Chapter

Hydropower in Russia: Case Study on Hydrological Management of the Volga-Kama Cascade

Pavel N. Terskii, Galina S. Ermakova and Olga V. Gorelits

Abstract

The capacity of hydroelectric power plants (HPPs) in the Russian Federation (RF) exceeds 50 GW. It is about 20% of the total capacity of all power plants in the country. The Volga River basin is the biggest in Europe with the catchment area of 1 360 000 km^2. It covers the most populated and most industrialized part of the European Russia. The largest cascade of reservoirs in Russia and Europe is the Volga-Kama cascade (VKC) constructed in 1930–1980. It consists of 12 great water reservoirs and HPPs with total capacity about 12 GW. The main peculiarity for the VKC management is the combination of different requirements by various economy sectors: safety, energy, navigation, water needs for domestic and industrial services, agriculture and fishery, recreation and ecological rules. These sectors often make conflicting demands for the VKC operation. The VKC management principle is to balance and satisfy all of them taking into account the changing climate and economical effectiveness. Modern decisions for the VKC management are based on two principles. First is the constant optimization of the whole VKC management rules, taking into account both climate change and the Strategy of the country development. The second is the constant technical modernization of the VKC equipment to achieve the best economical effectiveness and safety for ecosystems and population.

Keywords: Volga-Kama cascade, reservoirs, hydroelectric power plants, water resource management, water budget and regime, efficient operating, climate change

1. Introduction

Hydroelectric power plants (HPP) produce 16–17% of all electricity capacity in Russia. Currently in Russia there are [1]:

- 14 HPPs with installed capacity of over 1000 MW (6 of them in Volga river basin),
- 102 HPPs with installed capacity of over 10 MW,
- dozens of small HPPs.

Company "RusHydro" is one of the largest power generating companies in Russia. It is the leader in the generation based on renewable sources. "RusHydro" develops power generation based on the energy of water flow, sunshine radiation, wind power and geothermal energy [2]. There are several cascaded reservoirs constructed on the Great Russian Rivers – Angara and Yenisei cascade, Zeya and Bureya cascade, Lower Don cascade, Moscow river system cascade etc. The largest cascade of reservoirs in Russia is located on the rivers Volga and Kama.

The Volga River basin is the largest in Europe with catchment area about 1 360 000 km^2 (including Kama River basin). The total Volga River basin area is 40% of European territory of the Russia. The basin covers most populated and most industrialized part of European territory of Russia. It is populated with 58 mln. There are 7 cities with more than 1 mln population.

The Volga River is the longest river in Europe, its length from the source to the Caspian Sea is 3530 km. There are hundreds of tributaries along the main Volga River, the largest are Oka River (right tributary) and Kama River (left tributary). The Lower Volga region, including the unique ecosystems of Volga-Akhtuba Floodplain and Volga Delta – is the only natural part of the Volga River that is not affected by the backwater of anthropogenic HPPs dams. Annual average Volga water runoff (1881–2020) at the terminal gauging station "Volgograd" is 253 km^3. Maximum year runoff – 389 km^3 (1926), minimum year runoff – 160 km^3 (1975).

The largest cascade of reservoirs in Russia is the Volga-Kama cascade (VKC) constructed in 1930–1970s. The main reservoirs of VKC were fully completed by the beginning of 1960s. The VKC is the largest energy and transportation water system in the Europe (**Figure 1**).

