	3 600	1974-1977	59.4	1.72
	Boguchanskaya	445	4 000	2013-2015	58.2	2.0

3 Changes in the temperature regime of watercourses after regulation

As a result of the construction and operation of the last HPPs in the considered cascades (Krasnoyarsk and Boguchansk), the temperature regime in their downstream has also changed dramatically. The deep intake of water supplied to the hydroelectric units leads to the fact that its temperature in the river in the area below the dam decreases in summer, by an average of 6–10°C, and rises by about 6°C in autumn and by 2–3°C in winter [22-23]

This had a great impact on the ice regime: a) on the river. The Yenisei freeze-up in the downstream of the Krasnoyarsk HPP is absent for 100–200 km, depending on weather conditions and the amount of water discharge from the HPP [6; 14, 22, 24]; b) clearing of ice on the river. The Angara of the Boguchansky Reservoir and the beginning of navigation shift on average by 7–14 days in the direction of delay compared to river conditions [19].

Before the regulation of the river, at the confluence with the river. Angara, the Yenisei was the first to freeze, after which the mouth section of the Angara was covered with ice. At present, as a result of the later formation of freeze-up on the Yenisei, the ice cover of the lower Angara is established much later [24].

4 Transformation of the hydrochemical regime of rivers

The creation of large reservoirs on the watercourses under consideration radically transformed their ecosystems and hydrochemical composition. Due to a decrease in the flow velocity due to regulation and a decrease in the movement of water along the depth, the physicochemical characteristics of water change significantly.

The content of dissolved oxygen after the creation of the Krasnoyarsk reservoir practically does not differ from the natural one for the Yenisei River: the oxygen content is from 7 to 12 mg/dm3 [6, 8].

Oxygen deficiency has a local character and is confined to the middle of summer, which is especially pronounced in calm weather and high temperatures (Volkova, 1975). For the Angara river researchers also note low oxygen concentrations in the bays and near-bottom horizon of some areas of the Ust-Ilimsk and Boguchansk reservoirs [18].

4.1 Mineralization

According to the ionic composition of water of the Yenisei and the Angara rivers belong to the hydrocarbonate class of the calcium group [21].

The upper section of the Yenisei from the city of Kyzyl to the Krasnoyarsk reservoir, with typical features of a mountain river, is characterized by high mineralization with minimum values in spring flood - 850 and maximum in winter - 1850 mg/l. The cascade of the Yenisei reservoirs reduces the mineralization level to 65–123 mg/l [25]. At the mouth, from the city of Igarka and below, the chemical composition of the water of the Yenisei is almost homogeneous and is characterized by average mineralization values - 150 - 155 mg/l [6, 26].

At its source, the water of the river The Angara is very poorly mineralized; further downstream, under the influence of tributaries, this parameter changes unevenly [21]. Regulation of the flow of the river. Hangars and the creation of artificial reservoirs caused an increase in the amount of ions down the cascade: from 88–100 mg/dm^3 in the Irkutsk reservoir to 5–10 mg/l in Boguchanskoe. Here, the influence was not only of domestic and industrial wastewater, but also of the features of the geological structure of the rocks of the drainage basin, composed of marine Cambrian deposits [18].

