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CHAPTER

2

The Volga River

Natalya Mineeva[1], Valentina Lazareva[1], Alexander Litvinov[1], Irina Stepanova[1], Grigory Chuiko[1], Vladimir Papchenkov[1,†], Ludmila Korneva[1], Grigory Shcherbina[1], Ekaterina Pryanichnikova[1], Svetlana Perova[1], Yury Gerasimov[1], Dmitry Karabanov[1], Boris Levin[1], Elena Borovikova[1], Irina Voroshilova[1], Alexander Tsvetkov[1], Alexander Okhapkin[2], Galina Shurganova[2], Svetlana Dvinskikh[3], Victor Noskov[3], Alexander Kitaev[3], Margarita Alexevnina[3], Anna Istomina[3], Elena Presnova[3], Elena Seletkova[3], Mikhail Baklanov[3], Euvgeny[3], Zinov'ev[3], Martin Schletterer[4]

[1]Papanin Institute for Biology of Inland Waters, Russian Academy of Sciences, Yaroslavl, Russia [2]Nizhegorodski State University, Nizhni Novgorod, Russia [3]Permsky State University, Perm, Russia [4]University of Natural Resources and Life Sciences, Institute of Hydrobiology and Aquatic Ecosystem Management, Vienna, Austria

OUTLINE

† Deceased.

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2.1 Introduction

The Volga River, at 3690 km, is the longest river in Europe and 16th in the world. The Volga ranks fifth in Russia, following the Ob', Yenisey, Lena, and Amur in Siberia. The Volga flows into the Caspian Sea, the largest inland sea on earth (see map). There are about 151,000 rivers >10 km in length within the Volga catchment. Of these, 2600 flow into the Volga directly, and the Kama, Oka, and Sheksna rivers are the largest. The 1.4 million km^2 catchment area of the Volga drains about 33% of European Russia, covering various biomes from taiga to semidesert. The most northern point is at the source of the Visherka River in the Kama River basin at latitude 61°55′N, and the southern border runs along the outer edge of the Volga delta at 45°35′N. Its western border is at longitude 32°05′E and the eastern border is at 60°22′E (Butorin and Mordukhai-Boltovskoy, 1979) (Fig. 2.1).

Historically, the Volga has attracted the attention of many scientists from different fields, resulting in a large number of articles and books. Much of the principal information has been summarized previously in the monograph *The River Volga and its Life* published in Russian (1978) and later translated into English (Butorin and Mordukhai-Boltovskoy, 1979). The basic geographical and historical material used in this chapter was prepared using this monograph as well as material from the *Grand Soviet Encyclopedia* (Shmidt, 1928a), *Encyclopedic Dictionary* (Belevsky, 1892), and the open-access Internet site Wikipedia—Open Encyclopedia (http://ru.wikipedia.org/). Based on these publications, a chapter was prepared for the first edition of the book *Rivers of Europe* (Tockner et al., 2009). The present chapter is supplemented by data of recent years.

2.1.1 Human history

Initial records of the Volga were found in the works of the ancient Greek historian, Herodotus, in 500 BCE. In ancient history, the Volga was known as the Atil, Itil, or Idil, a Turkish name meaning "long river" or "river of rivers." The ancient scholar Ptolemy of Alexandria mentions the Low Volga in his *Geography*, calling it the Rha"generous." "Volga" is probably a Slavicization of proto-Baltic meaning "long river," "bright river," "holy river," or "Mother Volga." The Volga is considered to be the national property of Russia, often emotionally included in Russian songs, literature, films, and the fine arts.

The geographical situation of the Volga promoted human colonization by various nations and played an important role in the movement of people between east and west (from Asia to Europe) as well as south and north. The first humans in the Volga region are thought to be from the late Stone Age. The southern part of the Volga region was inhabited initially by nomadic tribes: Scythians, then Sarmatae, and since CE 400 by emigrants from Asia. Huns arrived in CE 500–600, Bulgarians occupied the middle region of the Volga, and Khazar Khaganate was formed in the Low Volga region in CE 700. The Slavonic Vyatichi, Olyane, Radimichi, Severyane tribes inhabited the upper region of the catchment.

In CE 1000, new nationalities colonized the Low Volga region from the Urals: Ugrs arrived from the Oka and Don basins, Pechenegs in CE 1000, and Polovtsy in CE 1100. Following the Khazar Khaganate decline, a Bulgarian empire flourished where the river Kama joins the Volga. By the end of CE 1100, Slavs along with the Finnish tribes Ves', Merya, Muroma, Cheremis, and Mordva lived in the Oka, Kama, and Vyatka regions of the upper Volga. In the beginning of the 13th century, Tatar-Mongols occupied the lower and middle Volga regions. Around 1240, a Mongol state, the Golden Horde, was established and endured up to the 16th century. The Kazan Khanate with its capital in Kazan was part of this state in the middle Volga from 1438 to 1552. The Russian state became prominent from the middle of the 15th century, i.e., Muscovite Russia gained independence from the Tatars in 1480. From 1721 to 1918, the Russian state was officially named the Russian Empire, and the Russian Federation since 1918 (the Soviet Union from 1922 to 91). The Volga region was important in various wars: peasant wars as well as revolts of peasants and Cossacks under the leadership of Stepan Razin and

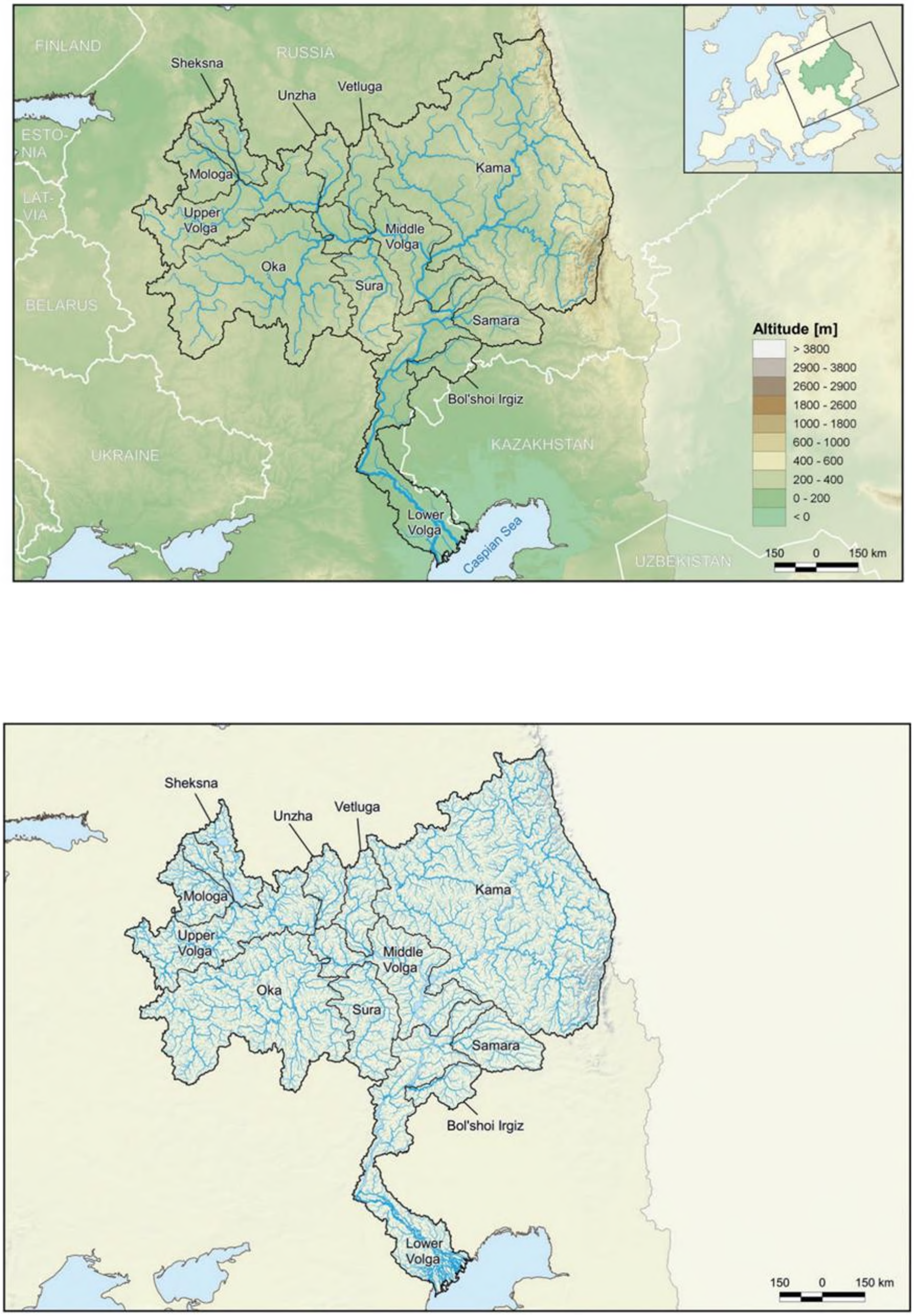

FIG. 2.1 Digital elevation model (upper panel) and drainage network (lower panel) of the Volga River basin

Yemelyan Pugachev in the 17–18th century, the Civil War of 1917–22, and the Battle of Stalingrad in 1942–43 during World War II. The present ethnographic composition of the Volga region consists of Indo-European (Russian majority, Ukrainians, Germans, Belorussians, Poles, Latvians), Finnish (Votyaks, Permyaks, Chemerisis, Mordvas, Karels), and Turkish (Bashkirs, Kyrgyzs, Tatars, Chuvashs) peoples. Kalmyks, representatives of Mongol nationality, form a separate group.

As of this writing, the Volga basin is divided into three sections referred to as the upper, middle, and Low Volga. Gorky Dam and Kuibyshev Dam are considered the border of the upper and middle Volga, and the middle and Low Volga, respectively. The present chapter includes subsections describing each region of the Volga, along with separate sections on its largest tributaries: Kama, Oka, and Sheksna.

2.2 Biogeographical setting

The Volga catchment is on the Russian plain, encompassing various latitudinal climatic zones. Atmospheric circulation and input of solar radiation increases from north to south (Pivovarova and Stadnik, 1988) and is strongly influenced from air masses generated by the Atlantic Ocean. Longitudinal zonation is emphasized by the transgression from taiga to semidesert, incorporating local human influences. The northern part of the catchment is in a forest belt that includes southern taiga and mixed coniferous–deciduous forests. The south/southeast of this forest belt includes the forest-steppe biome, and even farther south are found steppe, semidesert, and desert biomes. The desert biome is found only near Caspian lowlands adjacent to the southern Akhtuba floodplain. The Akhtuba floodplain and the Volga delta are intrazonal geographical regions, in sharp contrast to the desert belt.

2.2.1 Paleogeography of the basin

The modern Volga River valley was formed in the postglacial period, and the hydrographic network of the Russian plain was transformed during different geologic epochs. Tectogenesis of the Russian plain in the southeast from geosynclines to platform occurred in the Paleozoic, giving rise to a meridian flexure. The most intensive formation was in the Age of Reptiles (Obidientova, 1975). By the end of the Tertiary, the size and contour of the Ancient Sea (i.e., area of the modern Caspian Sea) changed several times. Regressions and transgressions of the Caspian Sea as well as modifications in principal watershed arrangement of the Russian plain continued into the Quaternary and Holocene. The Paleo-Volga and Paleo-Kama were the main rivers to transverse the eastern part of the Russian plain at this time. The Oka glaciation began about 700,000 years ago, lasting about 200,000 years, and was the first glaciation of the Volga River catchment. At this time, the formation of the Caspian Sea began as well as the first Quaternary Caspian transgressions (Baku transgressions).

During the last glaciation, the Valdai glaciation about 10,000 years ago, only a small area of the Volga River catchment bordered by the Valdai Hills was covered by ice. Fluctuations in the Caspian Sea since the end of the Khvalynsk transgression up to the present have been the most important postglacial changes in the Volga River catchment. There have been times in the last 200 years when the Caspian Sea was lower than today, the greatest decrease took place in the 5th and 6th century. The highest levels of the Caspian Sea, called the new Caspian transgression, were observed in the 14th–16th century and especially in the early 19th century. An increase in sea level has occurred since 1990.

2.3 Physiography and climate

2.3.1 Geological structure and relief

The Russian plain is derived of Precambrian crystalline rocks and covered by a thick layer of sedimentary rocks within the boundaries of the Volga catchment. This sedimentary layer exceeds 3000 m around the Moscow syncline, reaches 8000 m along the Glasov syncline near the Urals, and 10,000 m near the Caspian. The lowlands, at <200 m asl, occupy about 65% of the Volga catchment. Upland areas in the lowlands rarely exceed 200–250 m asl, although reaching 350–400 m at some points, and delineate the various subbasins of the Volga.

The Valdai Hills began forming in the middle Carbon period with a second lift occurring in the middle Pleistocene. The highest peak of the Valdai Hills is at 346 m asl at the head of the Tsna River that flows into Vyshnevolotskoe reservoir. The landscape of the Valdai Hills bear imprints of glaciation that ended some 15,000 years ago, including numerous lakes. Forests cover more than 60% of the area, and arable land is insignificant. The Valdai Hills reside mostly in the coniferous–deciduous forest biome with a small part in the taiga biome in the north. The soil is stony, and there are "erratic blocks" typical of terminal glacial moraines. Running from north to south, the Volga folds and forms a flexure referred to as the "seam" of the Russian plain. A narrow near-Volga trough extends from Kazan south to Volgograd where it expands and disappears in the vast pre-Caspian lowland. The Volga presently flows through this trough, taking the same course as its predecessor, the Paleo-Volga.

Areas of the near-Volga upland are distinctive, being best represented by the characteristic Zhiguli Hills. They are a fault mountain range, 75 km long and up to 370 m asl, situated in the Samara Bend (Samarskaya Luka) of the Volga. The Paleogene Sea was present here in the beginning of the Cenozoic. The northern slope of the Zhiguli Hills is covered with deciduous and pine forests, alternating with forest-steppe along the southern slope. In the west, the near-Volga upland gradually enters the Oka-Don Lowlands. The Volga floodplain extends over the lowland, replacing the ancient synclines of the Russian plain. Flowing from the Valdai Hills, the Volga enters the Volga lowlands. After crossing the southern Mologa-Sheksna depression, it flows through several interconnected lowlands: Yaroslavl-Kostroma, Unzha, Balakhna, Mari, Zavolzhye, and the near-Caspian. The Volga cuts through adjacent uplands near Plyos and Samarskaya Luka.

2.3.2 Climate

Climate of the upper Volga basin is moderate continental, characterized by above freezing air temperature for 7 months from spring through autumn and below freezing temperature for 3–4 months in winter. Mean annual air temperature decreases from 3.4°C in the west to 2.8°C in the east of the catchment. The warmest month is July, averaging 16.7–19.2°C, whereas January is the coldest month with mean temperatures ranging from −10.1 to −13.4°C.

Due to global warming since the mid-1970s, air temperature on the ET of Russia increased on average 0.43°C/decade (Second Assesment… 2014). Beginning in the 21st century, air temperature increased by 2–3°C in January and 1–2°C in July in the Rybinsk reservoir basin (Zakonnova and Litvinov 2016). Annual precipitation varies from 548 to 706 mm, although extremes of 1.5 times those values can occur during wet or dry periods. Maximum rainfall occurs in summer, and relative humidity varies from 55% to 75% in spring to 70%–90% in winter. Southerly, westerly, and north-westerly winds prevail, increasing from west to east. Monthly average wind speeds reach 3 m/s, being relatively constant in spring and summer and increasing sharply in autumn and winter.

Climate of the middle Volga basin is similar to that of the upper basin in winter, but the summer climate is about three times less variable. Mean annual air temperature varies from 3.1°C in the north to 5.3°C in the south. Below freezing air temperatures average 161 days in the north and 147 days in the south. The coldest month is January with average temperatures of −12.5 to −14.2°C, while July is the warmest month with average temperatures of 19.5–21.5°C. Relative humidity ranges from 50% in May to 90% in November and December. Annual precipitation ranges from 282 mm in the south to 626 mm in the north. Minimum precipitation occurs from January to April and maximum from August to November. Westerly winds with velocities up to 5 m/s are most common (42%), although southerly winds (48%) prevail during winter and westerly winds (46%) during summer.

Climate of the Low Volga basin is mostly continental, as the influence of the Caspian Sea is insignificant. Mean air temperature in the north and south varies from −9.6 and −6.9°C in January to 20.6 and 25.1°C in July, respectively. Easterly and south-easterly winds are predominant, bringing inland air masses and reducing relative humidity. Mean annual precipitation ranges from 340 mm in the north to 175 mm in the south.

2.4 Geomorphology, hydrology, and biogeochemistry

2.4.1 Geomorphic development of main corridor

The river network of the Volga looks like a branching tree in the north that evolves into a single trunk rooting as a delta in the Caspian Sea in the south. The Low Volga is divided into many side-arms and the 515-km-long Akhtuba is the largest. The delta at the confluence of the Volga and Caspian Sea occupies a total area of 6565 km^2. Twelve large reservoirs with a total storage of 168 km^3 and total area >23,000 km^2 are found in the catchment, nine of these directly on the Volga River (Table 2.1). Most of the Volga from the town of Tver to Volgograd is affected by an uninterrupted cascade of eight large shallow reservoirs, considerably slowing the flow velocity of the river (Table 2.2). The reservoirs differ in terms of morphometry, lateral inflow, water exchange, water chemistry, optical regime, and trophic status (Avakyan et al., 1987; Butorin and Mordukhai-Boltovskoy, 1979; Mineeva, 2004).

The Upper Volga—The Upper basin is boreal, covering 229,000 km^2. The source of the Volga is in the Valdai Hills at 228 m asl, occurring as a small brook flowing from a bog through the lakes Malyi Verkhit and Bolshoi Verkhit (Photo 2.1 A). It then flows through a chain of lakes (Sterzh, Vselug, Peno, and Volgo) that form Verhnevolzhskoe reservoir used to store water for navigation in the Upper Volga. The Verhnevolzhskaya dam was built below Lake Volgo in 1843 and completely rebuilt in 1943–47. Major rivers flowing into Verhnevolzhskoe reservoir include the Runa, Kud', and Zhukopa.