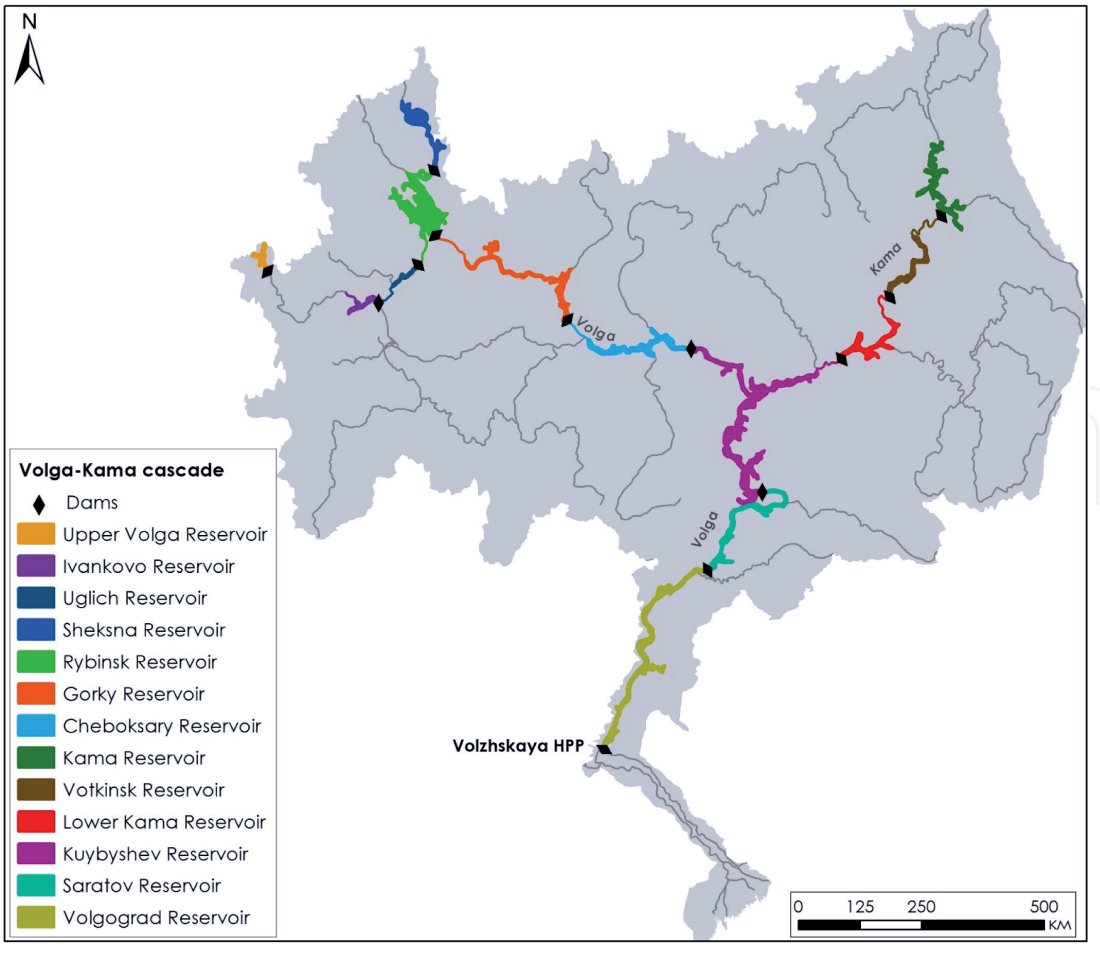


Figure 1.
Volga river drainage basin and VKC reservoirs.

Nowadays VKC includes 12 great water reservoirs with 12 Hydroelectric Power Plants (HPPs) and several small reservoirs without HPPs (**Figure 1**). Active storage of the VKC reservoirs is 80 km^3, total VKC storage – 175 km^3. Total design capacity of VKC HPPs is about 12 GW, actual capacity now is about 10,5 GW, annual hydropower generation – 35-40 billion KWh [2]. The HPPs of the VKC covering the peak part of the electricity consumption schedule are the backbone of the Unified Energy System of Russia, because it can increase electricity generation faster than other energy sources, such as nuclear or thermal power plants. The Volzhskaya HPP in the city of Volgograd – the downstream object of the VKC – is the largest HPP in Europe, with a total installed capacity of 2671 MW (**Figure 2**).

Construction of the Volga-Kama cascade was released as part of the great project "Big Volga", which was developed in the Soviet Union in the beginning of 1930s and was implemented from 1935 to 1960s. The "Big Volga" project assumed simultaneous solution of several serious problems of the European part of Russia economic development in 1930s: water transport, cheap energy, industrial and domestic water supply, agriculture and irrigation of arid regions, fisheries. There were several main purposes of the VKC construction. First was to create the transit waterway with guaranteed navigable depth about 4,5 m throughout the Volga River from upstream to the Caspian Sea, which connects the main industrial centers and raw materials regions. Second was to obtain huge amount of cheap energy. Third was the irrigation and industrial water supply.

Construction of three reservoirs in the upper stream of Volga river – Ivankovo, Uglich and Rybinsk – was the first step of the "Big Volga" project. It was started in 1930s - Ivankovo reservoir was built in 1937, but then the construction was suspended due to the Second World War. Uglich and Rybinsk reservoirs were completed only in 1955. The next step – creation of the Gorky, Kuybyshev, Kama and Volgograd (former Stalingrad) reservoirs – was fully completed by 1965 (**Figure 3**).

Figure 2.
Volzhskaya HPP in the city of Volgograd.

a) b)

Figure 3.
Uglich HPP (a) and Kama HPP (b).