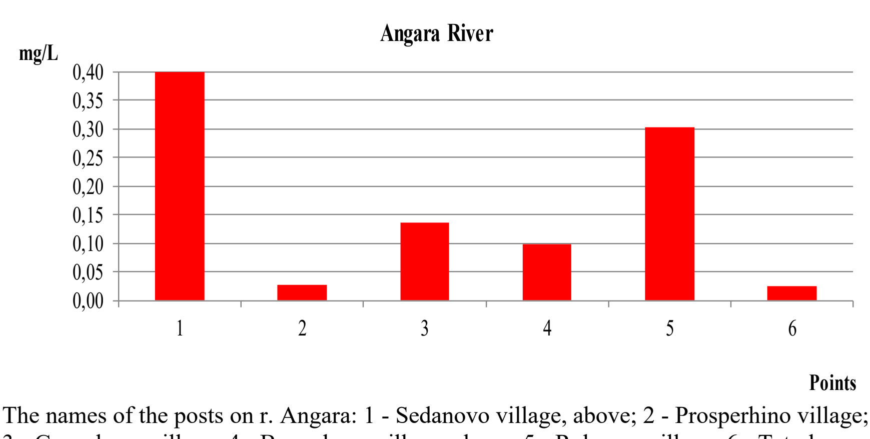
4.2 Nutrients

In the area of the upper section of the Yenisei River from the city of Minusinsk to the city of Divnogorsk (1 km below the Krasnoyarskaya HPP), an increase in phosphorus runoff was recorded from 0.005 during the period of natural runoff to 0.009 mg/l during the regulation period [9]. After the creation of the Krasnoyarsk reservoir, the influx of nitrogen and phosphorus into its downstream increased by approximately 50% [8, 14]. Below the city of Krasnoyarsk, with the addition of household and industrial effluents from the agglomeration, a zone of stable pollution with high values of nutrients was registered [14, 25]. Further, downstream on the river. Yenisei (before the confluence of the Angara River), with the intensification of self-purification processes in the summer, the concentration of biogenic elements and organic substances decreased. In winter, when the period of self-purification increases, the main mass of pollutants in an untransformed form is carried to the middle and lower sections, contributing to their eutrophication [14, 27].

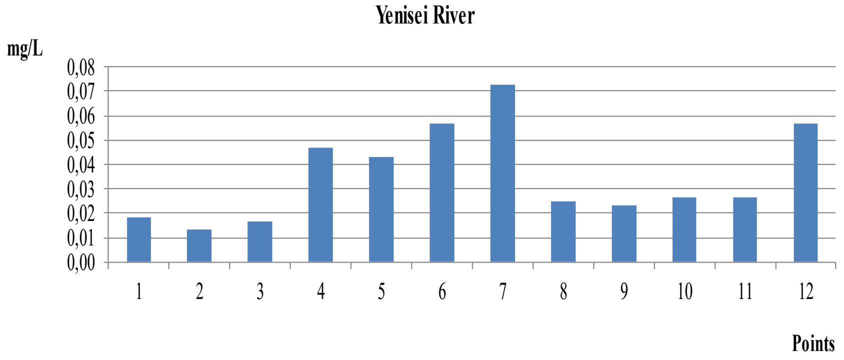
Spatial dynamics of the content of ammonium nitrogen in the river. Yenisei from the Krasnoyarsk reservoir to the city of Igarka (Fig. 2), made on the basis of the data presented in the Surveys of the Hydrometeorological Service for 2010 - 2012. indicates two zones of elevated concentrations - from the city of Krasnoyarsk to the city of Lesosibirsk and in the estuarine zone. At the same time, fishery MPCs are not exceeded [28].

The chemical composition of water and the content of biogenic substances in the waters of the river. The Angara rivers are formed due to the Baikal runoff, transformed in the reservoirs of the Angara cascade, in the surface waters of which an increase in the concentrations of mineral nitrogen and phosphorus is also noted [7, 18, 20].

The content of biogenic elements in the water of the Bratsk reservoir is almost an order of magnitude higher than their content in the water of the Irkutsk one. The main source of mineral forms of nitrogen in the water of the reservoirs are industrial and domestic wastewater, removal from agricultural land and atmospheric fallout. The saturation of the water of the Bratsk reservoir with phosphorus during the period of its operation increased by 3-7 times. A similar process is also observed in the surface waters of the Ust-Ilimsk reservoir - the concentration of nutrients in it is higher than in the overlying reservoirs of the cascade [7]. Spatial variability of ammonium nitrogen concentrations in the Angara River (Fig. 1) is highly variable and its content is almost three times higher than in the Yenisei River. It can be assumed that this is an indicator of an additive cumulative effect and a decrease in the self-cleaning capacity of the watercourse. The consequence of this process is a decrease in the degree of biodegradation of nitrogen and phosphorus compounds due to the low rate of water exchange in reservoirs (Table 2) and the high technogenic loading of the Upper and Middle Angara basins in HPP cascades. As a result, when the Angara flows into the Yenisei, there is a deterioration in water quality and an increase in various forms of nitrogen, phosphorus and organic matter in surface waters.