TABLE 2.1 General characterization of the Volga River Basin

	Upper Volga	Middle Volga	Lower Volga	Mologa (Upper Volga)	Sheksna (Upper Volga)	Unzha (Upper Volga)	Oka (Middle Volga)	Sura (Middle Volga)	Vetluga (Middle Volga)	Kama (Middle Volga)	Samara (Lower Volga)	Bol'shoi Irgiz (Lower Volga)
Mean catchment elevation (m)	162	201	88	150	145	158	169	201	143	233	160	89
Catchment area (km^2)	236,268	973,712	221,316	37,462	19,445	28,941	245,000	67,018	38,974	516,891	46,950	24,542
Mean annual discharge (km^3)	49.6	244.4	253.9	7.5	5.7	4.9	39.2	6.7	8.4	104.1	1.6	1.1
Mean annual precipitation (cm)	66.1	58.7	405	69.1	63.1	61.6	60.5	55.1	59.9	58.7	47.3	42.3
Mean air temperature (C)	3.5	3.1	6.4	3.6	3.1	2.8	4.8	4.4	3.1	2.0	4.3	5.7
Number of ecological regions	2	8	4	2	1	2	4	3	2	7	2	1
Dominant (>25%) ecological region	59; 60	28; 59	55	60	60	60	28; 59	28	60	60	55	55
Land use (% of catchment)												
Urban	0.3	1.1	1.1	0.1	0.2	0.2	2.1	1.2	0.5	0.5	1.0	0.6
Arable	24.4	49.5	54.8	24.5	24.5	12.4	53.6	71.9	31.5	35.2	73.5	40.6
Pasture	6.7	0.2	21.5	7.3	0.7	0.2	10.3	0.1	2.0	0.2	3.7	36.1
Forest	57.6	46.2	16.6	48.5	54.8	85.7	32.1	25.8	61.7	61.6	19.2	19.8
Natural grassland	0.0	1.5	2.4	0.0	0.0	0.0	0.0	0.9	0.0	1.0	2.4	2.6
Sparce vegetation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetland	6.5	0.0	0.0	14.5	3.7	0.9	1.5	0.0	4.3	0.0	0.0	0.0
Fresh waterbodies	4.5	1.5	3.6	5.1	16.1	0.6	0.4	0.1	0.0	1.5	0.2	0.3
Protected area (% of catchment)	6.1	5.2	7.0	8.0	11.7	3.1	5.1	4.2	2.9	5.1	1.7	5.1
Water stress (1–3)												
1995	1.0	1.3	1.3	1.0	1.0	1.0	2.0	1.1	1.0	1.0	1.0	1.1
2070	1.0	1.3	1.3	1.0	1.0	1.0	2.0	1.1	1.0	1.0	1.0	1.1
Fragmentation (1–3)	3	3	3	1	3	1	1	1	1	3	1	1

TABLE 2.1 General characterization of the Volga River Basin—cont'd

	Upper Volga	Middle Volga	Lower Volga	Mologa (Upper Volga)	Sheksna (Upper Volga)	Unzha (Upper Volga)	Oka (Middle Volga)	Sura (Middle Volga)	Vetluga (Middle Volga)	Kama (Middle Volga)	Samara (Lower Volga)	Bol'shoi Irgiz (Lower Volga)
Number of large dams (>15 m)	4	2	2	0	1	0	0	0	0	3	0	0
Native fish species	42	45	45	n.d.	21	n.d.	30	n.d.	n.d.	36	n.d.	n.d.
Nonnative fish species	14	19	17	n.d.	1	n.d.	9	n.d.	n.d.	5	n.d.	n.d.
Large cities (>100000)	2	18	8	0	0	0	10	2	0	6	2	0
Hunan population density (people/ km^2)	23	52	40	9	29	5	113	38	9	56	27	9
Annual GDP ($ per person)	3137	2206	2045	2916	3058	3138	2882	1727	2188	2027	2149	2016

n.d.: No data
For data sources and detailed explanation see Chapter 1.

TABLE 2.2 Physico-chemical and biological parameters of the Volga River based on Butorin & Mordukhai-Boltovskoy 1979, Kopylov 2001, and author's original data.

	Upper Volga reservoirs				Middle Volga reservoirs		Low Volga reservoirs		
Parameters	Ivankovo	Uglich	Rybinsk	Gorky	Cheboksary	Kuibyshev	Saratov	Volgograd	Unregulated
Length, km	120	143	250	430	341	510	312	540	576
Mean depth	3.4	5	5.6	5.5	4.7	9.3	7	10	n.d.
Water exchange, yr^{-1}	10.6	10.1	1.9	6.1	20.9	4.2	19.1	8	n.d.
Transparency, m	0.7	0.6	0.8	1.1	1.0	1.3	2.0	1.7	1.0
Water T, °C*	23.3	22.6	20.2	19.7	19.6	19.9	19.9	21.0	22.0
	19.9	21.2	19	18.6	19.5	18.7	19.4	20.1	21.7
Color	56	52	72	50	52	46	35	36	29
Conductivity, µSim/cm	262	268	269	223	253	304	351	349	337
O_2, mg/L*	7.9	8.9	9.1	9.2	8.0	8.4	8.9	8.7	8.7
	3.6	4.4	6.8	7.9	7.3	7.1	8.4	7.6	8.7
TN, mg/L	1.26	1.17	0.88	0.99	1.1	0.99	1.0	0.97	1.09
N-NO_3, mg/L	0.05	0.06	0.09	0.08	0.11	0.14	0.20	0.24	0.32
TP, µg/L	87	94	62	71	127	124	104	115	113
P-PO_4, µg/L	43	46	35	30	86	85	81	101	87
CHL, µg/L **	22.3	20.2	15.3	10.8	21.9	6.8	5.3	6.7	8.2
Sedimentary CHL+Pheo, mg/g dry wight ***	232	97	111	84	50	39	28	n.d.	n.d.
Phytoplankton biomass, g/m^3	3.88	4.68	3.29	2.01	2.82	0.80	0.64	0.68	2.89
Zooplankton biomass, g/m^3	3.0	3.9	1.7	0.6	0.6	0.3	0.3	0.3	<0.1
Zoobehthos biomass, g/m^2	20.7	22.9	58.2	26.7	6.2	29.3	9.4	n.d.	n.d.

Note. CHL – chlorophyll, Pheo – pheopigments, * – surface and bottom above and below the line, ** – Mineeva 2004, *** – Sigareva 2012, Sigareva & Timofeeva 2018.

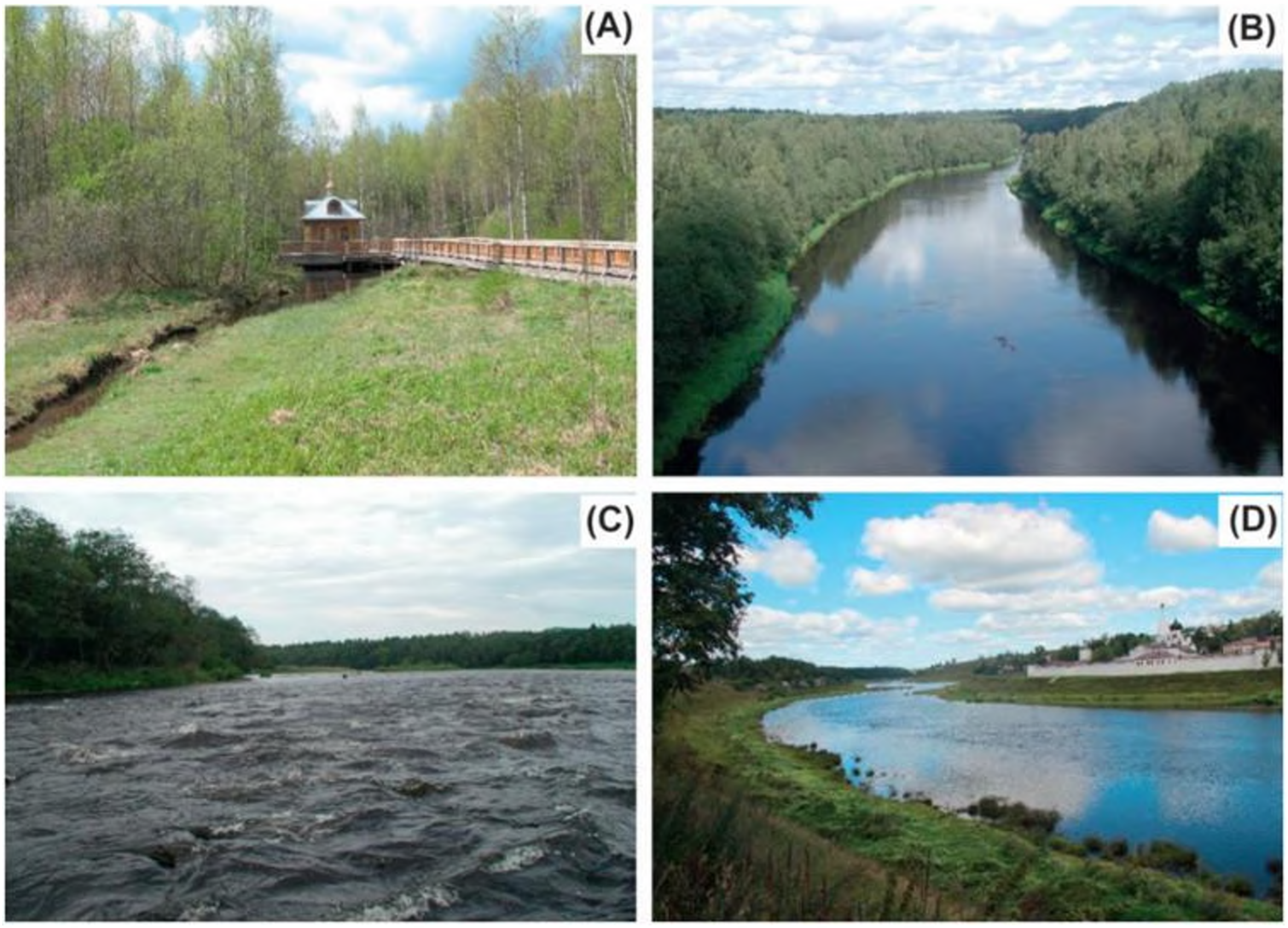

PHOTO 2.1 Upper Volga, headwaters. (A) Source of the Volga River, (B) Volga River at Klimovo, (C) biggest rapid in the Upper Volga, (D) Holy Dormition Monastery at the bank of the Upper Volga at Staritsa *Photo: M. Schletterer.*

Below Verhnevolzhskaya dam, the Volga flows through the Valdai Hills, decreasing from 200 to 150 m asl within 70 km. The Volga between Selizharovka junction and the lowlands is known as the rapids, having >20 rapids and shallows (Photo 2.1 B–D). The Volga enters the Verhnevolzhskaya lowland downstream of the town of Rzhev, becoming relatively rich in water. Below the mouth of the river Vazuza, the Volga turns sharply to the north and then northeast, flowing through the vast Verhnevolzhskaya lowland within the coniferous broad-leaf forest biome.

The next 145 km of the upper Volga resides in Ivankovo reservoir, the first stage in the Volga-Kama cascade chain, and lies within the coniferous–deciduous subzone of the forest biome (Photo 2.2 A). Forests cover 39% of the catchment area, bogs 2.8%, and lakes 2.2%. The main role of Ivankovo reservoir is water supply, typically discharging 57% of its total input. Major tributaries of the reservoir include the Tvertsa, Shosha, and Lama, contributing 35.7% of the total inflow to the reservoir (Vikulina and Znamensky, 1975; Butorin and Ekzertsev, 1978).

Below Ivankovo reservoir, the Volga turns northeast. In this area, the lowland is bordered on the southeast by the Klin-Dmitron ridge and the Uglich and Borisogleb uplands (Photo 2.2B). The elongate Uglich reservoir was constructed here in 1940. The reservoir lies in the forest belt, mainly in the coniferous–deciduous forest biome. The northern part extends into the southern taiga biome. Forests occupy 42% of the basin area, bogs 11%, and lakes 2% (Vikulina and Znamensky, 1975).

The river from Uglich to the Rybinsk hydroworks flows along the southern Volga part of Rybinsk reservoir, and represents the third stage in the Volga cascade system. The reservoir was filled after dam construction across the Volga River near Perebory and across the Sheksna River near Rybinsk. Rybinsk reservoir lies in the southern taiga biome of the forest belt, occupying the vast Mologa-Sheksna lowland. The Rybinsk reservoir flooded river channels and their floodplains, upper floodplain terraces, and the vast watershed between the Mologa and Sheksna Rivers. Forests occupy 52% of the basin area, bogs 9.5%, and lakes 5.5%. Altogether, 64 rivers flow into Rybinsk reservoir (Vikulina and Znamensky, 1975).

The 448-km-long river section between the towns of Rybinsk and Gorodets occupies the fourth stage in the Volga cascade system, represented by Gorky reservoir within the southern taiga biome of the forest belt. The upper part of this section between Rybinsk and Yaroslavl is a valley type river, whereas the middle part around the Kostroma confluence forms the lacustrine Kostroma expansion. The Unzha and Nemda rivers flow into the reservoir along the border between Yuryvets and Gorky dam. Forests occupy 57% of the basin area, bogs 6.3%, and lakes 4.4% (Vikulina and Znamensky, 1975). Gorky dam acts as a border between the upper and middle Volga.

The upper Volga network is best developed in the north, west, and northeast areas of the basin. Although the exact number of small rivers cannot be counted, the four major tributaries, Kostroma, Sheksna, Mologa, and Unzha have basin areas from 17,100 to 27,360 km^2 and annual discharges of 22–50 km^3. All other basins occupy between 1000 and 7000 km^2. Most tributary rivers are 100–400 km long, although 13 of these are shorter. Information on discharge is available for 24 rivers and 17 of these have an annual discharge $<10\ km^3$.

The Middle Volga—The middle basin occupies 1.21 million km^2. The fifth stage in the Volga cascade, Cheboksary reservoir (Photo 2.2 C; Table 2.2), is downstream of Gorky dam between the towns of Gorodets and Cheboksary. The basin lies in the forest belt with the northeast portion in the southern taiga biome and the northwest portion in the mixed coniferous–deciduous forest biome. From Gorodets to the mouth of the Oka River, the Volga flows through Balakhna Plain and has relatively asymmetric river banks. In general, the right bank is high and steep while the left bank is low and ramp shaped. Twenty-eight rivers flow into the middle Volga, the Oka being one of the largest.

The sixth stage of the Volga–cascade is Kuibyshev reservoir, the second largest reservoir in the world based on surface area. It lies in two vegetation zones: the coniferous-deciduous forest biome north of Kazan and the forest-steppe biome south of Kazan. Downstream of Kazan, the Volga flows sharply south along the eastern slope of the near-Volga upland. The right river bank is often high and steep, whereas the left bank is typically low and gently sloping. The Undorski mountain range rises north of Ulyanovsk, while the Belye (at 334 m asl) and Zhiguli (at 370 m asl) mountains lie to the south. Over 100 rivers flow into Kuibyshev reservoir, the largest being the river Kama (Znamensky and Chigirinsky, 1978) (Photo 2.2 D).

The Low Volga—The lower basin contains Saratov and Volgograd reservoirs, the Akhtuba floodplain, and the Volga delta (Photo 2.2 E,F; Photo 2.3 A–D). The Saratov reservoir above Balakov dam lies along the forest-steppe biome on its right bank and the steppe biome along its left bank. In the Zhiguli section, the river curves (called Samara Bend) and both banks are high and steep. The river then flows southwest at Syzran. The near-Volga upland (at 300 m asl) is found south of Samara Bend on the right side of the river. Within the Samara Bend, a narrow strip of floodplain with black poplars lies along the left bank where the floodplain and upland terraces usually are inundated. Saratov reservoir stores water only in spring when lowland rivers deliver snowmelt runoff (Znamensky and Chigirinsky, 1978).

The elongate Volgograd reservoir is the lowest manmade impoundment in the Volga cascade, residing mostly in the steppe biome. The semidesert biome begins downstream of the Eruslan junction. The right bank of the Volgograd reservoir is high and steep, and closely approaches the near-Volga upland. This upland separates the Volga and Don drainages. The main tributaries in the lower basin include the Eruslan on the left and the Tereshka on the right. Downstream, only a few small temporary streams join the Volga.

The Volga continues flowing southeast below Volgograd reservoir, and the major side-arm Akhtuba begins. This side-arm is 603-km long and forms the Volga-Akhtuba floodplain. The river then flows another 350 km, its width varying from 15 to 45 km, to the delta. This lower section covers about 7500 km^2. Here, the river and delta reside in the semidesert and desert biomes. Elevations are around 5–50 m asl in the north and from 0 to 28.5 m asl in the south. The lower floodplain and delta are intersected by at least 279 streams (4800 km in total length) flowing in various directions.

The Volga delta begins with the branching of the side-channel Buzan, 150 km from the confluence, and covers an area of about 12,000 km^2. The upstream area encompasses the transition zone with the Akhtuba floodplain, containing numerous oxbows and a few primary channels. Willows grow along the banks of the channels. In the middle area of the delta occur many "hillocks of Baer" (parallel east-west running sandy hummocks about 1.5–3 m high) together with numerous "ilmens" (lakelike water bodies <1 m deep that vary in size from a few hectares to several square kilometers) and primary channels that increase in size downstream. The middle area is about 30–50 km wide.

2.4.2 Hydrology

Hydrological regime of the Volga is determined by a combination of natural and anthropogenic factors. For the last 80 years, the following periods are allocated: construction (1936–59) and operation (since 1960) of the large Volga reservoirs; extremely low-water period (1971–77); a high-water cycle with the transgression of the Caspian (1978–99); and a modern stage of reducing the volume of the Volga runoff and lowering of the Caspian Sea level (2000–12). At the same time, in 2000–05, medium-water and high-water years prevailed, while in 2006–12 the frequency of low-water years increased (Golovatykh and Galushkina, 2014).

Water Flow—Presently, the hydrology of the Volga is controlled by flow regulation of the reservoirs. Because the reservoirs were built to control seasonal changes in flow, little effect was seen on river discharge, and the total annual discharge (Fig. 2.2) remains near that before the reservoirs. For example, the mean annual flow near Nizhny Novgorod (middle Volga) from 1876 to 1940 was 2876 m^3/s. After construction of Ivankovo and

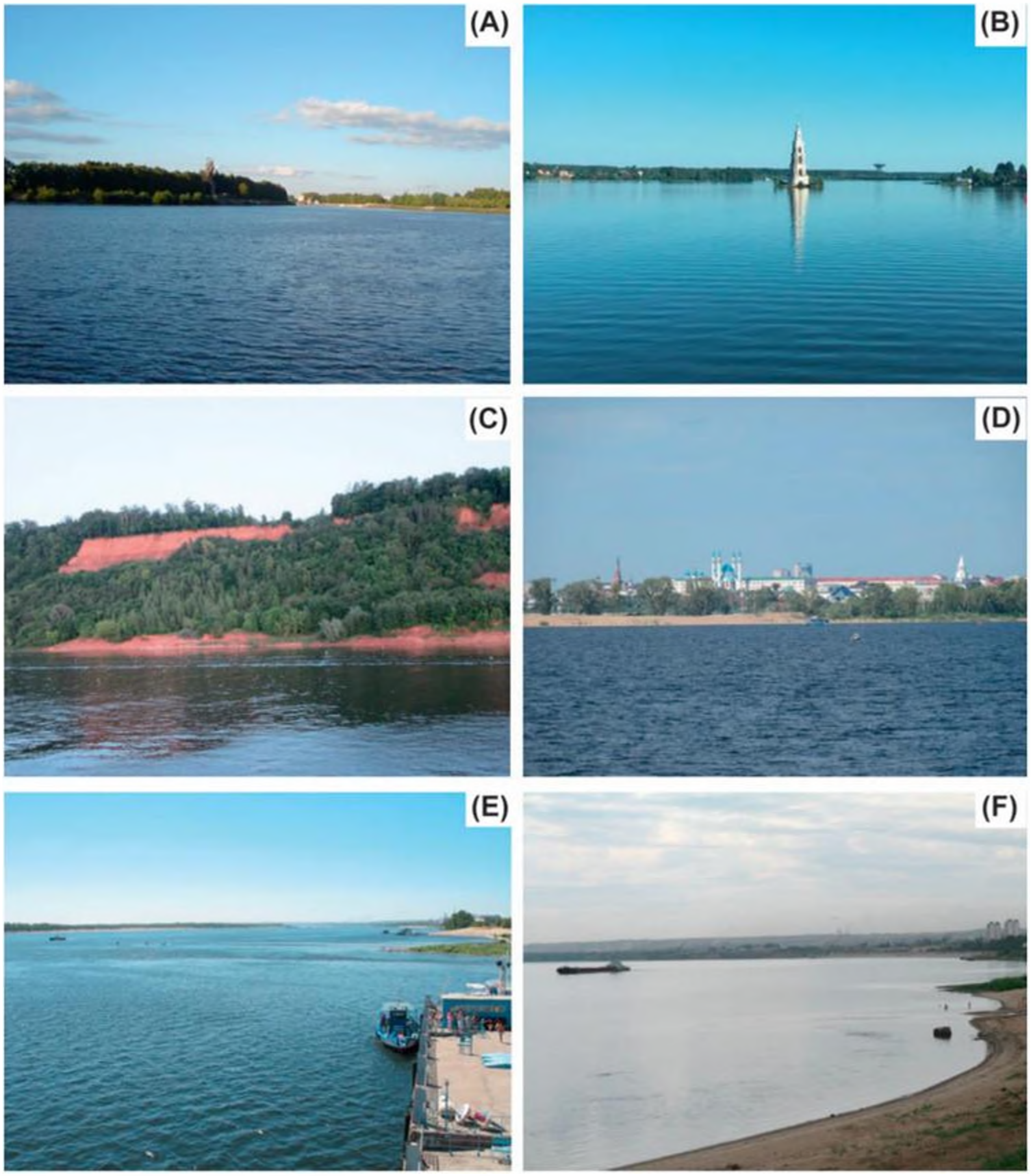

PHOTO 2.2 Upper Volga in Ivankovo (A) and Uglich (B) reservoirs (Photo: N. Mineeva). Middle Volga. The bank below Nizhni Novgorod (C) and Volga at Kazan' (D) (Photo: E. Izvekov). Low Volga near Volgograd (E, F) *Photo: M. Schletterer.*

Uglich reservoirs in the upper Volga and during the early construction stages of Rybinsk reservoir (1942–55), the mean annual flow in the middle Volga was 2780 m^3/s. After Gorky reservoir (1956–62), average annual discharge remained about 3000 m^3/s (Butorin and Mordukhai-Boltovskoy, 1979).