Votkinsk, Saratov, Lower Kama and Cheboksary reservoirs were built on the last stage of the construction.

Total head of Volga River from the source to the mouth – Caspian Sea – is about 256 meters. Total head of Volga River between the headwater of Ivankovo reservoir and tailwater of Volgograd reservoir is 135 meters, so it gives 8400 MW total actual capacity of the Volga hydroelectric power plants. Total head of Kama River between the headwater of Kama reservoir and tailwater of Lower Kama reservoir is 55 meters, so it gives 2150 MW total actual capacity of Kama hydroelectric power plants. The main characteristics of the VKC are shown in the **Table 1**, **Figure 4**.

Figure 5 demonstrates spatial heterogeneity of local catchment areas and local water inflow to reservoirs of the VKC. The 75% inflow is generated inside the biggest local catchments of Cheboksary, Kama, Lower Kama and Kuybyshev Reservoirs. Contribution of other reservoirs is less than 10% (for each of them).

DOI: http://dx.doi.org/10.5772/intechopen.100427

№	Name of the reservoir (name of HPP if different)	River, lake	Year of completion	Reservoir full storage, *cub. km*	Reservoir active storage, *cub. km*	Time scale of regulation	Purposes*	Installed capacity of the HPP (actual capacity if different), *MW*
1	Ivankovo Reservoir	Volga	1937	1.22	0.89	daily	PNSFR	28.8 (25)
2	Uglich Reservoir	Volga	1955	1.25	0.67	interannual	PNSFIR	120
3	Sheksna Reservoir	Sheksna, Beloe lake	1964	6.51	1.85	seasonal	PNFR	84 (24)
4	Rybinsk Reservoir	Volga, Sheksna, Mologa	1955	25.4	16.7	seasonal	PNSFR	356
5	Gorky Reservoir	Volga	1961	8.82	3.90	seasonal	PNSFR	520
6	Cheboksary Reservoir	Volga	1981	4.60	0	seasonal	PNSR	1370 (820)
7	Kama Reservoir	Kama	1964	12.2	9.80	seasonal	PNSR	552
8	Votkinsk Reservoir	Kama	1966	9.36	4.45	seasonal	PNSR	1020
9	Lower Kama Reservoir	Kama	1979	4.21	0.77	weekly, daily	PNSR	1205 (566)
10	Kuybyshev Reservoir (Zhiguli HPP)	Volga, Kama	1959	57.3	30.9	seasonal	PNSFIR	2467
11	Saratov Reservoir	Volga	1971	12.9	1.75	weekly, daily	PNSFIR	1403
12	Volgograd Reservoir (Volzhskaya HPP)	Volga	1961	31.5	8.25	weekly, daily	PNSFIR	2671
13	Volga-Kama cascade	Volga, Kama	1845–1981	175	80.0	interannual, seasonal, weekly, daily	PNSFIR	11797 (10544)

**All of the VKC reservoirs are complex multipurpose impoundments, including following purposes:*
P - power generation;
N - navigation;
S - domestic and Industrial water supply;
F - fisheries;
I - irrigation;
R - recreation.

Table 1.
Main characteristics of the VKC [1, 3].