The names of the posts on r. Angara: 1 - Sedanovo village, above; 2 - Prosperhino village; 3 - Govorkovo village; 4 - Boguchany village, above; 5 - Rybnoye village; 6 - Tatarka village, 1 km above



The names of the posts on r. Yenisei: 1 - Krasnoyarsk reservoir; 2 - Divnogorsk city, 4 km above; 3 - Divnogorsk city, 0.5 km below; 4 - Krasnoyarsk city, 9 km above; 5 - Krasnoyarsk city, 5 km below the city; 6 - Krasnoyarsk city, 35 km below; 7 - Strelka urban-type settlement, above the confluence of the Angara Rive; 8 - Lesosibirsk city, 4 km above; 9 - Lesosibirsk city, 2.5 km below; 10 - Podtesovo village, 5.5 km below; 11 - 17 km below the confluence of the N. Tunguska River; 12 - Igarka city, 1 km below

Fig. 2. Spatial variability of ammonium nitrogen concentration in surface waters in 2010 - 2012 (MPC = 0.4 mg/l).

4.3 4.3 Organic matter (OM)

The concentrations of dissolved and suspended OM along the Yenisei River vary widely. The highest content of OM is observed below the city of Krasnoyarsk and in the mouth area [29]. A.S. Prokushkin et al. (2018) in their work also note a trend in the increase in the concentration of dissolved OC in the channel runoff of the Yenisei River from source to mouth [16]. The significant role of not only the cascade of the Yenisei reservoirs, but also the largest right tributaries (the Angara, Podkamennaya Tunguska and Nizhnyaya Tunguska rivers) in increasing Maximum Permissible Concentration (MPC) levels in the river is obvious. Yenisei after their confluence. The reason for this is the influence of discharges of industrial and domestic wastewater and the influx of organic substances of natural origin (for example, hydrocarbons formed during the vital activity of living organisms) [13].

Regulation of the flow of the Angara River also led to an increase in the OM in the water of the reservoirs, which is a consequence of the manifestation of the “cascade” effect. Before the creation of dams, the interannual content of organic matter was quite stable. The total composition was dominated by persistent OM (86%), the oxidation processes of which are slowed down in winter.

During the period of operation of the Bratsk reservoir in its water, the amount of dissolved organic matter doubled, which amounted to 11.4 mg/l. High concentrations of OM in the extensions of the reservoir are observed during the activation of phytoplankton development, as well as in areas subject to anthropogenic impact [7].

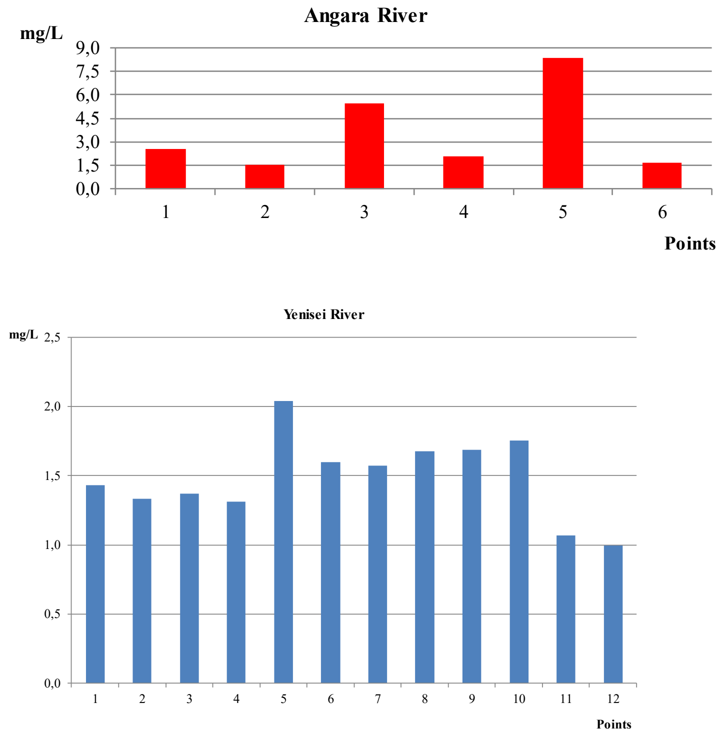
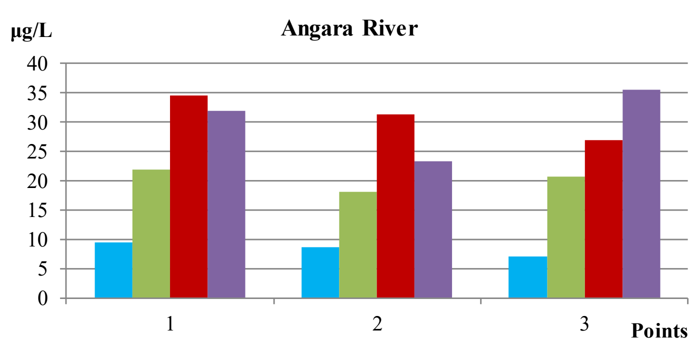


Fig. 3. Spatial variability of biological oxygen demand concentration (in 5 days) in surface waters in 2010 - 2012 (MPC = 2.1 mg/l).