Interannual variation in annual discharge ranged from 160 km^3 (1937) to 391 km^3 (1926), being influenced by various cyclic oscillations (Klige et al., 2000). Interannual variation (3.4–4.2 times) in surface inflow forms >95% of the total input to the catchment. High-water periods are typically 9%–16% greater than the long-term average value; while low-water periods are 16%–28% lower than average. Long-term average water discharge varies from 1.5 to 4.2 times in different basins of the Volga (Table 2.1).

The seasonal distribution in discharge depends on the quantity of water from tributaries during the year. The main water source of the Volga and its tributaries is snowmelt, deriving >50% of the annual flow in spring from snowmelt. Discharge in summer and autumn are essentially the same, and a minor increase in discharge occurs in October and November from precipitation. Discharge is low in winter and rarely exceeds 10% of the total annual flow. Interannual variation in water exchange ranges from 3.4 to 17.9/year in the upper Volga, 4.1–24.3/year in the middle Volga, and 5.4–23.8/year in the Low Volga. The Rybinsk reservoir has the lowest water exchange in the Volga cascade system.

Currents—Reservoir construction dramatically altered the flow regime in the Volga due to current

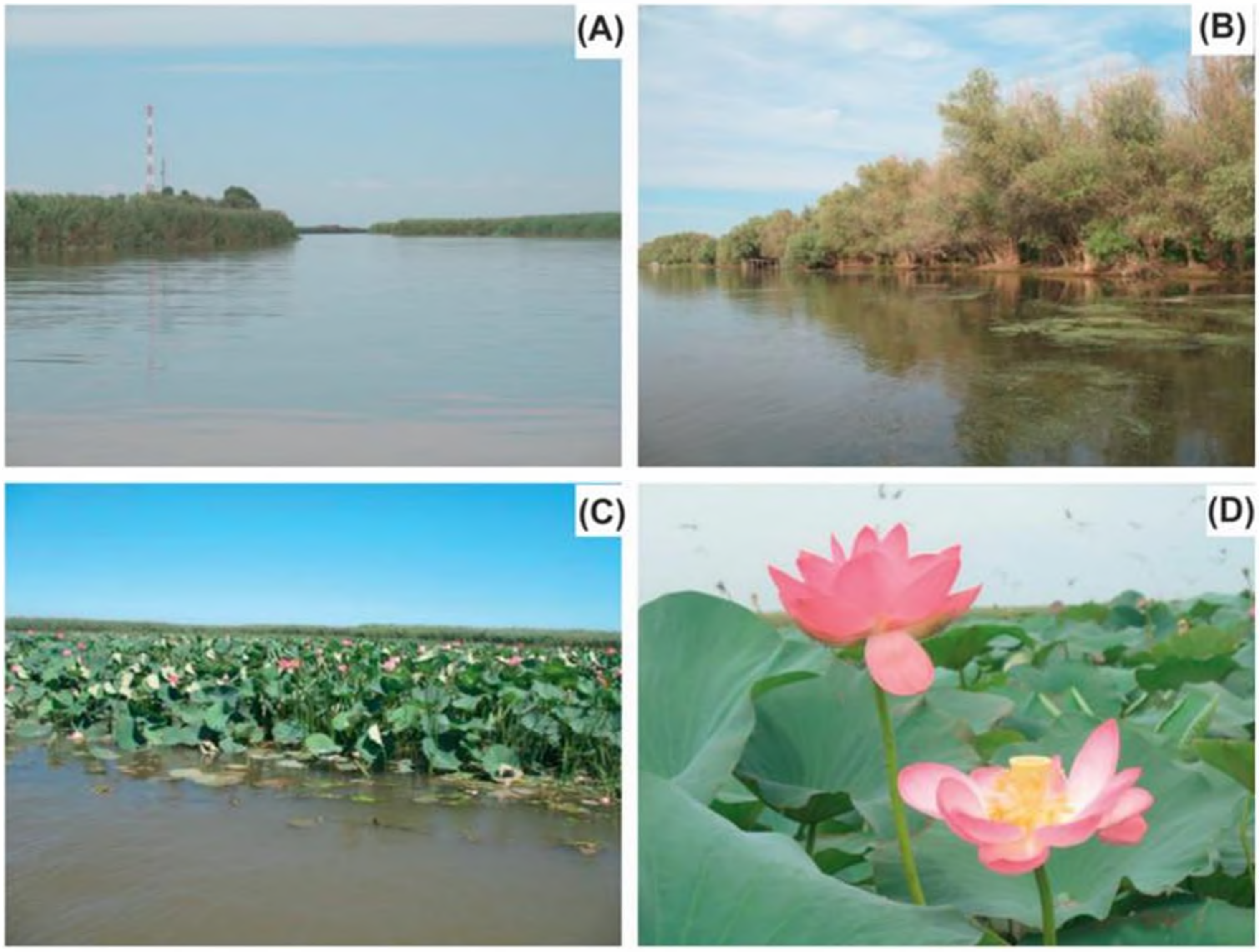

PHOTO 2.3 Delta of the Volga River (A, B) with thickets of the lotus *Nelumbo nucifera* (C, D) *Photo: M. Schletterer.*

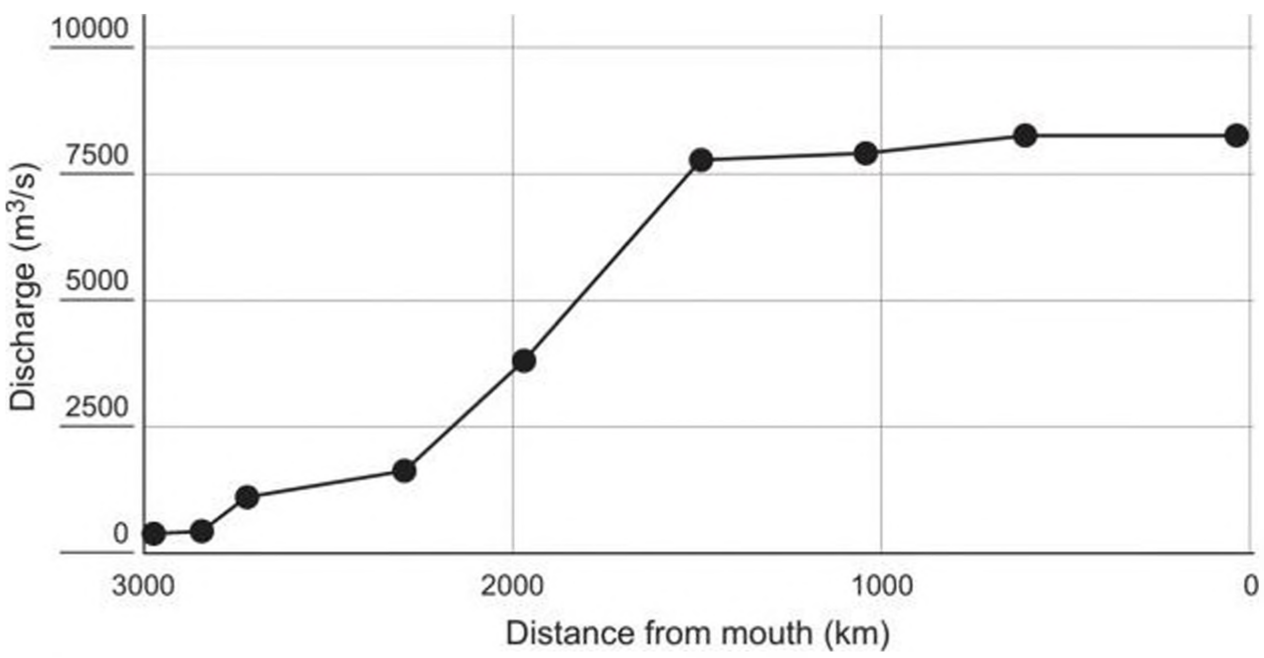

FIGURE 2.2 Changes in discharge of the Volga from its source to the mouth.

velocity decreases in impounded water bodies. Under natural conditions, mean velocities in the southern part of the upper Volga during low summer flows ranged from 0.26 to 0.32 m/s in deep areas to 0.50–0.70 m/s over shallow bars. During the annual spring flood, velocities increased to 1.50–1.70 m/s, decreasing to 1.25 m/s postflood. Flood velocities can reach 0.85 m/s in summer and 0.96 m/s in winter (Butorin and Mordukhai-Boltovskoy, 1979).

Currents in the present Volga system are complex, as river flows are influenced also by convective flows and wind effects formed in the reservoirs. As such, water circulation in the river depends on reservoir morphology and the interaction of these different factors. For instance, river channels dominate the morphology of Ivankovo, Uglich, Gorky, Saratov, and Volgograd reservoirs, whereas total water input governs hydrodynamic processes. Here, the highest flow velocity usually occurs during the spring flood and velocities decrease to a minimum in summer. Flow velocities become considerable again under ice cover in winter. In contrast, wind effect and bottom relief strongly influence hydrological conditions within the more lakelike Rybinsk and Kuibyshev reservoirs. Regardless, the head and tailwaters of reservoirs have distinctive current regimes due to activities of power stations. Reservoir drawdowns show wide daily

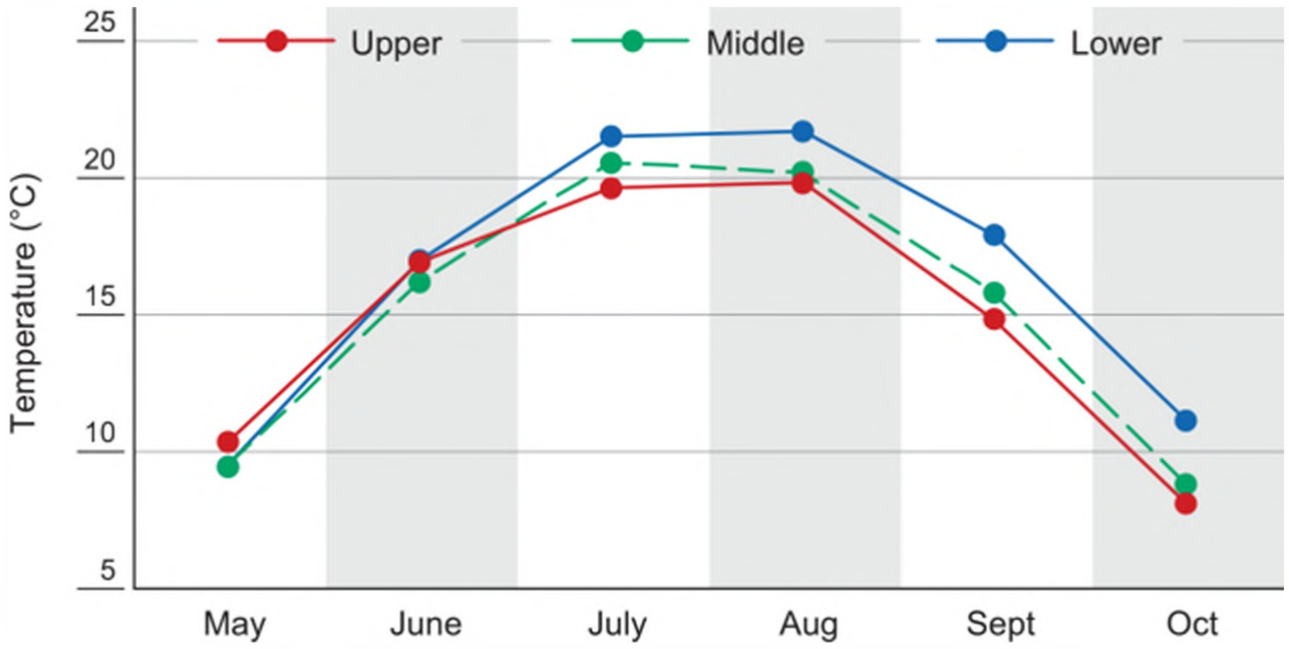

FIGURE 2.3 Annual temperature regime for the Upper, Middle, and Low Volga.

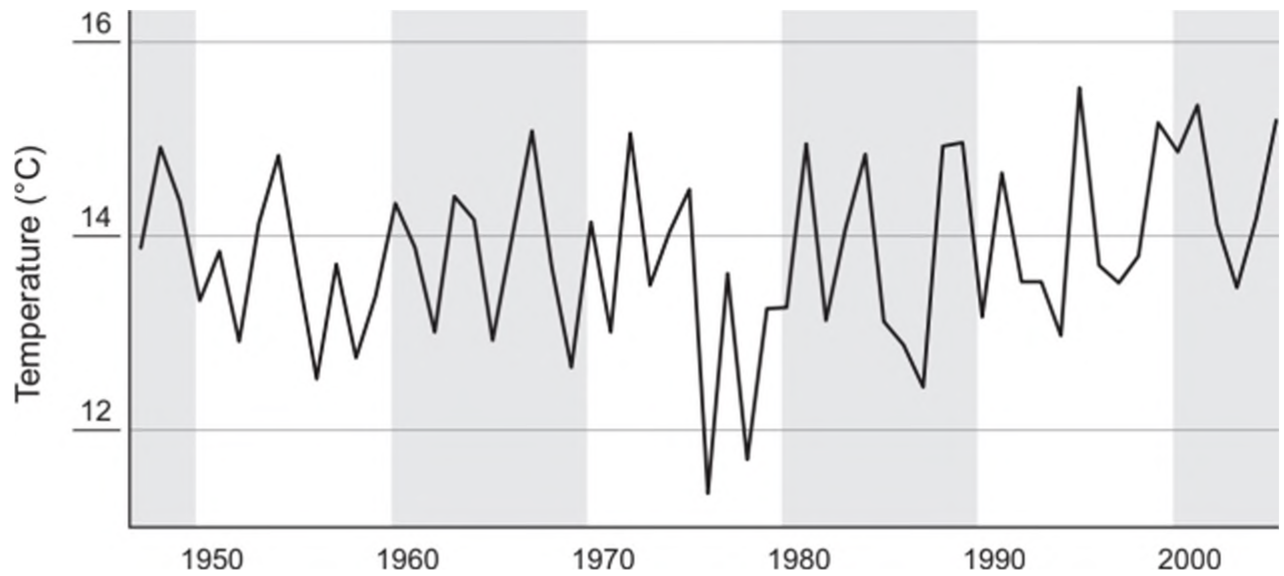

FIGURE 2.4 Long-term temperature records in the Volga.

and weekly variation, and flow velocities can change by an order of magnitude below reservoir dams.

Water temperature—The temperature regime of the Volga is typical of most waters in the boreal zone, following the seasonal pattern in heat input. Water temperature generally increases downstream, although sometimes being higher than air temperature in the north and lower in the south. Reservoirs also changed the thermal regime of the Volga. For instance, the average duration of ice cover increased by 8–20 days and now ranges from 158 days in the upper Volga to 101 days in the Low Volga. However, ice cover duration has decreased from 90 to 70 days in its lowest section near the town of Astrakhan.

In winter, temperatures within flowing reaches and shallow reaches are lowest and most uniform with depth. In deep lakelike areas, temperatures depend on heat exchange between the water and bottom sediments. A gradual increase in temperature due to heat emission of sediments leads to increases in water heat storage and reservoir stratification. The most intensive warming occurs during the spring flood from mid-May to early June. Accumulation of spring runoff water in reservoirs and the loss of winter water below dams decrease temperatures by 0.8–2.4°C in the Low Volga and increases water temperatures in the upper Volga. At the end of spring runoff, thermal stratification of water usually develops in reservoirs, but the timing is short and stratification is unstable. Temperature gradients observed at depths of 2–4 m are on average 1–3°C/m. Monthly average temperature of the surface layer is maximum in July, while the total water storage temperature is maximum in August. The seasonal temperature decrease begins in late August and is most intensive in September, especially in the upper Volga (Fig. 2.3). On average, the Volga contributes $\sim 104 \times 10^{17}$ J of heat per year to the Caspian Sea, and flow regulation has decreased the interannual fluctuation in heat runoff. Long-term records show an increase in mean air and water temperatures since the late 1970s (Fig. 2.4). Under global warming in the coastal zone of Rybinsk reservoir, air temperature has increased 0.55°C/decade and water temperature has increased 0.76°C/decade (Zakonnova and Litvinov 2016).

2.4.3 Biogeochemistry

Mineralization—The superfluous nature of the Volga results in relatively low water mineralization along the river. Total mineralization decreases with increasing discharge during spring runoff and high flows from rain, and increases during winter and summer low flows. Headwaters in the upper Volga are hydrocarbonate streams with low content of alkaline metals, chloride, and sulfate. Average mineralization values range from 100 to 270 mg/L in summer to 300–400 mg/L in winter. Mineralization decreases downstream of Rybinsk dam (Kopylov, 2001). In the middle Volga, the Oka River adds highly mineralized waters that have a high content of strong acidic ions. For instance, the average sulfate concentration in the Oka typically exceeds that in the Volga by four to six times, whereas hydrocarbonate concentrations are lower. Downstream of the confluence with the Oka, chemical stratification of the two rivers is evident although mixing increases toward the mouth of the river Sura. Downstream of the confluence with the Oka, mineralization in the Volga ranges from 150 to 340 mg/L in spring and summer to 220–400 mg/L in winter. Downstream of the Kama confluence, calcium and hydrocarbonate remain high, but chloride increases twofold and the concentration of alkaline metals also increases. The total amount of chloride and sulfate is almost equal that of hydrocarbonate. Here, mineralization varies from 180 to 380 mg/L in summer to 480–560 mg/L in winter. Lateral inputs in the Low Volga are small and the salt composition of the water remains similar to those below Kuibyshev reservoir. The index of total mineralization as electrical conductivity increases from the upper Volga to the Low Volga (Table 2.2). Intraannual variation in mineralization in the Low Volga is low with average May–October values of 160–420 mg/L and winter values of 230–470 mg/L (Butorin and Mordukhai-Boltovskoy, 1979). Long-term trends (1950–2000) indicate an increase in total mineralization of Volga waters, increasing from 185 to 210 mg/L in the upper Volga (Fig. 2.5).