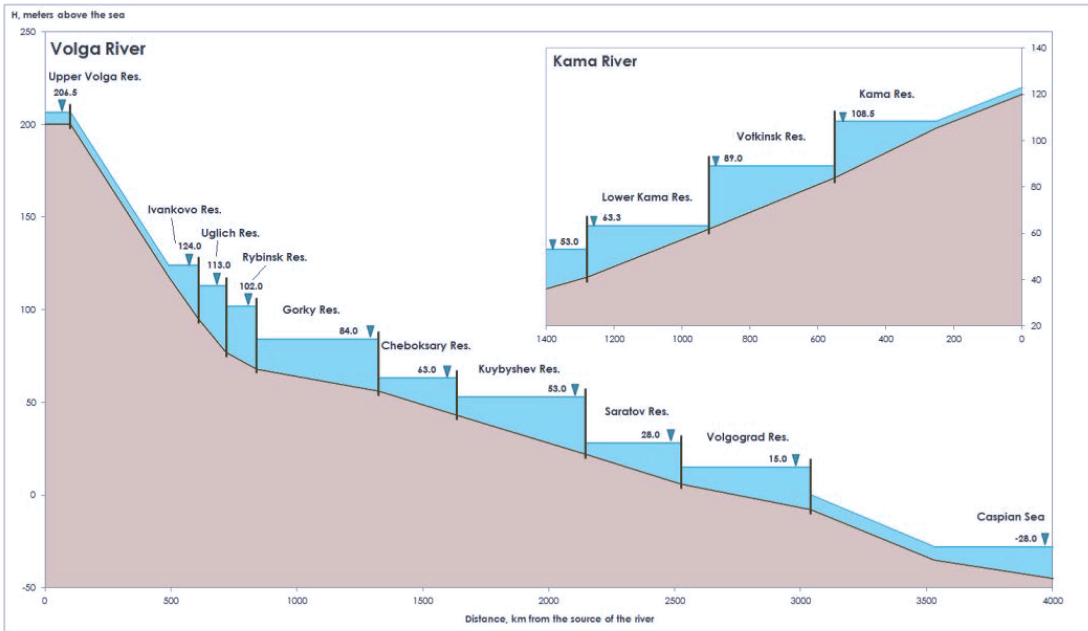
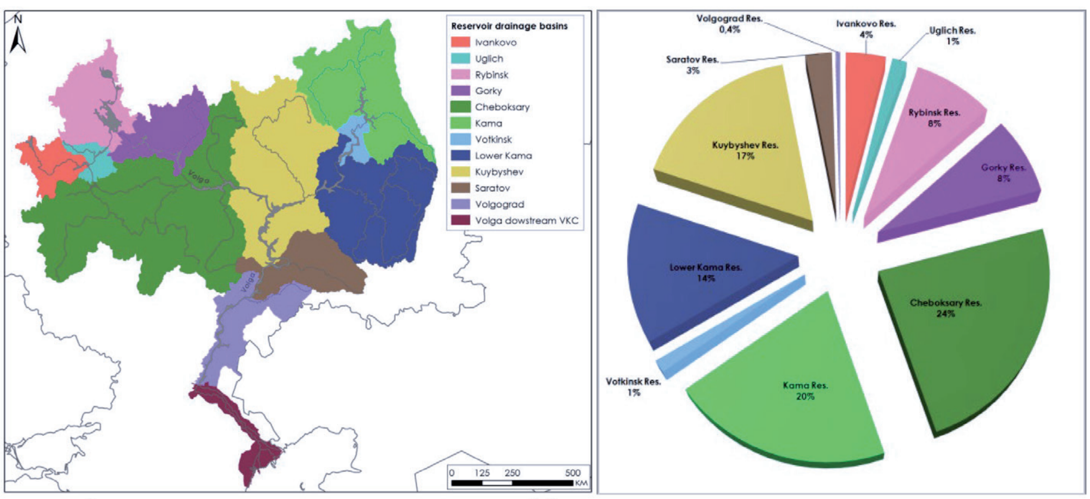


Figure 4.
VKC water surface profiles (based on materials [1, 4]).



a) b)

Figure 5.
Local catchments of the VKC reservoirs (a) and contribution of the local inflow to the VKC total inflow, % (b).

2. Natural and manmade changes in the water budget and regime

Volga River basin and all reservoirs of the VKC are located on the southern slope of the East European Plain. The basin has some unique geographic features. From Middle Ages till present days Volga River system with its hundreds tributaries were located within the borders of one state – Russia. This feature distinguishes the Volga River basin from the basins of major European rivers and determines the features of its economical and cultural development. For example, Danube River basin partially covers the territories of 19 European countries, Rhine River basin – 6 countries, basins of the Dnieper, Daugava, Neman, Maas, Oder Rivers – partially covers the territories of 3 countries.

Volga River runs into the largest inland water body in the World – into the Caspian Sea. This unique feature defines a unique ecosystem of the river basin and the Sea and allows us to investigate the hydrological regime of this huge ecosystem in the framework of single hydrological cycle, which is determined by climatic changes, the anthropogenic influence and the VKC operation.

Climate changes in the Volga River basin – is the most important challenge of the last quarter of XX Century and the beginning of XXI Century. Against the background of a general increase in air temperature these increase in the European territory of Russia reached 0.5°C over 10 years. The main increase of temperature occurred in the winter period of the year, together with increase of humidity years [5, 6].