Water quality can be significantly affected by flooded forests and soil organic matter [20].

An analysis of the spatial dynamics of the content of easily oxidizable organic substances (Fig. 3) of the considered water bodies indicates a high fluctuation in values and an excess of the MPC for fish in the Angara River (except for the village of Prospikhino), in contrast to the Yenisei River.

The distribution of trace element concentrations in the surface waters of the Angarsk-Yenisei cascade is determined by such factors as the composition of the source waters, hydrological and morphometric conditions, the structural features of the bedding rocks in each of the reservoirs, as well as the level of technogenic impact on the river basins.



The names of the posts on к. Angara: 1- Prosperhino village; 2 - Boguchany village, above; 3- Tatarka village, 1 km above

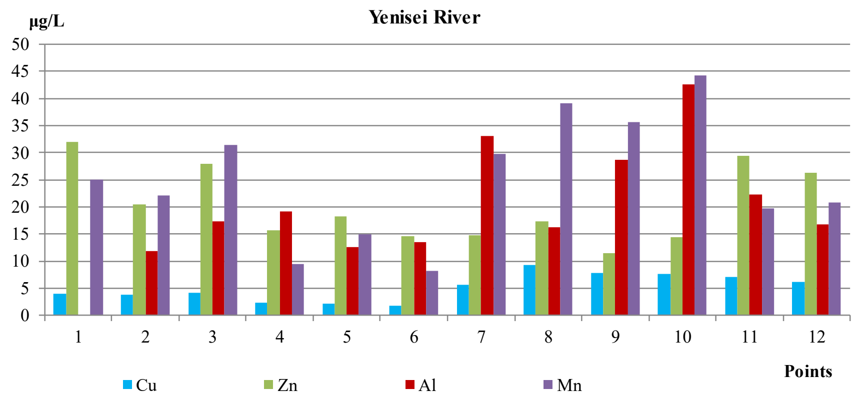


Fig. 4. Spatial variability in the concentration of metal ions in surface waters in 2010 - 2012 (MPC of Cu = 1, Zn = 10, Al = 40, Mn = 10 μg/l).

The characteristic polluting metals of the Yenisei river basin are ions of Al, Fe, Zn, Mn, Cu [30 – 32]. Large masses of trace elements are carried out in suspension after the cascades of hydroelectric power stations, where, under the diluting effect of tributaries, they pass into a soluble form - therefore, their concentrations increase before Krasnoyarsk and Lesosibirsk cities (Fig. 4).

Analysis of the temporal variability of trace elements and pollutants in the mouth of the river. The Yenisei shows that in recent decades the situation has stabilized, and no significant increase or decrease in concentrations has been recorded [33].

On the Angara River, a violation of the established fishery standards for the content of Fe, Mn, Cu, Zn, Al, Hg is regularly recorded [7, 13, 15].

According to the analysis of statistical material, the quality of water in the river. The Angara from the Irkutsk to the Boguchansk reservoir is deteriorating. The reason for this is both industrial wastewater discharges from enterprises in Eastern Siberia, and hydrophysical factors - a decrease in flow and water exchange [15]. As a result of cascade hydraulic construction, there is a decrease in the self-cleaning capacity of the river and an excess of the lower reaches of the Angara River MPC for Cu, Zn, Mn and oil products (Fig. 3, 4).

5 Water quality assessment

An integral assessment of water quality by the value of the specific value of the combinatorial water pollution index [33] was carried out using the State reports on the state and environmental protection of the Krasnoyarsk Territory and the Irkutsk Region from 2010 to 2021.