Suspended matter—High flow velocities within the river, as well as susceptibility to wind mixing in reservoirs, result in high levels of suspended matter in the Volga that affects water transparency. The amount and composition depends on the contribution from alluvial drift, reformation of river banks and beds, and phytoplankton production. Suspended matter content varies from 2 to 35 mg/L. Seasonally, turbidity is typically maximal during spring runoff, minimum in winter, and with periodic increases in summer and autumn from precipitation events. Prior to flow regulation, water transparency generally decreased downstream, whereas presently transparency is highest in the Low Volga. Chlorophyll content decreases from the upper to the Low Volga (Table 2.2), averaging 0.12%–0.42% of the total suspended matter (Mineeva, 2009).

Water color—Water color is associated with the content of humic organic matter. Due to features of the catchment area and decreased lateral inflow, water color in the Volga decreases from north to south. Based on color values, waters of the upper Volga are mainly mesohumic and meso-polyhumic. Occasionally, polyhumic waters with color >100 Pt–Co degree can be found. Seasonally, water color is highest during spring runoff with peaks in color after heavy rains. Water color is lower below Rybinsk dam and further downstream in the middle and Low Volga. Here, water color corresponds to a mesohumic type in the middle basin and to mesohumic and oligohumic type in the lower basin (Table 2.2).

Dissolved oxygen—In spite of flow regulation, the oxygen regime in the Volga remained favorable for hydrobionts and dissolved oxygen (DO) was rather high (Table 2.2). Vertical gradients in oxygen were rare, occurring only under ice cover in shallow floodplain areas where DO content can became low enough to kill fish. However, after 2010, the situation changed for the worse in the upper Volga. The favorable oxygen conditions for hydrobionts are currently found only in the first half of the ice-free period (May–July). In August, annually in Ivankovo and Uglich, and in various years in Rybinsk reservoir, low DO levels (<2 mg/L) at reservoir bottoms have been observed.

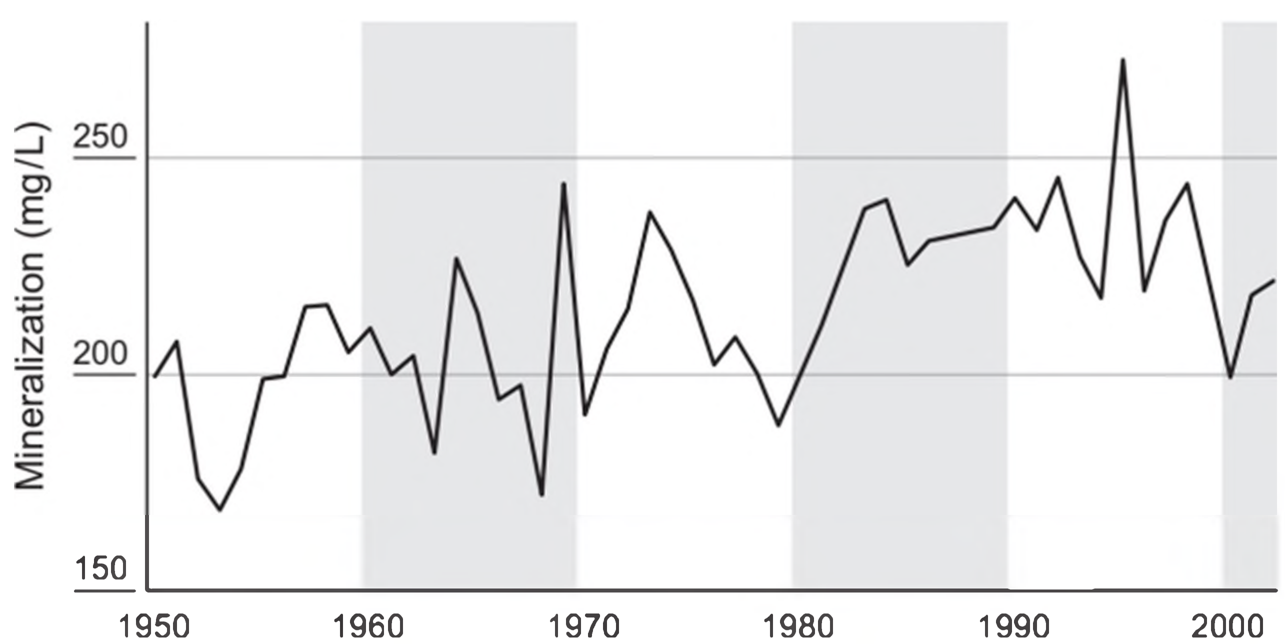

FIGURE 2.5 Long-term mineralization records in the Upper Volga according to (Zakonnova & Litvinov, 2005).

Bottom sediments—Before flow regulation, bottom sediments of the Volga down to the confluence with the Sheksna River were stony mixed with coarse sand. Following regulation, the river bed became gradually sandier. Downstream from the confluence with the Kama, bottom sediments were dominated by fine sand with areas of clay; areas of stony sediments were rare, and loam and mud sediments were deposited in deeper areas. The bed was covered with a mixture of loam, mud, and sand sediments in side-arms of the delta having slow currents (Butorin and Mordukhai-Boltovskoy, 1979). Sands and transformed soils are the most typical sediments in the littoral of the upper Volga, while gray clay silts cover deep channel areas. Brown and white silts are common in the middle and Low Volga, especially in areas of bank failure (Kopylov, 2001; Zakonnov 2005).

Transformation of river bed sediments began with the filling of the reservoirs. Early on, the abrasive action of water masses caused destruction of shorelines and erosion of the stream bed. At the same time, transported suspended matter deposited on the reservoir bottom formed secondary deposits that are now the main constituents of reservoir bottoms. The distribution of various sands characterizes the bed sediments of most reservoirs with gray muds common in areas next to the main channel. Muddy deposits predominate in the more lacustrine areas and near dams. The mean rate of deposition was estimated to be 1.7–2.5 mm/year (Butorin and Mordukhai-Boltovskoy, 1979). Today, the mean rate of deposition in reservoirs is 1.9–3.8 mm/year. These secondary deposits range from 85 to 300 cm in the upper Volga, 110–120 cm in the middle Volga, to 65–85 cm in the Low Volga (Zakonnov 2005). The type of deposits is associated with the content of bottom pigments that accumulate in sediments at a rate of 34–72 mg/m^2 per year and have a high percentage of phaeopigments (Table 2.2). Plant pigments comprise about 0.1% of the organic matter of sediments (Sigareva, 2012; Sigareva and Timofeeva, 2018).

Nutrients—Following flow regulation, the Volga maintains relatively high nutrient loads favorable for growth of phytoplankton. Anthropogenic inputs from the surrounding landscape sustain high levels in the total nitrogen (TN) and total phosphorus (TP) which currently, as before, make up at 0.40–4.09 and 0.026–0.270 mg/L, respectively (Table 2.2). Seasonally, little variation was found for TP or TN during the ice-free period in Rybinsk reservoir. Nutrient resuspension from bottom sediments also occurs in open, large, shallow areas subject to wind mixing. In terms of inorganic nutrients, nitrate and phosphate are high in concentration. Mineral nutrients decrease substantially in the upper Volga during phytoplankton blooms, becoming higher after elimination of algae, while phosphate concentrations may exceed 1.0 mg/L in the middle Volga even during periods of increased consumption of mineral forms of nitrogen and phosphorus by the algae.

Long-term trends show an increase in nutrient flow from the river into the Caspian Sea. The annual inflow of the TP varied between 25,800 and 32,600 tons in 1936–77 and 1986–2005 peaking 53,000–54,000 tons during the transgression of the Caspian (1978–85) and in 2006–12 with an increase in frequency low-water years. The annual input of TN was 308,800–366,000 tons in 1936–70 and 2000–05, but increased to 410,000–480,000 tons in 1971–99 and 2006–12. For the period 1936 to 2012, the annual runoff increased by 2.3 times for TP, 6.6 times for P_{org}, 1.2 times for P_{min}, 1.9 times for TN, and 4.5 times for N_{org}. Currently, the share of mineral N and P has decreased, leading to the predominance of N + P organic forms since 2004 (Golovatykh and Galushkina, 2014).

Pollution—Industrial and agricultural developments in the basin have resulted in an annual discharge of about 21 km^3 of wastewater, including 11 km^3 of untreated or insufficiently treated wastes. Annually, about 350,000 tons of nitrates, 90,000 tons of phenols, 521,000 tons of sulfates, 384,000 tons of chlorides, and 87,000 tons of organic matter are discharged with wastewater. The atmosphere of the Volga basin receives 20.6 million tons of toxic substances (Lukyanenko et al., 1994; Komarov, 1997, http://www.biodat.ru/doc/biodiv/part6b.htm). Serious pollution problems in the Volga catchment are associated with water abstraction for irrigation, industrial, and municipal needs. In 1993, total consumption of freshwater in the Volga catchment was 34 billion m^3: 47% for municipal needs, 29% for industrial production, and 24% for agriculture. The state of aquatic resources in the catchment indicates both qualitative and quantitative degradation that poses a serious threat to aquatic and terrestrial ecosystems (Avakyan, 1998).

2.5 Aquatic and riparian biodiversity

2.5.1 Free-flowing headwaters section

The headwaters of the Volga River are a unique system to define reference conditions for large- and medium-sized rivers in Europe (Schletterer et al., 2013, 2018). In its headwaters and below large seminatural lakes in the upper course, the Volga is a typical lowland river with good biological quality (zoobenthos, plankton, and fish). In this section, phytoplankton as well as zooplankton are well established and studied accordingly (Stolbunova, 2000; Komissarov and Phiodorova, 2009). In the free-flowing section in the headwaters with high flow velocities, bottom assemblages are good indicators for long-term monitoring (Schletterer et al., 2016).

Algae—Analyses of phytobenthos assemblages in the headwaters of the Volga revealed in total 433 diatom taxa, with the highest number of species in the genera *Achnanthes, Fragilaria, Navicula, Nitzschia*, and *Gomphonema* (Ismaiel et al., 2016). In summer low-flow-periods (June to August), in epilithic and soft sediments of the main channel and nine selected tributaries, there were 67 genera and 270 diatom taxa. Among them, *Cocconeis placentula, Achnanthidium minutissimum, Navicula capitatoradiata, Achnanthidium affine, Tabellaria flocculosa, Fragilaria capucina, Nitzschia palea, Cymbella naviculiformis, Navicula cryptocephala*, and *Eolimna minima* being dominant (Ismaiel, 2017).

Pennate diatoms were most common (49 genera and 169 species) in the main channel. The genera *Navicula* (48 species), *Fragilaria* (18 species), *Nitzschia* as well as *Achnanthes* (both with 17 species) formed the largest group. Species, which can form mass occurrences, i.e., *C. placentula, E. minima, A. minutissimum*, and *Planothidium frequentissimum*, were dominant (Schletterer et al., 2016a).

Zoobenthos—Due to catchment settings in the headwaters, a typical lowland fauna is found. The upper Volga lakes are characterized as *Chironomus plumosus* lakes. Below the lakes, the natural free-flowing section and its tributaries have a diverse potamal community. Within eight phyla, 352 taxa were identified (Schletterer, 2009), including, e.g., > 40 mayfly species with a couple of typical and rare potamal species (e.g., *Isonychia ignota, Ephoron virgo, Heptagenia sulphurea, Potamanthus luteus, and Prosopistoma pennigerum*). The Volga is an important refugia for the mayfly *P. pennigerum*, which is an outstanding flagship species (Schletterer and Fьreder, 2009; Schletterer et al., 2016b).

2.5.2 Upper Volga reservoirs

Plants—The upper Volga basin is located in the zone of southern taiga forests. Vegetation of the river and its littoral is diverse. Representative vegetation in the basin is a combination of osiers (*Salix acutifolia, S. triandra, S. viminalis*), oak (*Quercus robur*) and black alder (*Alnus glutinosa*) forests. Widely distributed are meadows covered by red fescue grass (*Festuca rubra*), foxtail (*Alopecurus pratensis*) and creeping bent grass (*Agrostis alba*). Lower areas of the floodplain are dominated by communities of reed canary grass (*Phalaroides arundinacea*) and narrow-leaved sedge (*Carex acuta*) (Isachenko and Lavrenko, 1980). River banks alternate between thickets of willow (*Salix triandra, S. cinerea*) and *Phalaroides arundinacea*. Gentle wet banks and dry shoals in bays are dominated by thickets of manna grass (*Glyceria maxima*), narrow-leaved sedge (*Carex acuta*), and swamp horsetail (*Equisetum fluviatile*). Periodically, there are growths of reed (*Phragmites australis*) and bulrush (*Scirpus lacustris*). In the river channel, pond grasses (*Potamogeton pectinatus, P. perfoliatus)* prevail. Aquatic vegetation is more diverse in reaches of rivers and bays of reservoirs in the upper Volga. Here, *Batrachium circinatum, Ceratophyllum demersum, Myriophyllum spicatum, Nuphar lutea, Nymphaea candida, Potamogeton lucens*, and *P. natans* dominate. At some sites occur the North American introduced species *Elodea canadensis*. Overall, the flora of the upper Volga and its reservoirs are represented by 138 species of higher aquatic plants.

Algae—Based on published data from 1953 to 2004 (Yakovlev, 2000; Korneva, 2015), 1329 phytoplankton species or 1609 species, varieties and forms have been identified in the upper Volga. Green algae (571) and diatoms (340) are taxonomically the most diverse planktonic algae. The greatest diversity of algae (972 species and 1172 species, varieties, and forms) has been found in Rybinsk reservoir having a vast littoral zone. The total number of algal taxa in Gorky reservoir is 754 and 846, in Ivankovo reservoir 672 and 780, in Uglich reservoir 406 and 464. Diatoms and blue-greens show major seasonal and long-term phytoplankton dynamics in the upper Volga reservoirs (Okhapkin et al., 1994; Lyashenko, 1999, 2000; Kopylov, 2001). Three peaks in diatom biomass occur during the open water season, i.e., spring, summer, and autumn, with a maximum peak in spring. Major species include *Aulacoseira islandica* (O. Müll.) Sim., *A. subarctica* (O. Müll.) Haworth, *A. ambigua* (Grun.) Sim., *A. granulata* (Ehr.) Sim., *Stephanodiscus hantzschii* Grun., *S. minutulus* (Kütz.) Cleve et Möller, *S. agassizensis* Hek. et Kling, *S. binderanus* (Kütz.) Krieg., *S. invisitatus* Hohn et Heller., *Asterionella formosa* Hass., *Diatoma tenuis* Agardh., *Skeletonema subsalsum* (A.Cl.) Bethge., and at times *Fragilaria crotonensis* Kitt., *F. capucina* Desm., *Synedra ulna* (Nitzsch.) Ehr., *S. acus* Kütz., and *Melosira varians* Ag. Small-celled algae typical of waters with high organic content such as genera *Stephanodiscus: S. hantzschii* and *S. minutulus*, as well as the brackish water species *S. subsalsum* were common in the 1960s. These species appeared along the entire Volga following completion of the main hydroengineering works. *S. subsalsum* invaded the Volga from the south and belongs to the Ponto-Caspian group. In the 1990s, the appearance of the brackish-water *Actinocyclus normanii* (Greg.) Hust. was registered in Rybinsk reservoir (Genkal and Yelizarova, 1996). It entered from the Baltic and Caspian Sea basins. Since 2000, this species has been actively spreading in Rybinsk and Gorky reservoirs. In 2000, the diatoms *Cyclotella radiosa* (Grun.) Lemm. and *Cyclostephanos dubius* (Fricke) Round began to dominate phytoplankton of Ivankovo and Rybinsk reservoirs. These species are common algae in Sheksna population and more than 60% of the biomass. This difference is due to the high oxygen deficit observed since 2013 in the water column in the Volga channel in summer (Lazareva et al., 2018b). In Ivankovo and Uglich reservoirs, the most abundant copepod crustaceans are *Thermocyclops crassus* (Fisher), *Mesocyclops leuckarti* (Claus), *Acanthocyclops americanus* (Marsh.), and *Eudiaptomus gracilis* Sars. The small Rotifera *Brachionus angularis* Gosse, *Asplanchna priodonta* Gosse, *A. henrietta* Langhaus, *Conochiloides coenobasis* Skorikov, *Pompholyx sulcata* Hudson, and species of *Polyarthra*, *Synchaeta* and *Keratella* are also common. Cladocera (*Daphnia cucullata* Sars, *D. hyalina* (Leydig), and *D. galeata* Sars) are rare and few. In unregulated parts of the upper Volga, Rotifera, mainly the genera *Brachionus* and *Keratella*, dominate. On the contrary, in Rybinsk and Gorky reservoirs, along with copepods *Mesocyclops leuckarti* (Claus), *Thermocyclops oithonoides* (Sars), and *Eudiaptomus gracilis* Sars, there is a high abundance of cladocerans *Daphnia galeata* Sars, *Bosmina longispina* Leydig, and *B. longirostris* (O.F. Müller). *Conochilus hippocrepis* (Schrank), *Synchaeta pectinata* Ehrenberg, *Polyarthra major* Bruckhardt, *P. luminosa* Kutikova, and *Euchlanis dilatata* Ehrenberg are numerous among Rotifera (Lazareva, 2010a; Lazareva et al., 2014,2018a).

Two seasonal maxima in zooplankton can be observed. Cladocera makes up to 60%–70% of the total biomass in June, while Copepoda and Cladocera (up to 80% of biomass) prevail more often in August. Since 1980s, larvae of the mollusk *Dreissena polymorpha* (Pallas) with *D. bugensis* Andrusov since late 1990s make 50%–70% of zooplankton. Number of *D. polymorpha* veliger reached 1.3–1.5 million/m^3 in July–August in the mid-1990s in Ivankovo and Uglich reservoirs (Stolbunova, 1999). The abundance of veligers of both species fell sharply to 5–50,000/m^3 after the abnormally hot summer of 2010. Zooplankton abundance differs among reservoirs as well. Mean summer (June–August) abundance is 120,000–210,000/m^3 in Ivankovo and Uglich reservoirs but is much lower (60,000–100,000/m^3) in Rybinsk and Gorky reservoirs. Mean summer biomass varies from <1 to 15 g/m^3 with the greatest above Uglich reservoir in the Volga (Table 2.2, Fig. 2.6 B). Long-term fluctuations in zooplankton abundance occur at about 10-year intervals for density and about 20-year intervals for biomass (Lazareva et al., 2001, 2014, 2016, 2018a, Shurganova et al., 2005, Stolbunova, 2007, Lazareva, 2010a, b, Shurganova and Cherepennikov, 2010).

Zoobenthos—Freshwater zoobenthos is the most diverse group of animals in the Volga River basin and includes more than 600 taxa (Butorin and Mordukhai-Boltovskoy, 1979; Yakovlev, 2000; Shilova and Zelentsov, 2003). The bottom fauna include organisms of macrozoobenthos 2–3 mm in size and larger. At present, over 140 macrobenthic species are found in flooded channels of the upper Volga. The high diversity is characteristic of the smaller animals, the meiobenthos. Gorky and Rybinsk reservoirs have over 220–240 taxa (Gusakov, 2005; 2007).