These climate changes significantly affect the water inflow to VKC. The temperature and humidity changes are resulted in the total annual inflow increase to VKC by 13% in last 40 years. Mean annual inflow to VKC for the period 1946–1977 is 248 km^3, while for the period 1978–2020 it is about 280 km^3 (**Figure 6**) [7, 8]. But between the sub-periods 1978–1995 and 1996–2020 there are significant positive changes in Evaporative Index end Dryness Index in the Volga basin, which caused a decrease in the inflow to the cascade from 295 km^3 (1978–1995) to 268 km^3 (1996–2020). The nowadays sub-period of 1996–2020 shows decreases in local inflow to VKC reservoirs and consequently decreases in water runoff through the Volzhskaya HPP into the unique ecosystems of the Lower Volga wetlands in the past couple of decades. Such climate-induced changes in the parameters of hydrological regime could explain only a part of the observed runoff decreases and changes in evaporative loss. The remaining, unexplained part is most likely related to the considerable changes in land-use at the agricultural regions of the Volga River catchment and other anthropogenic pressures [9].

Although climate changes much more strongly affects the seasonal inflow redistribution during last 40 years. The main feature of seasonal redistribution is alignment of intra annual unevenness of water inflow: great increase (about 63%) of winter water inflow because of warm and humid winters, increase (33%) of summer-autumn water inflow and slight decrease (2%) of spring flood period water inflow (**Figure 7**).

Significant intra annual water inflow redistribution caused the changes in the VKC operation. The winter water runoff and winter generation increased strongly.

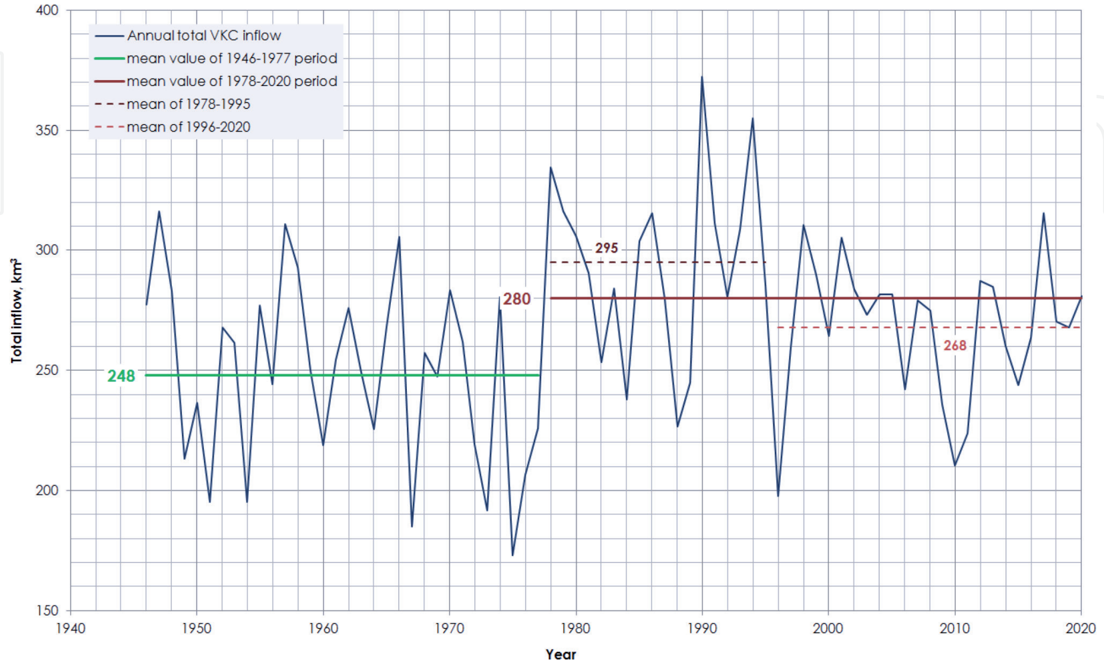


Figure 6.
Total annual inflow to the VKC (based on materials [7, 8]).