On the Yenisei river (Fig. 5), two peaks of a significant deterioration in water quality are recorded - below the city of Krasnoyarsk and below the confluence of the river. Angara, which is associated with a decrease in the self-cleaning capacity of the watercourse after the cascades of HPPs in the Angara-Yenisei region and a high level of watercourse pollution by industrial and domestic wastewater from the Krasnoyarsk agglomeration. Further, following the flow, after the village. Podtesovo (55 km below the city of Lesosibirsk) - there is an improvement in water quality, the main reasons for which are the diluting effect of large tributaries (the rivers Kem, Sym, Dubches, N. Tunguska, Kureika, etc.) and a significant distance - more than a thousand kilometers. In addition, a small anthropogenic load on the territory of the Lower Yenisei basin provides an increased ability of the river to recover, therefore, the values of the UKIZV index decrease in the sections "17 km downstream of N. Tunguska" and "Mt. Igarka, 1 km below.

Water quality in the Angara river (Fig. 4) deteriorates from the Irkutsk (class 1, "conditionally clean") to the Boguchansky reservoir (class 3, "polluted"). The deterioration of the water condition occurs due to the discharge of industrial wastewater from the largest non-ferrous metallurgy enterprises in Eastern Siberia, the petrochemical, chemical, hydrolysis, forestry and woodworking industries, as well as domestic wastewater from settlements [15].

Since the Angara is a cascade of dams and reservoirs almost throughout its entire length, there is a gradual deterioration in water quality from source to mouth, apparently there is a cumulative effect of pollution. Only after the Irkutsk reservoir does a significant deterioration in water quality occur (due to the high value of water exchange, see Table 2).

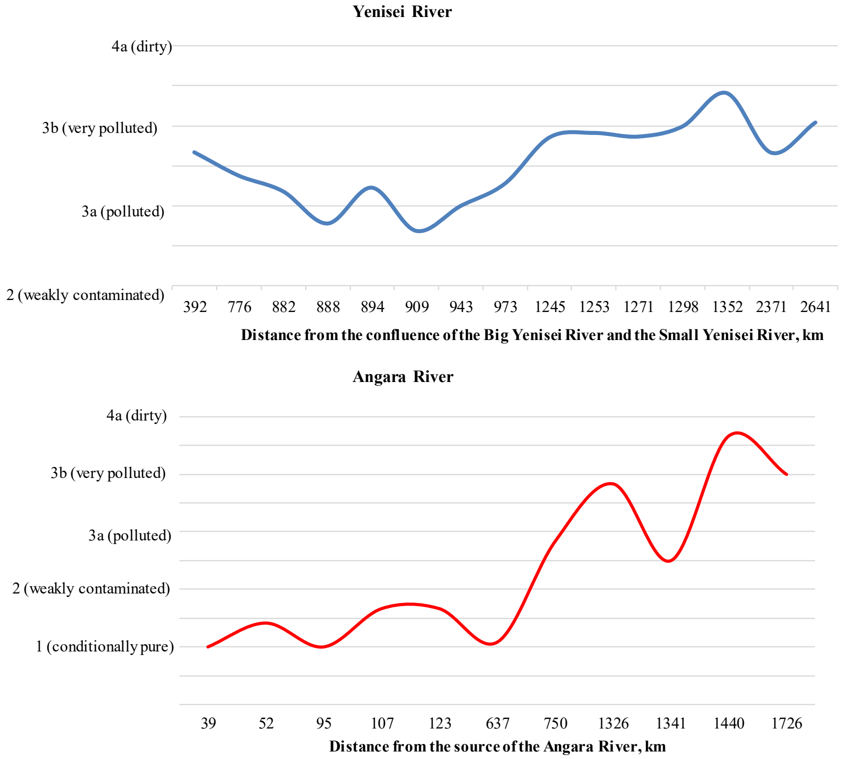


Fig. 5. Dynamics of the Average Long-Term Specific Combinatorial Water Pollution Index (2010-2021).

6 Conclusion

The article attempts to systematize disparate open data on the hydrochemical composition of regulated rivers in the Angara-Yenisei region. At the same time, the authors were most interested in the effect of the HPP cascade effect on changes in the hydrochemical regime of reservoirs and downstream sections of the Yenisei river and Boguchanskoye reservoir on the Angara River (Fig. 6).

The water temperature in the reservoirs that close the cascades of HPPs on the Yenisei and Angara rivers in spring and summer has become lower, and higher in the autumn-winter period. Thermal stratification was formed in the near-dam part due to the warming and inflow of warmer flood waters into colder winter waters.