The majority of zoobenthos belongs to Chironomidae, heterotopic organisms that spend most of their life cycle in the aquatic environment. Oligochaetes and mollusks are the most numerous among homotopic animals, comprising 71%–85% of the total species number in different areas of the Volga. Among them, six Oligochaetes (*Tubifex newaensis* (Mich.), *T. tubifex* (Müller), *Limnodrilus claparadeanus* Ratzel, *L. hoffmeisteri* Claparede, *Potamothrix hammoniensis* (Mich.), *P. moldaviensis* (Vejd. et Mr.), chironomids *Chironomus plumosus* (L.), *Procladius choreus* (Mg.) and mollusks (*Dreissena polymorpha* (Pallas) with *D. bugensis* (Andrussow)) form >90% of zoobenthic numbers in deep water reaches. Larvae of Chironomidae (*Chironomus muratensis* Ryser et al., *Lipiniella araenicola* Shil., *Stictochironomus crassiforceps* (K.), *Polypedilum bicrenatum* K., *Cladotanytarsus mancus* (Walk.) as well as the oligochaete *Tubifex newaensis* and amphipod *Gmelinoides fasciatus* (Stebb.) dominate shallow waters. Five macroinvertebrates including two Coleoptera species (*Ditiscus latissimus* L. and *Graphoderus bilineatus* (Deg.), Odonata (*Leucorrhinia pectoralis* (Charp.), and two mollusks (*Anisus vorticulus* Troschel and *Unio crasus* Philips) are under danger of extinction.

Macrozoobenthos biomass in the deep waters of reservoirs depends considerably on the thickness of silt sediments and the flow regime. Highest values, 100–200 g/m^2, were found in channel sections of the reservoirs where bottom sediments were mostly gray mud. Oligochaetes and larvae of chironomids form the basis of number and biomass. Mean biomass of meiobenthos in Rybinsk reservoir was 3.3 g/m^2 in the littoral zone and 13.8 g/m^2 at deep sites, comprising mainly crustaceans, chironomids, and mollusks (Gusakov, 2007) and biomass decreases toward the mouth (Fig. 2.6 C).

Fish—Ichthyofauna of the Volga is represented by 23 families with the most diverse being cyprinids (36 species), percids (9 species), and salmonids (8 species) (Berg, 1948, 1949a,b). Prior to regulation, there were up to 69 fishes comprising five groups. Group 1 are species living all along the river such as sterled sturgeon, roach, dace, chub, ide, redeye, zherekh, belica, undermouth, bleak, bystranka, silver bream, bream, white-eye bream, blue bream, sabrefish, sazan, sheatfish, pike, burbot, pikeperch, Volga pikeperch, and perch. Group 2 species inhabit separate sites of the basin or tributaries such as river lamprey, trout, taimen, grayling, and minnow. Group 3 species occur in brackish waters of the delta such as Caspian kilka, stickleback, needle-fish, and some sculpins. Group 4 are anadromous species such as beluga, sturgeon, stellate sturgeon, ship, Volga and black-backed shad, lamprey, sheefish, and Caspian salmon. Representatives of the group fattened in the Caspian Sea, go upstream in the river to spawn, and then migrate downstream back to the sea with fry. Sturgeons reached the town of Rzhev, black-backed shad arrived at the Oka and Kama Rivers, and Ponto-caspian alosa (Alosa caspia) arrived at Yaroslavl. Group 5 are semianadromous fish inhabiting the desalinated part of the Caspian Sea and spawn in the delta at a distance of 600 km, including sterled sturgeon, bream, vobla (*Rutilus rutilus caspicus*), pikeperch, Volga pike-perch, sheatfish, three species of clupeids, kilka, rearl roach, barbel, shemaya, and vimba.

Regulation of the Volga resulted in the disappearance of a distinctive ichthyofauna in the upper, middle, and Low Volga. Before filling of reservoirs, ichthyofauna of the upper Volga consisted of 38 species of residential fish and 6 species of anadromous fish, i.e., Caspian lamprey, Russian sturgeon, beluga, stellate sturgeon, sheefish (Caspian migrants), and eel (Baltic migrant). From the source up to the Sheksna confluence, grayling dwelled in the main channel, while trout inhabited some tributaries. Ecological composition of the ichthyofauna in the Volga and tributaries did not strongly differ and consisted of the same reophilous elements typical of the entire catchment (Yakovlev, 2000).

After filling the reservoirs, Caspian anadromous fish disappeared. At present, grayling, Volga undermouth, and chub form small local populations in tributaries and in the Volga upstream of the town of Tver. The 25 mainly limnophilous species can be found in Verkhne-volzhskoe reservoir, although eutrophication resulted in the gradual disappearance of vendace, a valuable coregonid fish (Ivanov and Pechnokov, 2004). There is no reliable information on self-reproducing populations of trout. The only residential species of sturgeon in the upper Volga basin, sterled sturgeon, which was among the earlier trade fish can be found as a small self-reproducing population in Gorky reservoir. Relic populations are found in Lake Beloye, and vendace and smelt settle in the upper Volga and along the Volga cascade. Dominating fish species are bream, roach, blue bream, silver bream, sabrefish, perch, and pikeperch, all limnophilous fishes. At present, the annual catch is about 300 tons in Ivankovo reservoir, 200 tons in Uglich reservoir, 1500 tons in Rybinsk reservoir, and 350 tons in Gorky reservoir. Catches consist mainly of bream, roach, blue bream, and pikeperch (Kopylov, 2001; Ivanov and Pechnokov, 2004).

Since the 1930s, attempts of acclimation and breeding of some species have been undertaken. However, only sazan and peled formed small self-reproducing populations, and the occasional acclimation of Amur sleeper and guppy. Since the 1980s, self-reproducing species of Baltic and White Sea basins (nine-spined stickleback) and euryhaline Ponto-Caspian species (Ponto-Caspian tyulka, southern ninespine stickleback, round goby, Caspian bighead goby, stellate tadpole-goby) are present. Self-reproducing populations are formed also by round goby, kilka and bitterling. Altogether, there are self-reproducing populations of 49 nonnative species in the upper Volga.

2.5.3 Middle Volga reservoirs

Plants—The middle Volga lies within forest, forest-steppe, and steppe biomes. In the north, it lies in the zone of spruce and northern broad-leaf forests, in the zone of herb-feather grass steppe in the south, and within meadow steppe mixed with broad-leaf and pine forests in the center (Isachenko and Lavrenko, 1980). After construction of Cheboksary and Kuibyshev reservoirs, virtually no floodplain vegetation was preserved in the middle Volga. The banks of the middle Volga reservoirs are mostly open meadow or meadow-steppe. On the banks of islands in forest-steppe and, especially, in forest zones, osier thickets (*Salix triandra*, *S. viminalis*, etc.) are found. Aquatic vegetation is rich and diverse (95 associations 43 formations). The greatest area is occupied by narrow-leaved cattail (*Typha angustifolia*), reed (*Phragmites australis*), manna grass (*Glyceria maxima*), bulrush (*Scirpus lacustris*), pondweed (*Potamogeton pectinatus*, *P. perfoliatus*, *P. lucens*, *P. natans*), and hornwort (*Ceratophyllum demersum*). Aquatic flora is represented by 142 species of macrophytes, including 61 genera and 38 families. Most diverse are the pond grasses (*Potamogeton*) at 21 species and 14 hybrids. High diversity is found in the flora of damp sandy and rubble shoals in Kuibyshev reservoir, where the boundaries of many southern, western, and eastern species overlap. Introduced plants are abundant. The most widely spread are *Elodea canadensis* and *Bidens frondosa*.

Algae—During 1957–95, the number of phytoplankton taxa in the middle Volga reservoirs accounted for 1335 species (1628 species, varieties, and forms) and was similar to that in the upper Volga (Yakovlev, 2000; Trifonova, 2003; Korneva, 2015) (Table 2.3). The greatest phytoplankton diversity was found in Kuibyshev reservoir (1161–1405 taxa). In Cheboksary reservoir, the number of taxa is equal to that in Gorky reservoir located upstream. Algal flora of the middle Volga and especially in Kuibyshev reservoir is characterized by a high diversity of euglenoids.

The diatom spring bloom is dominated by *Stephanodiscus hantzschii*, *S. minutulus*, *S. binderanus*, *Aulacoseira islandica*, *Asterionella formosa*, *Melosira varians*, and at times species of the genus *Synedra*, *S. ulna*, *S. acus*. In summer, the complex is replaced by a combination of diatoms, cyanobacteria, and green algae. Among them, the most typical are the diatoms *Aulacoseira granulata*, *A. ambigua*, *A. subarctica*, *Cyclotella meneghiniana*, *Skeletonema subsalsum*, *Stephanodiscus invisitatus*, *S. agassizensis*, *Fragilaria crotonensis*, *Diatoma tenuis*; cyanobacteria *Aphanizomenon flos-aquae*, *Microcystis aeruginosa*, *M. wesenbergii*, *M. pulverea* (Wood) Forti emend. Elenk., species of the genus *Anabaena*; and chlorophytes *Pediastrum*, *Coelastrum*, *Chlamydomonas*, *Oocystis*, *Scenedesmus*, *Monoraphidium*, *Planctococcus*, and *P. morum*. At times, euglenoids (*Euglena*, *Trachelomonas*, *Phacus*) dominate in Cheboksary reservoir in summer. Diatoms form a significant part of the algal community in autumn (Okhapkin, 1994; Trifonova, 2003). Since the 1980s, cryptomonads (*Cryptomonas*, *Chroomonas*) became an important component of the late spring and autumn phytoplankton community (Okhapkin, 1994; Pautova and Nomokonova, 2001). The invasive diatom species, *Actinocyclus normanii* began dominating since the 1980s in Kuibyshev reservoir in summer and autumn (Genkal et al., 1992). Mean annual phytoplankton biomass during the ice-free period of 1956–92 increased from 1.6 to 16.3 g/m^3 and reached maximal values in the 1970s in Kuibyshev reservoir; recent values are also high (Table 2.2).

Zooplankton—Zooplankton of the middle Volga consists of over 200 species of the same large taxa, i.e., Cladocera, Copepoda, and Rotifera, as in the upper Volga. Among them, the Rotifera (50% of total species number) and Cladocera (~30%) prevail. The same taiga species as in the upper Volga are numerous for a large length of the river up to the Kama confluence (Lazareva et al., 2014,2018a). Below the mouth of the Kama, taiga species are supplanted by invaders from the Caspian, mainly Copepoda *Heterocope caspia* Sars, *Eurytemora caspica* Sukhikh et Alekseev, and *Calanipeda aquaedulcis* Kritschagin. Northern species of crustaceans *Bosmina longispina* Leydig, *Daphnia galeata* Sars, and *Mesocyclops leuckarti* (Claus) in small numbers are present in the channel of the Volga and are most abundant in high water years, e.g., 2017. The composition of the dominant Rotifera above and below the mouth of the Kama is mostly similar, including numerous species such as *Synchaeta pectinata* Ehrenberg, *S. tremula* (O.F. Müller), *Polyarthra major*Bruckhardt, *P. luminosa* Kutikova, *Brachionus calyciflorus* Pallas, and *Euchlanis dilatata* Ehrenberg.

Crustacea are the most abundant zooplankton in the middle Volga. Copepods make up >40% of the total biomass in Cheboksary reservoir and >70% in Kuibyshev reservoir. Quite numerous (6000–20,000/m^3) are the veligers of *Dreissena polymorpha* and *D. bugensis* with numbers comparable to that of Rotifera. Mean summer zooplankton abundance is 6000–120,000/m^3 and mean biomass varies from 0.1 to 1.7 g/m^3 in river reaches to 0.3–5.4 g/m^3 in lentic habitats (Rosenberg and Vykhristyuk, 2008; Lazareva et al., 2014,2018a; Shurganova et al., 2014, 2017). The average biomass in Cheboksary reservoir is twofold higher than that in Kuibyshev reservoir (Table 2.2). Long-term zooplankton dynamics show an increase in the amplitude in annual biomass as well as tendency for a decrease overall.

Zoobenthos—More than 110 macrozoobenthic taxa have been identified from the middle Volga (Perova et al., 2018). The richest in number are Chironomidae and Mollusca. At present, oligochaetes, chironomides, and mollusks make up the most in zoobenthic number and biomass. The Ponto-Caspian gammarides *Dikerogammarus haemobaphes* (Eichw.), *Pontogammarus obesus* (G. Sars), and *P. robustoides* (Grimm) also are abundant (Butorin and Mordukhai-Boltovskoy, 1979; Borodich and Lyakhov, 1983; Bakanov 1988, 2005). The two mollusk species under danger of extinction, *Anisus vorticulus* and *Unio crasus*, inhabit the middle Volga. The nonnative Ponto-Caspian mollusk *Dreissena polymorpha*, as well as amphipods *Dikerogammarus haemobaphes*, *Pontogammarus obesus*, *P. sarsi* (Sowin.), *Stenogammarus dzjubani* (M.-Bolt. & Ljach.), and *Corophium curvispinum* G. Sars that are common today had been found in the basin before Cheboksary and Kuibyshev reservoirs were filled.

Before regulation, average macrozoobenthos biomass in the channel did not exceed 5 g/m^2 (Butorin and Mordukhai-Boltovskoy, 1979; Borodich and Lyakhov, 1983). In Kuibyshev reservoir, it was 12.1 ± 2.3 g/m^2 in 1985 and is almost double today (Table 2.2). As Cheboksary reservoir bottom became siltier, macrozoobenthos biomass within the channel increased in 2001 up to 9.7 ± 2.1 g/m^2 and has only slightly changed at present. Previous biomass of benthos consisted of oligochaetes (Bakanov 1988) and now mollusks dominate (42%–70%).

Fish—There are 19 fishes in Cheboksary reservoir, and only 11 of them (vendace, smelt, guppy, nine-spined stickleback, Amur sleeper, stellate tadpole-goby, monkey goby, Caspian bighead goby, round goby, tubenose goby) have self-reproducing populations. Since the 1950s, 21 nonnative species were found in Cheboksary reservoir. Most nonnative species first appeared in 1950–60, including five salmonids and four cyprinids, while six percids appeared in the mid-1990s. Cyprinid species were observed at a single time in the reservoir, and among salmonids only vendace and smelt formed self-reproducing stocks. Percids, in general, can be found everywhere. The single representative clupeid, the tyulka, is highly abundant (Dgebuadze & Slyn'ko 2005).

Before filling Kuibyshev reservoir, 47 fishes inhabited this reach of the Volga. After the reservoir was filled in 1956, the number of species increased to 64 (Dgebuadze & Slyn'ko 2005), most of them represented by typical limnophilous cyprinids and percids. Self-reproducing fish include two species of silver carp, Asian carp, peled, buffalo, some occasional mysids (i.e., Ponto-Caspian needle-fish, round goby, stellate tadpole-goby), nonnative fish from the north (i.e., vendace, European smelt), and some fishes from the south (i.e., Ponto-Caspian tyulka). Altogether, nine species are self-reproducing and 12 species belong to occasional nonnative ichthyofauna. Species such as round goby, Amur sleeper, and pipefish reproduce successfully and have increased in number. More recently, grayling and common undermouth were found, and paddlefish and channel catfish are self-reproducing. Amur bitterling, Siberian loach, and guppy were found but their distribution is still unknown, and individuals of Siberian sturgeon and bester (beluga x sterled) also may be encountered.

Few invasive species have self-reproducing populations in the middle Volga, and they are mostly insignificant in number. More valuable fish introduced by direct efforts are rare and do not have self-reproducing populations. The basic fishery consists of limnophilous species, mainly cyprinids and percids that are typical of the present Volga. Presently, the annual catch is about 2000 tons in Kuibyshev reservoir and 200 tons in Cheboksary reservoir, consisting mainly of bream, roach, silver bream, and blue bream (Ivanov and Pechnokov, 2004).

2.5.4 Low Volga reservoirs

Plants—The Low Volga flows through herb-feather grass, fescue-feather grass, and deserted wormwood-fescue-feather grass steppes (Lipatova, 1980). Remnants of floodplain vegetation in the Low Volga are preserved on islands in Saratov and Volgograd reservoirs and within the Volga-Akhtyubinsk floodplain, being represented by osiers (*Salix acutifolia, S. triandra, S. viminalis*), white willow (*Salix alba*), black poplar (*Populus nigra*), elm (*Ulmus laevis*), and oak (*Quercus robur*) forests, fescue (*Festuca valesiaca*) and herb-fescue steppes, and coach grass (*Elytrigia repens*) and herb-coach grass halophyte meadows turning into sedge and boggy meadows of *Carex acuta, Sparganium erectum, Alisma plantago-aquatica*, and *Butomus umbellatus* in depressions (Lipatova, 1980). Aquatic vegetation is less diverse than in the upper and middle Volga. Here the main vegetation in shallows is semisubmersed species dominated by reed *Phragmites australis* and narrow-leaved cattail *Typha angustifolia*. Submersed plants are dominated by pondweed *Potamogeton perfoliatus*. In lower reaches of the river, *Phragmites australis* is replaced by *Phragmites altissimus*, developing sprouts 4–6 m high. Overall, the aquatic flora in the Low Volga is represented by 135 species of vascular plants.

Algae—From 1968 to 2002, 1003 species (1179 species, varieties, and forms) of phytoplankton had been recorded in the Low Volga reservoirs (Yakovlev, 2000; Trifonova, 2003; Korneva, 2015). Phytoplankton of Saratov reservoir is the most diverse (Table 2.3). Diatoms and green algae are the richest in terms of species diversity in the Low Volga, although the number of taxa is lower (1179) than found in the upper and middle Volga.

Diatoms and cyanobacteria are the most important members of the Low Volga phytoplankton community. Diatoms *Stephanodiscus hantzschii, S. binderanus, Aulacoseira islandica, Asterionella formosa, Diatoma tenuis, Melosira varians*, and *Skeletonema subsalsum* most often dominate in spring. In summer, diatoms *Skeletonema subsalsum, Aulacoseira granulata* and cyanobacteria *Aphanizomenon flos-aquae, Microcystis aeruginosa, M. wesenbergii, M. pulverea* and species of *Anabaena* form an important part of the phytoplankton community. Chlorophytes (species of *Pediastrum, Scenedesmus, Monoraphidium, Coelastrum, Actinastrum, Chlamydomonas*, and *P. morum*) are also abundant at this time (Gerasimova, 1996; Daletchina and Silnikova, 2001; Pautova and Nomokonova, 2001; Poptchenko, 2001; Trifonova, 2003). The invasive diatom *Actinocyclus normanii* became a significant component of the summer-fall phytoplankton in the Low Volga since 1980. From 1980 to 1990, the proportion of nonheterocystous cyanobacteria of *Oscillatoria, Phormidium, Lyngbya, Aphanothece*, and *Synecocystis* increased. In the 1990s, cryptomonads became an important part of the phytoplankton community. Spring and summer complexes of algae continue to develop in autumn.

The number of algae in the unregulated section of the Low Volga is even less than in the Saratov and Volgograd reservoirs. In 1964–69, richness totaled only 287 species, varieties, and forms (Voloshko, 1971), increasing to 390 in 1984–91 (Labunskaya, 1995). According to Labunskaya (1995) and our data (Korneva, 2015), diatoms dominated during the ice-free period in 1989–91. The spring complex consists of *Stephanodiscus hantzschii* and *Aulacoseira islandica*, while in summer it includes *Aulacoseira granulate, Skeletonema subsalsum, Actinocyclus normanii*, and blue-green algae *Aphanizomenon flos-aquae* and *Microcystis aeruginosa*. In 1997, 127 taxa of algae were found in this reach of the Volga. Together with the common diatoms and cyanobacteria, *Oscillatoria* (cyanobacteria) and *Chroomonas* (cryptomonads) were recorded as common (Trifonova, 2003).

Average annual phytoplankton biomass during the ice-free period of 1984–1990 ranged from 0.6 to 7.6 g/m^3 with maximal values in 1989 (Labunskaya, 1995). In general, the species diversity of phytoplankton decreases from the upper to Low Volga. In recent years, the proportions of invasive brackish-water diatoms, nonheterocystous cyanobacteria, and mixotrophic cryptomonads have increased in the Volga. Average annual phytoplankton biomass during the ice-free period of 1968–93 increased from 0.7 to 14.5 g/m^3 and reached maximal values in the 1970s in Volgograd reservoir. In Saratov reservoir, maximal biomass of phytoplankton reached 12.6 g/m^3 in 1988 and 1989; today's values, as in the middle Volga, are not as high (Table 2.2).