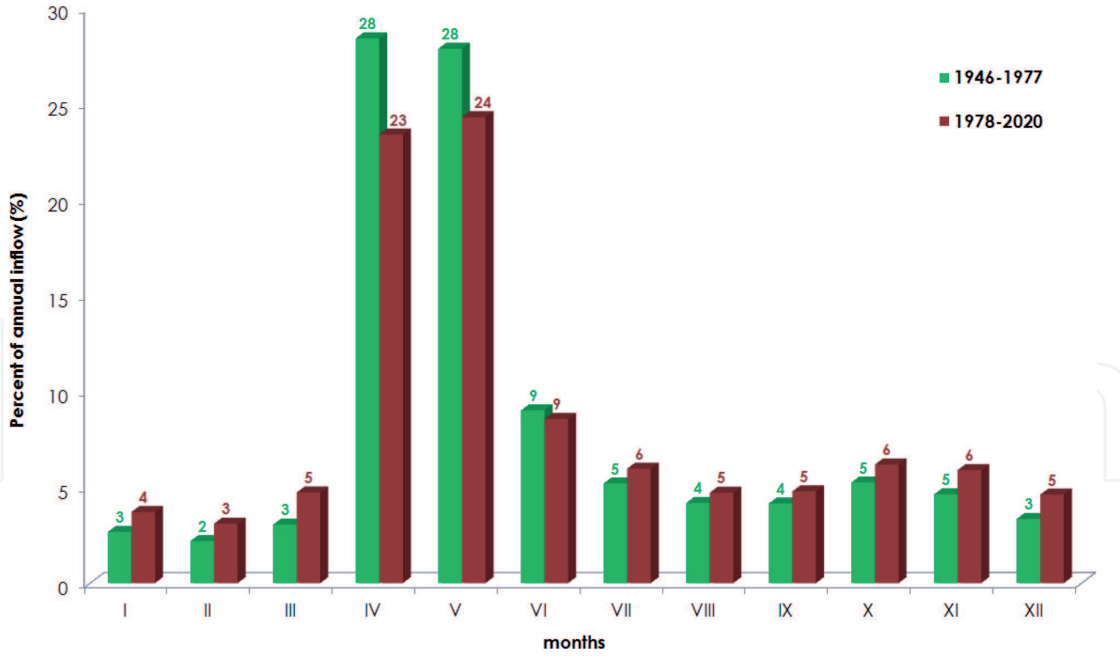


Figure 7.
Redistribution of the intra annual water inflow (based on materials [7, 8]).

3. Management principles

All of the VKC reservoirs are integrated-purpose water bodies. The complexity of the reservoir operation problem depends on purposes compatibility. If the purposes are more compatible - less effort is needed for coordination [10]. The main peculiarity for the VKC management is the combination of many requirements of various sectors of the economy: technical safety, energy, navigation, water needs for domestic and industrial services, agriculture and irrigation, fishery, recreation and ecological requirements. These sectors usually make conflicting demands to the VKC operation. The VKC management principle is to balance water users and consumers' demands and satisfy all of them taking into account the current conditions of a changing climate and the changed regime of local inflow to the VKC reservoirs and resulting total runoff downstream the cascade to the Lower Volga and Caspian Sea [5, 11].

There are several types of water consumption: domestic water supply, industrial and agricultural water consumption, irrigation. The largest water consumers are concentrated in the certain places associated with large cities. However, smaller ones are widely distributed along the lateral tributaries.

The important water users are hydropower engineering, water transport, fishery and recreation. To meet the requirements of these users, it is necessary to fill the reservoirs and not to exceed regulated water levels during the spring flood period. Reservoirs of the VKC serve to moderate both the flood risk and risk of summer droughts.

The reservoir operation is the water resource management, which regulates the water regime in interannual, seasonal, weekly and daily scales (sub-daily regulation also exists). The methods of reservoir operation are divided into operating curve method and rational operation [12]. Operating curve method makes possible the reservoirs functioning without detailed hydrological information and without enough range of hydrological forecast. The regulation procedures are being made depending on the operating curve, which represents the linkage between the day-by-day upstream water level and the discharge through the dam. The operating curve preparation is the goal of the water regime calculations based on stochastic programming for the optimal discharge planning.

Nevertheless, the operating curve cannot provide the reservoir regulation in case of emergency hydrological situations and in case of rapid change in the water management plans. Rational reservoir regulation begins to be implemented by applying the multiple forecast calculations of local inflow. In case of moderate situation (without rapid change in inflow forecast), rational regulation does not require excluding the operating curve from regulation. Rational regulation is prior to the operating curve method in case of complicated hydrological situation and changing inflow forecast.

This combination of the VKC regulation methods is based on the assessment of the forecast and hydrological situation (forecast-situational regulation). This kind of regulation is applied for different water seasons – spring and rain floods and flashes, summer and winter low water periods.

It begins with the hydrological forecast of the VKC distributed lateral inflow, compared to the water consumption plans and initial water level conditions for all reservoirs. Then different scenarios between the lowest and the highest water inflow are calculated and these results are used for the operation. If the real inflow begins to differ from the chosen plan, the scenario is being changed to fit the real inflow.