A decrease in current velocities in reservoirs led to intensive burial of biogenic elements (Fig. 2). The resulting reservoirs "bloomed" and most of the phosphorus and nitrogen passed into organic compounds. To a greater extent, this phenomenon is typical for the Angara - regulation has turned the river into a chain of reservoirs with a stagnant hydrological regime with high concentrations of nitrogen, phosphorus and organic matter compounds.

Exceeding the fishery standards for nitrogen compounds and organic matter has determined a significant increase in indicators of additive impact on water bodies. The reason for this is the inflow of sewage discharges from economic and industrial enterprises of Eastern Siberia. Also, in a number of cases, natural conditions add their contribution to pollution: in the water, the transformation of organic matter that came from forest landscapes is carried out and / or deposited into the river network.

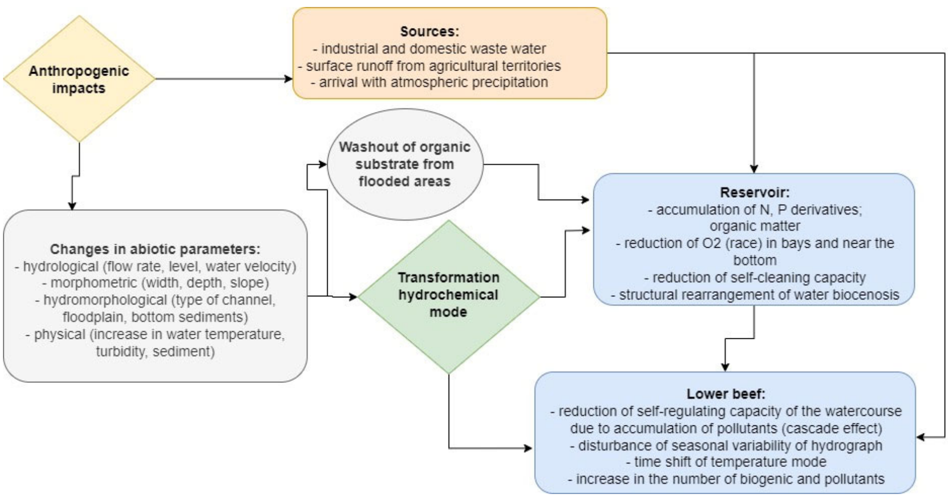


Fig. 6. Chain reaction of changes in hydrochemical processes in cascades of HPP reservoirs and downstream sections of rivers in the Angara-Yenisei region.

The movement of river water along the cascade of reservoirs is accompanied by an increase in the concentrations of most trace elements and organic matter, which are not typical for reservoirs in the cascade. In the surface waters of the study area, violations of fishery standards for the content of Al, Fe, Zn, Mn, Al¸Cu, phenols and oil products are often noted.

All these facts lead to the ecological restructuring of all hydrobiont communities. Due to the changed habitat conditions, the species composition of fish populations in the reservoirs of the Angaro-Yenisei region and their lower pools began to differ significantly from the natural ones. The main factors of impact on aquatic bioresources of the construction of HPPs are: a change in the structure, composition and productivity of the food base of fish, a change in the structure and composition of ichthyocenosis, a violation of the conditions for feeding, migration and wintering of fish, a change or degradation of spawning grounds [22].

At the same time, the probability of manifestation of negative changes in the sanitary and hygienic quality of the aquatic environment increases with an increase in the concentrations of chemicals relative to natural conditions, which is the cause of the cascade effect (Fig. 6).

Based on the above, it is possible to single out the so-called "marker substances", the increase of which indicates the effect of HPP cascading on the hydrochemical composition of surface waters - these are ammonium, nitrite and nitrate nitrogen, total phosphorus and phosphates, easily and difficultly oxidized organic substances.

This review becomes relevant in connection with the plans of En + Group to build the fifth hydroelectric power station, Nizhneboguchanskaya, in the Angarsk cascade, in the area of the village. Shiverskiy. It should be noted that the planned reservoir will be small in size - 1.37 km^3 and an average depth of 7 m. The water exchange of the reservoir according to the average long-term flow is 65 times a year [1]. As the earlier generalizations show, it is the high flow of the reservoir that reduces the cascading effect and contributes to a lower accumulation of biogenic substances and OM in surface waters.

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