Zooplankton—As well as in the other basins, zooplankton in the Low Volga consists of Cladocera, Copepoda, and Rotifera. There are more than 200 species found with a prevalence of Crustacea (>60% of the total), basically Cladocera (>30%). In Saratov and Volgograd reservoirs, an abundant mixture of northern taiga and southern brackish-water species of crustaceans occur. The usual species are *Daphnia galeata* Sars, *Bosmina longirostris* (O.F. Müller), *B. longispina* Leydig, *Cornigerius maeoticus* (Pengo), *Mesocyclops leuckarti* Claus, *Heterocope caspia* Sars, and *Calanipeda aquaedulci*-sKritschagin. The prevalent Rotifera species, *Euchlanis dilatata* Ehrenberg, *Synchaeta pectinata* Ehrenberg, *S. tremula* (O.F. Müller), and species of *Polyarthra* are the same as in the middle Volga.

Copepoda and Cladocera make up 50%–90% of the total biomass. Seasonal development of zooplankton is characterized by a summer peak. Mean summer abundance is 8000–32,000/m^3 (Lazareva et al., 2018a). In some years, maximum biomass reaches 1.2 g/m^3 in Saratov and Volgograd reservoirs (Malinina et al., 2016). As in the middle Volga, there are veligers of *Dreissena polymorpha* and *D. bugensis* with numbers comparable to that of Rotifera. Long-term zooplankton dynamics also show an increase in the amplitude in annual biomass. Summer zooplankton biomass is low, being on average ~ 0.3 g/m^3 (Table 2.2).

Zoobenthos—Before the Volga was transformed into a system of reservoirs, the macroinvertebrate fauna in the Low Volga was quite similar to that in the middle Volga. The oligochaetes *Tubifex newaensis* and Caspian gammarids *Pontogammarus sarsi* dominated in biomass (Butorin and Mordukhai-Boltovskoy, 1979). After the two lower reservoirs were filled, a number of rheophilic Ponto-Caspian crustacean species disappeared. Nevertheless, the fauna of the submerged river channel in the middle and Low Volga remained similar until today. New findings of a number of Ponto-Caspian species in Kuibyshev and Saratov reservoirs support this idea (Pirogov et al., 1990; Dgebuadze et al., 2003; Dgebuadze & Slyn'ko 2005).

The total species number of macrozoobenthos in the Low Volga is about 40 (Perova et al., 2018), and among them the Chironomidae and Mollusca are the most diverse (Nechvalenko, 1976; Butorin and Mordukhai-Boltovskoy, 1979; Zinchenko, 2002). The highest quantity and biomass is found in the same oligochaete, chironomid, and mollusk species as the ones dominating the upper and middle Volga. Additionally, the Ponto-Caspian gammarids *Dikerogammarus haemobaphes* and *Pontogammarus obesus* are common. Four inhabitants of the Low Volga benthic fauna are in danger of extinction: Odonata (*Coenagrion ornatum* Selys. and *Leucorrhinia pectoralis*) and mollusks (*Anisus vorticulus* and *Unio crasus*).

Due to higher current velocities, macrozoobenthos biomass in the main channel has not changed since reservoir construction and averages about 3 g/m^2. During the first years in Volgograd reservoir, macrozoobenthos biomass did not differ from that of Saratov reservoir. However, by 1985, it had increased by more than threefold, reached 10.5 ± 3.5 g/m^2 and remains within this range at present (Table 2.2). Crustaceans, polychaetes, and oligochaetes dominate biomass. Locally, very high biomass values were noted in 2015, reaching >44 g/m^2 for dreissenids on sandy soil in the upper section of Saratov reservoir. Most biomass was represented by the gammarid *Dikerogammarus haemobaphes*. On sandy soils, where dreissenids were absent, macrozoobenthos was represented by the Caspian amphipods *Pontogammarus sarsi* and *Pontogammarus abbreviatus*. A high abundance (7.2 g/m^2) was noted in the lower tail of Samara reservoir.

Fish—At present, ichthyofauna of the Low Volga consists of 69 species. After filling of Volgograd reservoir, anadromous fish as well as a number of rheophilous species at sites above the dam disappeared. Limnophilous fish such as roach, ide, bleak, silver bream, bream, white-eye bream, blue bream, sabrefish, sazan, crucian carp, tench, sheatfish, pike, burbot, pikeperch, Volga pikeperch, perch, and ruffe became common and dominate the fishery (Reshetnikov, 1998).

A total of 18 new fishes have appeared in the Low Volga. Nonnative fishes in Saratov reservoir suggest that the species have a different origin (Dgebuadze & Slyn'ko 2005). Peled, vendace, and smelt came in 1960 downstream from the upper basins. Species such as Amur sleeper, Caspian bighead goby, tubenose goby, stellate tadpole-goby, pipefish, and southern ninespine stickleback formed self-reproducing populations. Because of direct introduction, Asian carp, white and spotted silver carp, smallmouth and black buffalo, and Siberian sturgeon appeared in the reservoir, mainly during the 1980s. However, these introductions were not successful because of the small number of fish introduced, and none have been found in the fishery catch in recent times.

New fishes appeared in the Volgograd reservoir since 1969, within 10 years after filling (Dgebuadze & Slyn'ko 2005), including the European vendace, smelt, and peled among them. However, only vimba, Amur sleeper, Caspian bighead goby, tubenose goby, stellate tadpole-goby, pipefish, and the southern ninespine stickleback that appeared in late 1990s have self-reproducing populations. A number of valuable species appeared because of direct introduction from 1967 to 90, including white and spotted silver carp and Asian carp, smallmouth and black buffalo, black carp, and vimba. These nonnative fishes have little significance in the commercial fishery, averaging about 1% of the total catch. The small-sized Amur sleeper and sculpins are caught by anglers. Today, the annual catch is about 700 tons in Saratov reservoir, and 1000 tons in Volgograd reservoir, consisting mainly of bream, roach, silver bream, and perch (Ivanov and Pechnokov, 2004). The Low Volga had major fishery importance before building of the dam near Volgograd, with an annual catch over 12,000 tons. At present, there is no commercial fishery in the lower basin.

Regulation of the Volga resulted in the disappearance of a distinctive ichthyofauna in the upper, middle, and Low Volga. The fish population now consists mainly of typical limnophilous species that differ little along the river because of the invasion of nonnative species. These species enter because of direct introduction of valuable fish as well as the occasional expansion and accidental intrusion.

2.5.5 Invasive species in the Volga River

Reservoir systems of the Volga are a recipient zone and a channel of spreading for species from both northern and southern water bodies. There are two groups of invasive algae and invertebrate species (Mordukhai-Boltovskoy and Dzyuban, 1976; Lazareva, 2008; Romanova, 2010; Popov, 2011,2013; Korneva, 2014). The **Boreal-Arctic complex** of species can be considered as alien only outside the forest zone in the Middle Volga below Kazan. The **Ponto-Caspian complex** of strong alien species penetrated the Volga from the Caspian, as well as river estuaries and the coastal zone of the Black and Azov seas. Nonnative species of fish originated from three faunistic groups, i.e., Arctic, and Chinese-lowland (plain) group, and the most significant from the Ponto-Caspian group.

Algae—The number of invasive species of planktonic algae in inland water bodies increased significantly in the second half of the 20th century. Alien species of algae found in the Volga basin are mainly diatoms (Table 2.3). Two of them, *Skeletonema subsalsum* and *Actinocyclus normanii*, have high abundance.

Zooplankton—At present, zooplankton alien species in the Volga river include 24 taxa of copepods, cladocerans, and rotifers (Table 2.4). The flow of northern crustacean species southward, downstream in the Volga, formed immediately after Rybinsk reservoir was impounded in the late 1940s. By the early 1970s, six crustaceans from the northern Lake Beloe naturalized in the Low Volga reservoirs contrary to the assumption that Saratov reservoir would be the southern boundary for northern lacustrine species of that group (Mordukhai-Boltovskoy and Dzyuban, 1976). *Bosmina longispina* and *Cyclops kolensis* are still the most abundant zooplankton species in the Low Volga (Malinina, 2003; Romanova, 2010; Popov, 2011). The *Bythotrephes* genus in the Volga is represented mainly by hybrid forms *B. cederstroemii* x *B. brevimanus* and *B. cederstrumii* x *B. arcticus* (Litvinchuk, 2007; Litvinchuk and Litvinchuk, 2016; Korovchisky, 2015, 2016, 2018). A number of southern species moved into the upper Volga in the 1980s–1990s. Currently, climate warming caused the north expansion in the upper Volga of some freshwater species formerly inhabiting only the middle and Low Volga (Rivier, 1993; Lazareva, 2008; Popov, 2011). In the 2010s, some of these settled and became numerous, not only in the upper Volga but also in the Kama and Sheksna rivers.

Zoobenthos—A total of 44 invasive species (about 20% of all benthic species) comprise macrozoobenthos in the Volga reservoirs (Table 2.4). Among them are 27 crustaceans, seven mollusks, and 10 annelids. The number of invasive species increases downstream of Volga's cascade from the upper Volga to the middle and Low Volga. It consists of 1–2 species in deep sites of Ivankovo and Uglich reservoirs, 7 species in Rybinsk reservoir, 10 in Gorky, 13 in Cheboksary and Kuibyshev, and 17 in Saratov reservoir. When sampling deep and shallow areas, 29 species were found in Kuibyshev reservoir, 33 species in Saratov reservoir, and 37 species in Volgograd reservoir (Kurina, 2017b).

Molecular studies performed during the last 10 years revealed new species, clarified issues of colonization of the Volga basin by dreissenids as well as detected hybridization between alien species. The invasive species *Corbicula fluminea* (Müller, 1774) was detected for the first time in the Volga (Gorky Reservoir) in 2015 as inferred from COI fragment of mtDNA (Pryanichnikova & Voroshilova, unpublished data). All individuals were of the morphotype R. Twenty sequences of COI fragment belonged to the same haplotype (NCBI: AF196280) that is widely distributed in North America and Europe (Siripattrawan et al., 2000; Lee et al., 2005; Pigneur et al., 2014). None of the genetic diversity is probably explained by a founder effect.

New data on colonization of Volga basin by *Dreissena polymorpha* (Pallas, 1771) were obtained using molecular markers. Study of COI fragment revealed low haplotype and nucleotide diversity of *D. polymorpha* populations throughout the Volga basin. The Black Sea population of *D. polymorpha* was suggested as a source for the established population in the upper Volga (Gelembiuk et al., 2006; May et al., 2006, Voroshilova et al., 2011). However, our unpublished study on

TABLE 2.3 Invasive species of planktonic algae in the Volga basin.

Taxa	First finding	References
Bacillariophyta		
Skeletonema subsalsum (Cleve-Euler) Bethge	1954, Northern Caspian, mouth of the Volga	Proshkina-Lavrenko and Makarova (1968)
Skeletonema Potamos (C.I. Weber) Hasle in Hasle & Evensen	1970s–1980s, all reservoirs of the Volga	Genkal (1992)
Thalassiosira lacustris (Grun.) Hasle	1964–65, Sheksna reservoir	Kuzmin (1976)
Thalassiosira incerta Makar.	1969, from mouth of the Kama to Low Volga	Makarova et al. (1976)
Conticribra guillardii (Hasle) K. Stachura-Suchoples et D.M. Williams	1970s–1980s, Saratov reservoir, lower reaches of the Volga	Makarova 1988, Genkal (1992)
Thalassiosira pseudonana Hasle & Heimdal	1969–72, all reservoirs of the Volga	Butorin and Mordukhai-Boltovskoy (1979)
Conticribra weissflogii (Grunow) Stachura-Suchoples et Williams	1969–72, all reservoirs of the Volga	Butorin and Mordukhai-Boltovskoy (1979)
Thalassiosira proschkinae Makar.	1985–86, mouth of the Volga	Genkal and Labunskaya (1992)
Actinocyclus normanii (W. Gregory ex Greville) Hust.	1986, Northern Caspian, Saratov reservoir	Kiss et al., 1990, Zelenevskaya 1998
Thalassiosira faurii (Gasse) Hasle	1989–91, Cheboksary, Kuibyshev, Volgograd reservoirs	Genkal and Korneva (2001)
Thalassiosira gessneri Hustedt	1989–91, Kuibyshev reservoir	Genkal and Korneva (2001)
Cyclotella ambigua Grunow	1989–95, Kuibyshev reservoir	Genkal et al. (2006)
Halamphora coffeiformis (C. Agardh) Levkov	2009, Kuibyshev reservoir	Tarasova and Burkova (2010)
Chaetoceros muelleri Lemm.	2009, Kuibyshev reservoir	Tarasova and Burkova (2010)
Cyclotella choctwhatcheeana Prasad emend. Genkal	2011, Oka River	Genkal and Okhapkin (2013)
Cyclotella marina (Tanimura, Nagumo et Kato) Akй-Castillo, Okolodkov et Ector	2011, Oka River	Genkal and Okhapkin (2013)
Plagiotropis lepidoptera (W. Greg.) Kuntze	2014, Vetluga River	Okhapkin et al. (2016a)
Dinophyta		
Peridiniopsis kevei Grigor. et Vasas	1989, Rybinsk reservoir	Korneva et al. (2015)

COI sequences of samples from the Sheksna River (upper Volga) revealed the haplotypes specific to the Low Volga (NCBI: DQ840123, DQ840124). This finding confirms a previous hypothesis that colonization of the Volga basin occurred via different routes (Voroshilova et al., 2011).

Nontypical shells among dreissenids in the Volga basin were found (Voroshilova, 2016). Individuals from the Rybinsk reservoir were recognized as an interspecies hybrid between *D. polymorpha* and *D. bugensis* based on molecular markers (Voroshilova et al., 2010).

Fish—Based on different systematic reports, there are ca. 124–140 fish species in reservoirs of the Volga-Kama basin. The share of alien species ranges from 8% to 32% in reservoirs of the Volga and 2%–16% in reservoirs of the Kama. Fish invaders are a stable but often small component of littoral communities. The study of the distribution of fishes (Table 2.5) beyond the historical range makes it possible to reconstruct the colonization process in three consecutive stages: (1) changing distribution boundaries, (2) acclimatization and development of new habitats, (3) completion of introduction and definition of a niche of the invader in the structure of local communities.

Changes in the gene pool of introductions serve as a marker of the stages of fish species distribution beyond the historical range. Results of species identification of mass alien fish species up to the family level in the Volga-Kama basin using the DNA-barcoding procedure (Ward et al., 2009) are shown in Fig. 2.7.

TABLE 2.4 Invasive species of zooplankton and macrozoobenthos in the Volga basin.

Taxa, group	First finding	Modern expansion	References
Zooplankton			
Heterocope caspia Sars, PC, bw	Before 1950s, Low Volga below Saratov	Low and middle Volga to the Kama mouth, Kama to the city Berezniki (59°N). Numerous.	Mordukhai-Boltovskoy and Dzyuban (1976), Lazareva et al. (2018a)
Cornigerius maeoticus (Pengo), PC	Early 1970s, Volgograd reservoir	Low and middle Volga to the Kama mouth (55°N). Common but few.	The same
Daphnia cristata Sars, *Bosmina longispina* Leydig, *B. coregoni* Baird, *Bythotrephes longimanus* Leydig, *Cyclops kolensis* Lill., *Eudiaptomus gracilis* Sars, NBA	Late 1940s before regulation	Kuibyshev, Saratov, and Volgograd reservoirs. Began to spread downstream the Volga after Rybinsk reservoir was impounded. Naturalized in the Low Volga by the early 1970s.	The same
Calanipeda aquaedulcis Kritschagin, M, bw	1960s, Volgograd reservoir	Low and middle Volga to the Kama mouth (55°N). Numerous.	V'yushkova & Gurova (1968), Lazareva (2018)
Cercopagis (s. str.) *pengoi* (Ostroumov, 1891), PC	1970s, Kuibyshev reservoir	Low and middle Volga to the Kama mouth, Kama near the city Perm (58°N). Common but few.	Romanova (2010), Popov (2011), Lazareva et al. (2018a)
Eurytemora caspica Sukhikh et Alekseev, PC, bw	Early 1980s, Kuibyshev reservoir	Low and middle Volga to the Kama mouth, Kama to the city Berezniki (59°N). Numerous.	Timokhina (2000), Lazareva et al. (2018a)
Podonevadne trigona ovum (Zernov), PC	Early 2000s, Volgograd reservoir	Volgograd reservoir, 2011 in small numbers in Saratov reservoir near the Volzhskaya HPP dam, but later (until 2017) in Volgograd reservoir only.	Malinina (2003), Popov (2012), Lazareva et al. (2018a)
Kellicottia bostoniensis (Rousselet), NA	2005, Sheksna reservoir	Ivankovo, Uglich, Cheboksary, and Kama reservoirs. Extends in the Volga basin from west to east.	Lazareva and Zhdanova (2014), Krainev et al. (2018), Shurganova et al. (2017)
Heterocope appendiculata Sars, *Limnosida frontosa* Sars, *Bosmina coregoni kessleri* Uljanin, BA	1996–2005, Kuibyshev and Saratov reservoirs	Kuibyshev, Saratov, and Volgograd reservoirs. Found either yearly or locally in certain years.	Romanova (2010), Popov (2011), Lazareva et al.(2018a)
B. crassicornis (P.E. Müller), BA	1996–2005, Kuibyshev and Saratov reservoirs	Kuibyshev, Saratov, and Volgograd reservoirs. Ordinary species.	The same
Asplanchna henrietta Langhaus, *Acanthocyclops americanus* (Marsh.), SS	1980s, Ivankovo and Rybinsk reservoirs	All reservoirs of the upper Volga and Kama. Common forms of the modern plankton.	Kopylov (2001), Lazareva (2008), Lazareva et al. (2018a)
Diaphanosoma orghidani Negrea, SS	1980s, Ivankovo reservoir	All reservoirs of the upper Volga and Kama, Sheksna reservoir. Southern species moved into the upper Volga in the 1980s. An expansion has begun since 2003–2004, and now they are common forms of plankton.	Korovchinsky (2004), Lazareva (2012), Lazareva et al. (2018a)
Brachionus diversicornis (Daday), SS *B. budapestiensis* Daday, SS	1980s, Rybinsk reservoir	All reservoirs of the upper Volga and Kama, Sheksna reservoirs. Until late 1970s in the Low Volga only. Permanent in Saratov reservoir since 2005, in lower sites of Cheboksary reservoir since 2015.	Kopylov (2001), Lazareva et al. (2013, 2018a)