The main operating method for the low-water season is the compensatory regulation. Upstream reservoir storage gives the guaranteed discharge to provide the uninterrupted discharge through the downstream reservoir. The capacity of the VKC in the low-water season depends on the cascade regulation in the spring flood season. There are three main optimization tasks to operate the reservoirs: to choose the most rational regime of the spring flood transit, to choose the regime of water use during the low-water season or period, to optimize the cascade regulation using the operating curves. There is special software to meet this challenge. WATER RESOURCES and CASCADE systems serve the goal of choosing the VKC operating regime. ECOMAG is the distributed hydrological model with integrated operating curve method. It is used to calculate the distributed water inflow to the VKC [13, 14].

4. Problems and modern decisions

Multiple purposes of the VKC use leads to several types of conflicts between main users. According to [9] these conflicts are: conflicts in space, conflicts in time, conflicts in discharge. These conflicts have to be resolved in the most effective way by the reservoirs operation.

The main problems of the VKC operation are as follows:

- river runoff is the stochastic process with the significant calculation uncertainties;
- climate induced changes of annual and intra annual water inflow to the VKC, that are observed for last 40 years, require revision of current operating rules;
- the reservoirs capacity is limited with the construction and safety storage;
- multiple purpose regulation requirements meet conflicts among demands of various water users and consumers;
- during the low-water (and even average) years all water users and consumers are not ensured with water supply with the same high reliability.

To solve these problems the strategic and tactical planning has to be used. Strategic planning attended to solve the long term goal choice problem, i.e., the preferable realizable set of the values of water availability for its users and the key parameters of the VKC functioning. Tactical (annual) planning with decisions made at the level of Interdepartmental Working Group with the aim to take into account the specific hydrological and water-management conditions of the current year. These goals can be achieved by constructing the wide range of attainable probabilities. The final compromised decision is based on Pareto boundary for these multiple attainable probabilities by the consolidated negotiations between the main water users [14].

Modern decisions for the VKC management are based on two branches. First is the constant scientific-based optimization of the whole VKC management rules, taking into account both climate change and the Strategy of the country development.

One of the optimization perspectives is the change in the VKC operation by using the variable (against planned one) forecast-based water release in the spring flood period in the highest and lowest zones of inflow probability curve. It looks possible with help of long-range hydrological forecast (about 1 month). In case of estimated high water inflow reservoirs should release additional water volume. In case of low water forecast – reservoirs should decrease water discharge. It allows to decrease subsequent water volume, needed to fill reservoirs, and to increase water capacity for the Lower Volga supply. This kind of operation is mentioned for the pre-flood period in the Rules [14], but real methodology and legislative basis are not developed yet. Moreover it will require the revisions of the Rules.

The second is the technical modernization of the VKC to achieve the best effectiveness and safety. It should provide the required energy supply based on lower winter discharge. Filling the Cheboksary and Lower-Kama reservoirs up to projected levels can provide the ability to operate the effective and total storage of VKC in more efficient way [15].

5. Conclusions

The main environmental effect of river regulation in general and hydropower reservoir operations in particular is the alteration of the stream flow regime at various time scales, including seasonal, monthly, daily and sometimes hourly. This effect is fully manifested in the only natural area of VKC - the Lower Volga, including the unique ecosystem of Volga-Akhtuba floodplain, where the UNESCO Biosphere Reserve is located, and Volga Delta. The change in the spring flood regime led to a serious change in the landscapes and water bodies of the whole Lower Volga and the steppe formation of the northern part of Volga-Akhtuba floodplain. This negatively affected the state of the entire ecosystem of the Lower Volga, including Volga Delta and Northern part of the Caspian Sea [11].

The main results of VKC operation to the beginning of XXI Century are as follows:

1. Guaranteed navigable depths of about 4,5 m are provided throughout the Volga and Kama Rivers from upstream to the Caspian Sea.

2. Reducing the threat of floods and droughts are provided by VKC operation with seasonal, weekly, daily regulation.

3. VKC cheap electricity enters the Russia's Unified Energy System. VKC generation covers the peak loads in the Unified Energy System of Russia.

4. Water storage in VKC reservoirs provides sustainable water supply for the cities (population), industry (plants and factories), agriculture and irrigation, recreation and fishery.

5. Climate changes and water use protocols emphasize that reservoir operation should have flexible structure and scenario concept based on modern scientific and computational achievements.

VKC management and operation improvement is the governmental goal of whole institutes. Authors only may suggest some general vectors to solve main problems of the VKC operation. First - to increase the density of hydrological gauging network in the VKC catchment to have the basis for improvement of the stochastic description of the water inflow. Second - to develop more effective medium and long range hydrological forecasts. Because of problem of water inter annual and long-term temporal distribution these improved forecasting methods should support the decreasing of water losses during flood periods and save it for the deficit periods by dynamical storing it in the VKC. Finally - to develop the legislative basis for new implementation of variable operating rules of water management of the VKC.

Acknowledgements

The chapter is based on materials and data collected under the State contract #10-GK/FCP-2013 “Water management complex of the Russian Federation in 2012-2020” realized by Zubov State Oceanographic Institute (SOI) with significant contribution of Russian Academy of Science Water Problem Institute (WPI), Kostyakov All-Russian Research Institute for Hydraulic Engieneering and Land Reclamation (VNIIGIM), Caspian Research Institute for fishery, Hydrometeorological Research Center of Russian Federation (Hydrometcenter).

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

Authors are thankful to members of Automated Methods lab in SOI and personally to Igor Zemlyanov (PhD, head for the lab, vice director of the Institute) for the overwhelming support, Aleksander Buber (VNIIGIM), Mikhail Bolgov (WPI) and Vladimir Kryzhov (Hydrometcenter) for consultations.

Author details

Pavel N. Terskii[1]*, Galina S. Ermakova[2] and Olga V. Gorelits[2]

1 Faculty of Geography, Lomonosov Moscow State University, Moscow, Russia

2 N.N. Zubov State Oceanographic Institute, Roshydromet, Moscow, Russia

*Address all correspondence to: pavel_tersky@mail.ru

References

[1] Dvoretskaya M I, Zhdanova A P, Lushnikov O G, Sliva I V. Handbook of Renewable energy. Hydroelectric power plants of Russia. St. Petersburg: Polytechnic Publishing House; 2018. 224 p.

[2] The official website of the "RusHydro" company. Available from: http://www.eng.rushydro.ru/company/in_brief/ [Accessed 2021-04-21]

[3] Georgievsky V Y, editor. Scientific and applied reference book: Long-term characteristics of water inflow into the largest reservoirs of Russian Federation. Moscow: RPC Ofort; 2017. 132 p.

[4] Kryzhov V N, Gorelits O V. The Arctic Oscillation and its impact on temperature and precipitation in Northern Eurasia in the 20th Century. Russian Meteorology and Hydrology. 2015; 40: 711-721. DOI: 10.3103/S1068373915110011

[5] Juzbaši A, Kryjov V N, Ahn J- B. On the anomalous development of the extremely intense positive Arctic Oscillation of the 2019-2020 winter. Environment Research Letters. 2021; 16, 05500. DOI:1088/1748-9326/abe434

[6] Georgievskii V Y, Alekseev L P, Litova T E, Dubrovskaya K A, Zadonskaya O V, Fuksova T V. Water inflow into the reservoirs of the largest hydroelectric power plants in the Russian Federation for different time intervals. Database Official Registration Certificate RU 2016621140, 22.08.2016 (In Russian)

[7] State report "Water resources conditions and use in Russian Federation in 2015". Available from: https://water-rf.ru/water/gosdoc/378.html [Accessed: 2021-04-25]

[8] Ahlén I, Vigouroux G, Destouni G et al. Hydro-climatic changes of wetlandscapes across the world. Sci Rep. 2021; 11, 2754. DOI: 10.1038/s41598-021-81137-3

[9] Jain S K, and Roorkee NIH. Introduction to reservoir operation. Technical Report. 2019.

[10] Gorelits O V, Ermakova G S, Terskii P N. Hydrological regime of the lower Volga river under modern conditions. Russian Meteorology and Hydrology. 2018; 43, 10: 646-654. DOI:10.3103/S1068373918100035

[11] Levit-Gurevich L K. Rational water resources management of reservoirs on the example of Volga-Kama Cascade. Izvestia of Samara Scientific Center of the Russian Academy of Sciences. 2012; 14 (4): 2343-2354.

[12] Danilov-Danilyan V I, editor. Justification for water management strategies. 2006. 336 p.

[13] Motovilov Y G. ECOMAG: a distributed model of runoff formation and pollution transformation in river basins. IAHS Publ. 2013; 361: 227-234.

[14] Bolgov M V, Buber A L, Komarovskii A A. Searching for Compromise Solution in the Planning and Managing of Releases into the Lower Pool of the Volgograd Hydropower System. 1. Strategic Planning. Water Resources. 2018; 45: 819-826. DOI: 10.1134/S0097807818050044

[15] Draft of the Rules for the Use of the Kuybyshev, Saratov, Volgograd Reservoirs. Federal Agency of water resources: Moscow, Russia, 2012. Available from: http://nvbvu.ru/files/4517.pdf [Accessed 2021-08-26]