Keratella tropica (Apstein), SS	1989, Rybinsk reservoir; 2005, Saratov reservoir	Low and middle Volga up to the city Koz'modem'yansk.	Rivier (1993), Popov (2011), Lazareva et al. (2018a)
Conochiloides coenobasis Skorikov, SS	1997–1999, Rybinsk reservoir	All reservoirs of the upper Volga and Kama.	Lazareva (2007), Lazareva et al. (2018a)
Macrozoobenthos			
Dreissena bugensis (Andrusov, 1897), PC	1993, Kuibyshev reservoir	Upper Volga and Kama.	Antonov (1993), Perova et al. (2018)
Dreissena polymorpha (Pallas, 1771), PC	The whole Volga before regulation	Upper Volga and Kama.	Benning (1924), Perova et al. (2018)
Corbicula fluminea (O.F. Müller, 1774), SA	2015, Gorky reservoir	Gorky reservoir.	Pryanichnikova et al. (2019)
Lithoglyphus naticoides (C. Pfieffer, 1828), PA	1950s, Low Volga	All reservoirs of the Volga except for Ivankovo reservoir.	Tyutin and Slynko (2008), Perova et al. (2018)
Theodoxus astrachanikus Starobogatov in Starobogatov, Filchakov, Antonova et Pirogov, 1994, PC	Low Volga, probably as *Theodoxus pallasi* (Lindholm, 1824)	Low Volga.	Zinchenko and Antonov (2005), Perova et al. (2018)
Adacna colorata (Eichwald, 1829), PA	1960s, Volgograd reservoir	Kuibyshev reservoir and Low Volga.	Butorin and Mordukhai-Boltovskoy (1979), Kalayda (2003), Filinova (2012)
Physella acuta (Draparnaud, 1805), NA	2000s, delta of the Volga	Kuibyshev reservoir, Volga reach.	Kantor and Sysoev (2005), Yakovleva et al. (2010)
Quistadrilusmultisetosus (Smith, 1900), NA	2013, Rybinsk reservoir	Rybinsk reservoir.	Pryanichnikova et al. (2017)
Potamothrix heuscheri (Bretscher, 1900), *P. vejdovskyi* (Hrabe, 1941), PC	1960s, Upper Volga	All reservoirs of the Volga.	Shcherbina et al. (1997), Perova et al. (2018)
Psammoryctides moravicus (Hrabe, 1934), Cosm	Rybinsk reservoir	Reservoirs of the upper and middle Volga.	Shcherbina (1998), Arkhipova (2005), Perova et al. (2018)
Bothrioneurum vejdovskyanum (Stolc, 1886), Cosm	Rybinsk reservoir	Rybinsk reservoir.	Arkhipova (2005)
Archaeobdellaesmonti (Grimm, 1876), PC	1990, Low Volga	All reservoirs of the Volga except for Uglich reservoir.	Bakanov (1993), Perova (2011), Perova et al. (2018)
Caspiobdella fadejewi (Epshtein, 1961), PC	1960s, Volgograd reservoir	All reservoirs of the Volga.	Lapkina et al. (2002), Kopylov (2001)
Hypania invalida (Grube, 1860), PC	1960, Volgograd reservoir	All reservoirs of the Volga	Yoffe (1968), Perova et al. (2018)
Hypaniolakowalewskii (Grimm in Annenkova, 1927), PC	1960, Volgograd reservoir	Kuibyshev reservoir.	Yoffe (1968), Zinchenko et al. (2008)
Manayunkina caspica Annenkova, 1928, PC	1991, Kuibyshev reservoir	Kuibyshev reservoir.	Zinchenko and Golovatyuk (2001), Yakovleva and Yakovlev (2010)

Continued

TABLE 2.4 Invasive species of zooplankton and macrozoobenthos in the Volga basin.—cont'd

Taxa, group	First finding	Modern expansion	References
Caspiocuma campylaspoides (Sars, 1897), PC	1976, Kuibyshev reservoir	Kuibyshev reservoir.	Borodich (1979), Yakovleva and Yakovlev (2012)
Chaetogammarus warpachowskyi Sars, 1897, PC	Low Volga before regulation	Kuibyshev reservoir and Low Volga.	Mordukhai-Boltovskoy et al. (1969), Filinova et al. (2008)
Chaetogammarus ischinus (Stebbing, 1899), PC	Low and middle Volga before regulation	Low Volga reservoirs.	Benning (1924), Butorin and Mordukhai-Boltovskoy (1979), Sonina and Filinova (2011), Kurina (2017b)
Chelicorophium curvispinum (Sars, 1895), PC	Low and middle Volga before regulation	Middle and Low Volga.	Benning (1924), Butorin and Mordukhai-Boltovskoy (1979), Kurina (2017b), Perova et al. (2018)
Chelicorophium sowinskyi (Martynov, 1924), PC	Low and middle Volga before regulation	Kuibyshev and Volgograd reservoirs.	Benning (1924), Yakovleva and Yakovlev (2010), Filinova (2012)
Dikerogammarus caspius (Pallas, 1771), PC	Early 1980s, Volgograd reservoir	Low Volga reservoirs.	Sonina and Filinova (2011), Kurina (2017b)
Dikerogammarus haemobaphes Eichwald 1841, PC	Low and middle Volga before regulation	All reservoirs of the Volga except Ivankovo and Rybinsk reservoirs.	Benning (1924), Butorin and Mordukhai-Boltovskoy (1979), Bakanov (2003), Perova et al. (2018), Zhgareva and Pryanichnikova (2018)
Dikerogammarus villosus (Sowinsky, 1894), PC	Volga after 1951	Middle and Low Volga reservoirs.	Benning (1924), Butorin and Mordukhai-Boltovskoy (1979), Filinova (2012), Perova et al. (2018)
Eriocheir sinensis (Milne-Edwards, 1853), SA	Mid 1970s, Saratov reservoir	Rybinsk reservoir, Middle and Low Volga.	Shakirova et al. (2007)
Gmelinoides fasciatus (Stebbing, 1899), LB	1960s, Gorky reservoir	All reservoirs of the Volga, Sheksna reservoir.	Yoffe (1968), Matafonov (2003), Filinova (2012), Perova et al. (2018)
Jaera sarsi Valkanov, 1936, PC	Low Volga	Saratov reservoir	ordukhai-Boltovskoy and Dzuban (1976), Zinchenko and Kurina (2012)
Katamysis warpachowskyi Sars, 1893, PC	1999, Volgograd reservoir	Kuibyshev reservoir and Low Volga.	Filinova (2003), Zinchenko and Kurina (2012)
Limnomysis benedeni (Czerniavsky, 1882), PC	1975, Saratov reservoir	Saratov reservoir.	Borodich (1979), Kurina (2017b)

Paramysis intermedia (Czerniavsky, 1882), *P. lacustris* (Czerniavsky, 1882), *P. ullskyi* Czerniavsky, 1882, PC	Low and middle Volga before regulation	Kuibyshev reservoir and Low Volga.	ordukhai-Boltovskoy and Dzuban (1976), Kurina (2017b), Filinova (2003, 2012), Perova et al. (2018)
Pontogammarus crassus = *Obesogammarus crassus* (Sars, 1894), PC	1970s, Volga near Volgograd	Kuibyshev reservoir.	Yakovlev and Yakovleva (2005)
Pontogammarus obesus = *Obesogammarus* obesus (Sars, 1894), PC	Low and middle Volga before regulation	Middle and Low Volga.	Sonina and Filinova (2011), Kurina (2017a,b), Frolova and Tarbeev (2017)
Pontogammarus maeoticus (Sovinskij, 1894), PC	Low Volga before regulation and delta	Kuibyshev reservoir and Low Volga.	Filinova et al. (2008), Kurina (2017a,b)
Pontogammarus robustoides (Sars, 1894), PC	Low Volga before regulation	Middle and Low Volga.	Mordukhai-Boltovskoy (1979), Yakovleva and Yakovlev (2010), Frolova and Tarbeev (2017)
Pseudocuma cercaroides (Sars, 1894), PC	1999, Volgograd reservoir	Kuibyshev reservoir and Low Volga.	Filinova et al. (2008), Zinchenko and Kurina (2011), Yakovlev and Yakovleva (2012)
Pterocuma pectinata (Sowinski, 1893), PC		Kuibyshev and Volgograd reservoirs.	Filinova (2012), Yakovlev and Yakovleva (2012)
Pterocuma rostrata (Sars, 1894), PC		Saratov reservoir.	Zinchenko and Kurina (2011)
Pterocuma sowinskyi (Sars, 1894), PC	1973, Middle Volga	Kuibyshev and Saratov reservoirs.	Borodich (1976), Zinchenko and Kurina (2011), Perova et al. (2018)
Shablogammarus chablensis (Carausu, 1943), PA	2000, Volgograd reservoir	Kuibyshev and Saratov reservoirs.	Filinova et al. (2008), Kurina (2017a)
Stenogammarus dzjubani Mordukhai-Boltovskoy & Ljakhov, 1972, PC		Kuibyshev and Saratov reservoirs.	Kurina (2017a)
Stenogammarus similis (Sars, 1894), PC	2005, Kuibyshev reservoir	Kuibyshev and Saratov reservoirs.	Zinchenko et al. (2008), Kurina (2017a)
Stenogammarus compressus (Sars, 1894), PC		Kuibyshev reservoir.	Kurina (2017a), Perova et al. (2018)

BA, Boreal-Arctic; *Cosm*, Cosmopolitan; *LB*, Lake Baikal; *Mt*, Mediterranean; *NA*, North American; *NBA*, Northern Boreal-Arctic; *PA*, Ponto-Asov; *PC*, Ponto-Caspian; *SA*, Southeast Asia; *SS*, Southern species expanding the range to the north; *bw*, brackish water.

TABLE 2.5 Invasive species of fish in the Volga basin.

Taxa, group	Reservoir-donor	Modern expansion	References
Clupeonella cultriventris (Nordmann, 1840), PC, sw	Residential freshwater populations of the middle Volga (Saratov Bay).	All reservoirs of the Volga and Kama	Karabanov (2013)
Coregonus albula (Linnaeus, 1758), BA, fw	Waterbodies of the European North.	Upper and middle Volga up to Zhiguly HEPS	Borovikova (2013, 2017), Gerasimov (2015)
Syngnathus abaster Risso, 1827, PC, sw	Not established reliably. Probably the northeastern desalinated areas of the Azov Sea.	Reservoirs of middle and Low Volga, reservoirs of Low Kama.	Kiryukhina (2013)
Proterorhinus spsp. (cf. *semipellucidus*), PC, sw	Not established reliably. Probably the Black Sea-Azov basin.	All reservoirs of the Volga and Low Kama.	Neilson and& Stepien (2009), Gerasimov (2015)
Ponticola gorlap (Iljin, 1949), PC, sw	Desalted part of the Northern Caspian.	Middle and Low Volga reservoirs	Data of Laboratory of fish ecology
Neogobius fluviatilis (Pallas, 1814), PC, sw	Azov-Black Sea basin.	Middle and Low Volga reservoirs	Data of Laboratory of fish ecology
Neogobius melanostomus Pallas, 1814), PC, sw	Desalted part of the Northern Caspian.	All reservoirs of the Volga and Kama up to upper site of the Votkinsk reservoir	Brown and& Stepien (2008), Karabanov et al., (2014)
Benthophilus stellatus (Sauvage, 1874), PC, sw	Kuibyshev reservoir. Accidental introduction from the Azov-Black Sea basin.	Middle and Low Volga reservoirs, sporadically up to Rybinsk reservoir. A rare species.	Kodukhova et al. (2016)
Perccottus glenii Dybowski, 1877, Ch, p	Basin of the Amur River.	Littoral of the Volga reservoirs, a rare species.	Data of Laboratory of fish ecology

BA, Boreal-Arctic; *Ch*, Chinese; *PC*, Ponto-Caspian; *fw*, freshwater; *p*, plain; *sw*, saltwater.

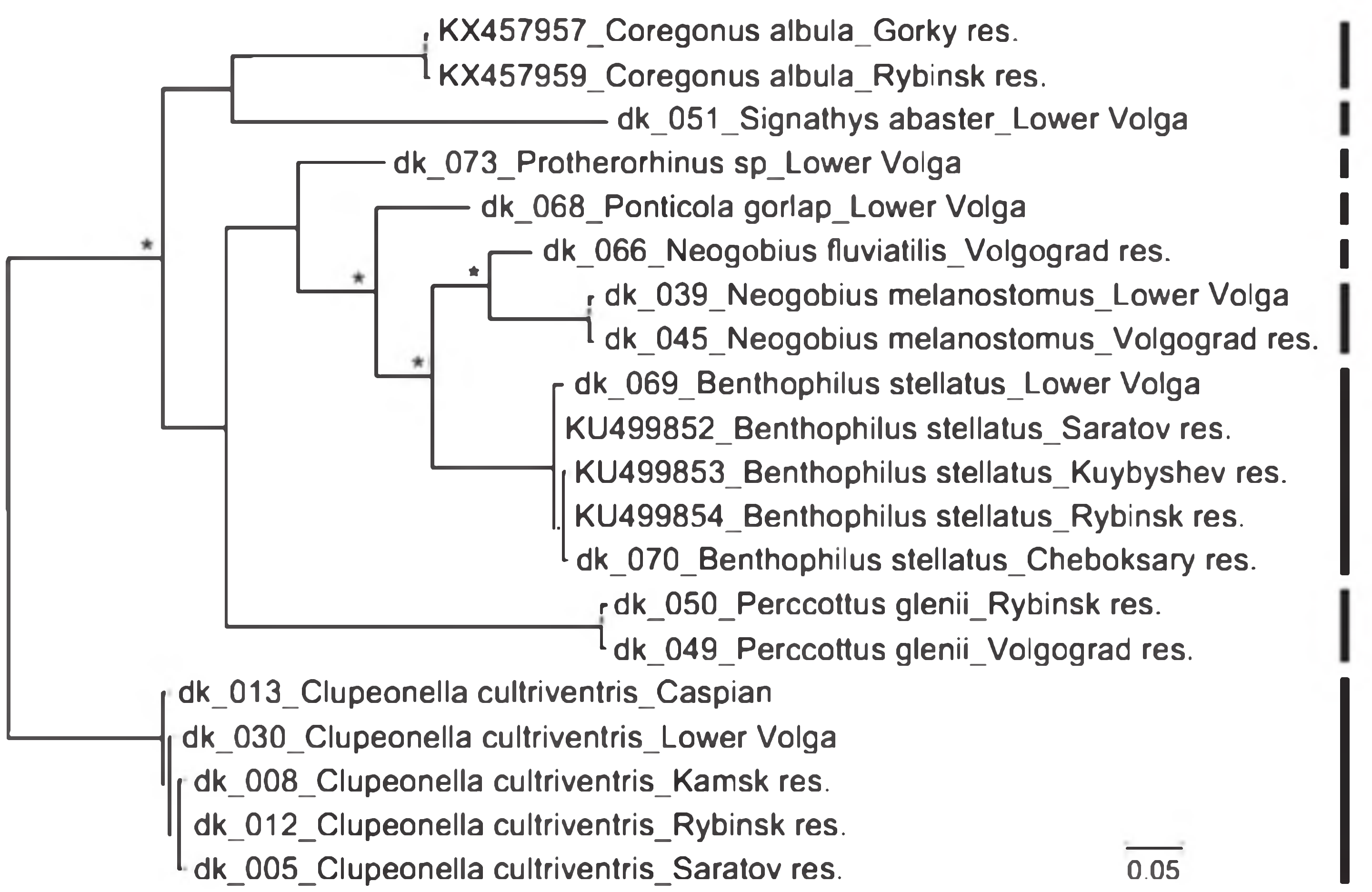

FIGURE 2.7 "Tree of genes" at the locus COI (658 b.p.) for alien fish species of the Volga-Kama basin according to (Ivanova et al., 2007). Phylogenetic reconstruction web-iq-tree (Trifinopoulos et al. 2016). *—values over 0.75 for bootstrap analysis and SH-aLRT test. Thick line on the right shows the selected operational taxonomic units with Bayesian implementation of the general mixed Yule-coalescent model (bGMYC) (Reid and Carstens 2012), 0.95<P<1.

2.5.6 Molecular studies on fish in the Volga

Molecular studies performed during last 10 years significantly clarified fauna composition as well as phylogeographic patterns. Finding of the Ukrainian brook lamprey *Eudontomyzon mariae* (Berg, 1931) in the middle Volga was subsequently confirmed by three molecular markers of mtDNA. Moreover, one more undescribed species of *Eudontomyzon* was discovered in tributaries of the middle Volga that are close to tributaries of the Dnieper River, where this new undescribed species is widely distributed (Levin, 2001; Levin et al., 2016). The distribution of both *Eudontomyzon* spp. is restricted at the upper reaches of the middle Volga tributaries bordering the Don and Dnieper tributaries.

High level of polymorphism of two mtDNA molecular markers was revealed for populations of the vendace *Coregonus albula* L. from both the upper and middle Volga (Borovikova, 2013; Gerasimov, 2015). Haplotype (H) and nucleotide (π) diversity was 0.5967 and 0.0058, respectively, as assessed by ND1 fragment. A new cyprinid species *Gobio volgensis* Vasil'eva, Mendel, Vasil'ev, Lusk and Lusková (2008) was recognized in place of the previously stated *Gobio gobio* (Linnaeus 1758). Recent phylogenetic and phylogeographic study of the genus *Rutilus* suggests that the Ponto-Caspian taxon *R. caspicus* is invalid and together with other invalid taxa within Ponto-Caspian clade, could be referred to species *R. lacustris* (by priority of description). Both *R. rutilus* s. str. and Ponto-Caspian clade (*R. lacustris*) sympatrically occur in the Volga basin with a wide zone of contact (ca. 1700 km). The spatial pattern of haplotype diversity and the shape of haplotype network argued for rapid postglacial colonization of the Volga River (Levin et al., 2017).

The tubenose gobies of the genus *Proterorhinus* from the Rybinsk (upper Volga), Cheboksary, Kuibyshev (middle Volga), and Volgograd (Low Volga) reservoirs were studied for polymorphism of cytochrome *b* (*Cytb*) gene fragment of mtDNA (Sorokin et al., 2011; Medvedev, 2013; Slynko et al., 2013). All Volga samples had only one haplotype, the same as gobies from the Caspian Sea and suggest that Volga populations were derived from the Caspian Sea population. There is a discussion about species belonging to *Proterorhinus* from the Caspian Sea basin. Identification of this species as *P. marmoratus* is doubtful. The latter was described from the Black Sea (Pallas, 1814), but significant divergence in *Cytb* fragment between Caspian and Black Sea lineages was detected with *p*-distance of 9.8% −11.1% (Slynko et al., 2013). Two other taxonomic names, *P. nasalis* (De Filippi) and *P. semilunaris* (Heckel), were proposed for species from the Caspian Sea basin (Sorokin et al., 2011; Slynko et al., 2013). Additional molecular studies are needed to clarify this issue (Gerasimov, 2015).

The genetic polymorphism of the round goby *Neogobius melanostomus* (Pallas) from the upper Volga was studied using two mtDNA markers (Borovikova et al. unpublished data). This study confirmed that colonization of the Volga by the round goby has occurred from different basins. The population from the upper Volga is purely of Caspian Sea origin, while middle and Low Volga was colonized by populations from both Caspian and Black/Azov Seas (Brown and Stepien, 2008).

2.6 Management and conservation

2.6.1 Economic importance

The geographic situation of the Volga and its large tributaries allowed for the development of trade relations between West European countries and pre-Caspian countries of middle Asia by the 8th century. Russia was originally founded along the Volga, partly by Viking entrepreneurs using it as a road to the south from an entry point near Archangel. From the earliest times, the Volga was a great trade way. Cloth, metal fabrics, and precious stones were transported from Central Asia to the north. Furs, wax, honey, and slaves were moved from Slavic and Bulgarian lands to Caspian countries. Trade declined in the 11th century following the fall of the Khazar Khaganate, and the Tatar invasion virtually eliminated economic activity in the middle and Low Volga regions since the 13th century. During this period, the river routes from northeast Russia to Veliki Novgorod played an important role in barter exchange with Europe. It's been only since the 14th century that trade has revived throughout the entire Volga with large market centers appearing along the Volga following liberation from Tatar control.

The main tradeways moved to the west in the 18th century. Transportation increased into the Volga's northern tributaries (rivers Tvertsa, Mologa, Sheksna), and their upper reaches were connected with rivers of the Baltic system by a network of man-made canals. Inland water transport was completed on the Volga by the middle of the 19th century. Today, the Volga is connected with the Baltic Sea by the Volga−Baltic water way (Vyshniy Volochek and Tikhvin systems), with the White Sea via the Northern Dvina system and the White Sea-Baltic Canal, and with the Sea of Azov and the Black Sea through the Volga-Don Canal. The construction of reservoirs resulted in an increase of guaranteed depth up to 4 m along the whole length of the river that, in turn, boosted freight turnover from 27.4 million tons in 1930 to 300 million tons in 1990. Some large reservoirs also included hydroelectric power stations in the 1930s with a current gross output of 11,098,000 kilowatts and total energy generation of 3968 billion kilowatt-hours.

The Volga catchment occupies more than a third of the European area of Russia and 8% of the total area of Russia. At present, it is the most populated region in the Russian Federation. The region is divided into 39 administrative units with a total population of some 60 million (40% of the country's population). Around 45% of industrial and 40% of agricultural products are produced here. A total 426 of 1057 Russian cities, including 7 cities with a population of more than 1 million people and 10 with populations from 500,000 to 1 million, are situated in the region. The Volga and its tributaries account for 70% of the goods carried by river transport in Russia. More than half of all fish and 90% of all sturgeons from inland water bodies are caught in the Volga catchment (Avakyan, 1998). Vast woodlands are typical for the upper Volga basin. Large areas of the middle and some of the Low Volga basin are occupied by grain and technical crops, and melon farms and private garden plots are common. There are oil and gas fields in the Volga-Urals region, and major deposits of potassium salts are found near the city of Solikamsk. Table salt is mined in the Low Volga basin around lakes Baskunchak and Elton.

2.6.2 Conservation and restoration

In the Volga basin, the protected territories, i.e., preserves, forest reserves, national parks, recreational zones, etc., make an appreciable part of the catchment area. There are five large biosphere reserves and two national parks: Pereslavskiy (1988, 230 km^2) and Khvalynskiy (1994, 255 km^2). A network of nature reserves covering more than 6000 km^2 reside in the Volga catchment. Principal information on reserve activity, their flora and fauna is summarized in Sokolov and Syroechkovsky (1988), 1989, Krever et al. (2009), Brynskikh et al. (2010), Internet sites "National Parks and Reserves" (http://www.nparks.ru), "Specially Protected Natural Territories" (http://oopt.aari.ru/oopt), "Reserves of Russia" (http:www.sevin.ru/natreserves).

The Darwin State Wildlife Biosphere Reserve was established in 1945 and included in the international network of biosphere reserves in 2002. It is situated in the upper Volga basin within the territory of Vologda and Yaroslavl provinces and covers an area of 1126 km^2 including 455 km^2 area of the Rybinsk reservoir. About 30 species of fish, 7 species of amphibians, 5 species of reptiles, 222 species of birds, 37 species of mammals, 579 species of higher plants with 37 rare species, ~70 species of mosses, >60 species of lichens, and 123 species of pileate fungi are found in the reserve.

The reserve is a place of conservation of the rare birds black-throated loon *Gavia arctica* (L.), osprey *Pandion haliaetus* (L.), white-tailed eagle *Haliaetus albicilla* (L.), golden eagle *Aquilla chrysaetos* L., Greater Spotted eagle *Aquilla clanga* (Pall.), eagle-owl *Bubo bubo* (L.), and ptarmigan *Lagopus lagopus rossica* Serebr, all in the Red Data Book of the Russian Federation. The area has a high abundance of brown bear *Ursus arctos* L. and white-tailed eagle *Haliaetus albicilla* (L.). The population density of osprey *Pandion haliaetus* (L.) on the peninsula is the highest in Europe, and perhaps in the world.

The Kerzhenskiy Reserve, 310 km^2, was founded in 1993 in Nizhniy Novgorod province. It occupies the Kerzhenets River basin (the Volga's left tributary) within the middle Volga. In 2002, the reserve was included in the UNESCO network of biosphere reserves as "NizhegorodskoyeZavolzhie," Natural areas of southern taiga and the Kamsko-Bakaldinsky group of marshes representing wetlands of international importance were restored at this territory. About 630 species of higher plants, 184 species of mosses, 206 species of lichens, and 369 species of fungi are found in the reserve. *Cephalanthera rubra* (L.) Rich., 1817 and *Neottianthe cucullata* (L.) Schlechter are included in the list of rare and protected plants of the Red Data Book of the Russian Federation. About 230 species of vertebrates including 46 species of mammals, 6 species of reptiles, 6 species of amphibians, and 21 fish species inhabit its territory. Of the 150 bird species, 13 species are listed in the Red Book of the Russian Federation. Among rare and endangered species are the desman *Desmana moschata* L., black stork *Cyconia nigra* L., golden eagle *Aquilla chrysaetos* L., white-tailed eagle *Haliaetus albicilla* (L.), peregrine *Falco peregrinus* Tunst., and osprey *Pandion haliaetus* (L.).

The large Volga-Kamsky Reserve founded in 1960 is located in Republic of Tatarstan covering an area of 421 km^2 with 13 km^2 of the Kuibyshev reservoir water area. The reserve includes clusters entering the World Network of Biosphere Reserves since 2005 (Raifa Forest and Mezhdurechye Sarali) and 2007 (Spassky Archipelago and Sviyazhsky Wetlands). Most of the Volga-Kamsky Reserve is covered by forests of taiga, oak, and steppe. In total, 866 species of vascular plants, 210 moss species, 240 lichen species, and more than 800 species of fungi grow on the reserve territory. Several rare species, such as red headband *Cephalanthera rubra* (L.) Rich., lily curly *Lilium martagon* L., etc., are included in the Red Data Book of the Russian Federation. Woods with pines, spruces, and oaks of 200–300 years old, remain. Since 1921, an arboretum exists in the Nature Reserve where European, Asiatic, and North-American trees and bushes grow. Some of them have spread into the forest areas of the reserve. Some 59 species of mammals, 230 species of birds, 6 species of reptiles, 10 species of amphibians, and 41 species of fish were recorded in the fauna. There are also acclimatized raccoon dogs *Nyctereutes procyonoides* (Gray), muskrats *Desmana moschata* L. and American mink *Neovison vison* (Schreber) in the reserve area. Rare and disappearing species, included in the Red Data Book of the Russian Federation inhabit the Reserve, are 14 bird species (white-tailed eagle *Haliaetus albicilla* (L.), fish hawk *Pandion haliaetus* (L.), black stork *Cyconia nigra* L., etc.) and one species of Chiroptera, the giant noctule *Nyctalus lasiopterus* Schreber.

The middle Volga complex Biosphere Reserve was created in 2006 on the basis of the Zhiguli State Wildlife Reserve established in 1996 in Samara province, and the Samarskaya Luka National Park. Biosphere Reserve covers an area of 300 km^2 with 176 ha of the Volga water area. About 1100 species of higher plants, 170 species of mosses, 200 species of lichens, and 30 species of pileate fungi are found in the reserve. About 300 species of vertebrates including 62 species of mammals, about 200 bird species, 9 species of reptiles, 8 species of amphibians, and 68 fish species inhabit its territory. Among them, endemics (5 plant species and 11 invertebrate species), relicts (more than 60 plant and 80 invertebrates species), and species that need special protection (e.g., merlin *Falco rusticolus* (L.), osprey *Pandion haliaetus* (L.), black griffon *Aegypius monachus* (L.), burial eagle *Aquila heliaca* (Sav.)) are of special interest. The 21 species of plants, 2 species of mammals and 19 species of birds are included in the Red Book of the Russian Federation.

The Astrakhan State Wildlife Biosphere Reserve was founded in the Volga delta in 1919. Presently it occupies 668 km^2, including 113 km^2 of the Caspian Sea. These open water areas and marshlands are of international importance (Ramsar Convention—the Volga Delta) and included in the international network of biosphere reserves. Approximately 314 species of higher plants are found here. More than 30 species of mammals, 283 bird species, and 56 fish species inhabit the area, and the Caspian Ornithological Station operates in the reserve. Rare species are included in the Red Book of the Russian Federation, including plants *Nelumbo nucifera* Gaertn. [incl. *N. caspicum* (DC) +Fisch., *N. komarovii* Grossh.]), *Aldrovanda vesiculosa* L., *Marsilea aegyptica* Willd. and 14 species of birds that nest or meet in breeding time: buff-backed heron *Bubulcus ibis* (L.) Wagler, spoonbill *Platalea leucordia* L., loaf *Plegadis falcinellus* (L.), sterkh *Grus leucogeranus* Pallas, little bustard *Tetrax tetrax* L., avocet *Recurvirostra avosetta* L., stilt *Himantopus himantopus* (L.), and saker *Falco cherrug* Gray. Six species of birds, including pink pelican *Pelecanus onocrotalus* L., Bewick's swan *Cygnus columbianus bewickii* Yarr., kulik sultanka *Porphyrio porphyrio* (L.), and a steppe eagle *Aquila rapax* (Temm.) were marked in the reserve territory as migratory or nomadic.

2.6.3 Conclusion and perspectives

Transformations of the Volga have caused major changes in water circulation that affected the energy flow and mass exchange such as water balance and exchange, variation in water levels, flow velocity, and thermal regime. The morphology of reservoirs is influenced by natural climatic factors (i.e., water quantity and quality) as well as human activities that regulate flow. Reservoirs represent unstable ecosystems; however, they are integral parts of the Volga. Together with positive aspects regarding economic development, the Volga transformation has had serious consequences such as flooding of productive lands, collapse of banks due to fluctuations in water level, and losses in the fishery.

At present, a fish community resembling the one before regulation inhabits only two reaches of the river. Such rheophilous species such as dace, chub, undermouth, zherekh, loach, gudgeon, minnow, and bystranka prevail in the headwaters of the Volga, and all typical river fishes can be found within the reach from the river mouth to Volgograd dam. However, their numbers decrease upstream because of unfavorable changes in hydrological regime after regulation. Among the sturgeons, belugas are now rare and sheefish (Caspian salmon) are essentially extinct. Regulation of the Volga resulted in the disappearance of a distinctive ichthyofauna in the upper, middle, and Low Volga. The fish population consists mainly of the same typical limnophilous species along the river because of the invasion of nonnative fishes.

The high density of humans and extensive industrial development caused a strong anthropogenic impact on the river and its biota. Consequently, conservation actions and nature management should emphasize preservation and recovery of the Volga catchment. The realization of a special federal program "Revival of the Volga" can help in this situation. This program aims at solving urgent problems concerning environmental safety from industrial production and the formation of sustainable economic developments (Komarov, 1997). Priority guidelines for major ecologically poor complexes include Development of master nonwaste technologies for reequipment and reconstruction of ecologically unsound developments in the region; development of environmentally safe production of chemicals as well as process technologies that together ensure an increase in ecological sound industry; realization of new technologies in industry; development of ecologically sound agriculture; rehabilitation of forests and prevention of their degradation, wildlife conservation, and development of wildlife reserves; creation of favorable conditions for development of the fishery;

reclamation and use of industrial and municipal wastes; organization of environment monitoring systems and development of a geo-information system; improvement of ecological conditions in cities; and development of ecological education and professional training.

2.7 Major tributeries of the Volga River

2.7.1 The River Kama

2.7.1.1 Introduction

The Kama (Photo 2.4 A,B) is the largest tributary of the Volga. Its name comes from the Udmurt "kam," meaning "river" or "current." The Kama-Vyatka area was originally colonized by Fins before the end of the 11th century. The first Russian boats arrived on the Kama during this period and resulted in various Russian settlements. The river was a major link of communication between Asia and Europe. For instance, Yermak the Cossack ataman traveled to Siberia on the Kama in the mid-16th century, thereby connecting Siberia with Muscovite Russia. The natural riches of the Ural region caused intensive development of the Kama catchment. The Kama is the fifth longest river in Europe after the Volga, Danube, Ural, and Dnieper (Shmidt, 1928b).

2.7.1.2 Paleography

The Kama valley is older than the Volga, being present already in the early Quaternary (Shklyaev, 1964). The Kama and its major tributary Vishera flowed to the Caspian Sea, but presently flows in the upper basin draining to the north. Later glaciation reformed its hydrographic network. The geology as well as the relief of the catchment is diverse. The Ural highlands are situated between the Russian plain in the west and Siberian plain in the east. The Russian plain and Ural Mountains are divided by an elongate pre-Ural marginal depression that forms the Yuryuzan-Salvinskaya plain and Belskaya depression. The present-day Urals were formed by neogenic and quaternary vertical block movements of ancient folded-fault massifs, erosive activity of rivers, and long-term weathering.

Sedimentary rocks (sand, clay, sandstone, conglomerate, limestone, shale) make up much of the geology in the catchment. Rocks differing in age and composition stretch longitudinally in the catchment. The Eastern European plain is composed of mainly horizontal beds of sedimentary rocks of Precambrian granite gneiss of the Russian plain. The most widely distributed are deposits from the Upper Permian period. Among them, Tatar deposits (in the western and central parts of the region) are represented by multicolored clays and marls often alternating with limestone and sandstone bands. In the upper Kama and Vyatka basins, beds of Jurassic and Lower Cretaceous marls, clays, and sands are superimposed on these deposits. In the Uval area of the Vyatsky basin, limestone and gypsum of the Kazan layer are interspersed among multicolored marls. Near the Kama river valley, Tatar deposits are

PHOTO 2.4 Main tributaries of the Volga River. (A) Lower reach of the Kama, (B) Kamskoye reservoir at Perm', (C) Sheksna river at Goritsy (Photo: V. Lazareva), (D) confluence of the Oka and Volga rivers at Nizhni Novgorod *Photo: E. Izvekov.*

replaced by Kazan deposits in which limestone and marl bands occur among red-colored clays and sandstones. To the east on the left bank of the middle Kama and along the lower river Belaya, lower Permian Ufa deposits with bands of gypsum occur.

Along the margins of the Russian plain are highly soluble lower Permian rocks causing extensive karstic formations. The pre-Ural depression is filled by weakly dislocated Permian sedimentary rocks including some typical salt-bearing sections near the city of Solikamsk and deposits of gypsum and anhydrites. In the plain, Paleozoic rocks are mostly covered by thin Quaternary deposits of mainly loam soils, and clays and sands in some areas. In the northern Kama catchment, fluvioglacial sands are underlain by clays. In tributary valleys of the Chusovaya, Sylva, and Iren, karstic areas develop under river deposits and nonkarstic and karstic rocks of carbonate, sulfate, and halogenous composition alternate.

2.7.1.3 *Physiography, climate, and land use*

The relief of the catchment is distinguished by the Ural Mountains in the middle, north and south; and the Eastern European plain (along with the pre-Urals) to the east. Coniferous forests similar to Siberian taiga occur in the upper catchment and deciduous forests are found in the lower catchment, both in the forest-steppe and forest biomes. However, large areas of the catchment have been deforested and are used for agriculture or mining.

The Ural Mountains are of moderate height (400–600 m asl) and have a weathered but strongly irregular surface. Some peaks in the south and north can reach 1500–1600 m asl. In the northern Urals, a system of parallel, gradually decreasing ridges are found to the west along with various forested plateaus at 400–500 m asl. The middle Urals (59°15′ to 55° NW) reach 500–600 m asl and consist of a rugged hilly plain with single irregularly spaced peaks, the highest being Sredniy Baseg at 994 m asl. Western foothills of the middle Urals are represented by low ranges rising within the plain, including among others Basegi (993 m asl), Belyi Spoi (568 m asl), Kirgishansky Uval (555 m asl), and Bardymsky (681 m asl). The southern Urals (55°30′ to 56° NW) are highly mountainous and contain some of the highest ridges, most of these found in the Belaya river basin. The southern Urals extend for 150–200 km in width and include the Uraltau Divide, a wall-like range reaching up to 1000 m asl.

The Eastern European plain has an undulating relief of elevated rugged interfluvial areas and wide gentle-terraced river valleys. In the upper Kama and Vyatka lies the flat upper Kama upland about 300 m asl with deeply incised rivers. The middle Vyatka flows southeast through the distinctive Vyatskiy Uval, running north south at 250–280 m asl. In the southern pre-Urals, the Bugulma-Belebeevskaya peak rises up to 450–480 m asl and is connected to the west with Obshchiy Syrt.

2.7.1.3.1 Climate

Climate of the region is continental with large variations in annual and daily temperature. Humid air masses from the Atlantic Ocean exert a strong influence on climate. Features of the relief cause the presence of latitudinal zones in climate in the plain and vertical climate zones in the mountains. Severe snowy winters and short cool summers in the north and frosty winters with little snow and comparatively hot summers in the far south characterize the general climatic differences with latitude. In winter, a Siberian anticyclone causes stable but frosty weather with more snow in the pre-Urals and on mountain slopes. Frequent cold air surges from the north and southern cyclones often bring sharp changes in weather. In summer, the area is influenced by low-pressure air masses from the Barents and Kara seas and the Azores. Air masses from the Azores bring hot dry weather.

Average annual air temperature in lowland areas of the Kama vary from 0 to 3°C north to south. The coldest month is January, ranging from −17 to −14°C south to east. Lowest air temperatures occur between December and February, reaching −48°C. Average daily temperatures > −5°C usually occur by the third week in March, and >0°C in the first week in June. The hottest month is July, averaging 16–17°C in the north and about 19°C in the south. Temperatures decrease to around 5°C in late September early October. Winter thaws are rare and short, often lasting for only several hours.

Annual precipitation varies widely but decreases north to south. In the north, annual precipitation reaches 1300–1600 mm. In mountain valleys, annual precipitation is about 850–950 mm. Annual precipitation is 800–900 mm in the northern middle Urals and 600–700 mm in the south. Annual precipitation is 1200–1500 mm in the southern Urals and 500–600 mm in the pre-Urals plain. Precipitation during the year occurs unevenly and is 1.4–1.7 times higher in summer than in winter. Heavy showers are frequent in the middle Urals and pre-Urals, but drought can occur in the south.

Snow cover can happen by September and is complete by late October early November. Spring thaw begins in mid-April in the south and late April in the north. In the mountains and in the northern foothills, spring thaw begins in May. In winter, southerly and southwesterly winds prevail. Wind direction is variable in summer, although northerly, northwesterly and westerly winds are most common. In the mountains, wind direction is affected by orography, and mountain-valley winds are common. Annual average wind velocity can vary 2–5 m/s.

2.7.1.4 *Geomorphology, hydrology, and biogeochemistry*

The Kama begins in the Ural Mountains, flows east in Udmurtia then southwest in Perm province before flowing again through Udmurtia into Tatarstan where it meets the Volga. The Kama flows into the Kuibyshev reservoir in the middle Volga. The length of the river is about 1800 km, and its catchment area is 507,000–522,000 km^2, depending on the source. Before construction of the Kama reservoir system, its length was 2030 km (Butorin and Mordukhai-Boltovskoy, 1979). The Kama main channel forms a large arch with only 445 km separating the river source and its mouth (Shmidt, 1928b).

Around 74,000 rivers and streams totaling 252,000 km in length are found in the Kama catchment. Shallow streams <10 km in length comprise the majority (94.5% of all rivers). The Kama River network lies in the Caspian Sea basin. The most dense river network (0.7–0.8 km/km^2) is in the northeastern mountains. River density decreases to 0.3–0.4 km/km^2 in the southwest because of the different climatic conditions (Agapitova, 1975; Balkov, 1979). River density within the Ural Mountains decreases from north to south.

Rivers of the Kama flowing through the Eastern European plain have well-developed valleys with wide floodplains and terraced slopes. The rivers have low gradients, many branches, and numerous islands and shoals. Current velocities are low. With relatively rapid changes in elevation, river valleys become narrow, floodplains disappear, current velocities increase and rapids appear. Rivers in the upper Kama flow through narrow valleys. The headwaters of many present-day rivers meander along relict ancient valleys in intermontane depressions. Over 200 rivers flow directly into the Kama (selected list in Table 2.1). Most right and some left tributaries flow from the north and are large deep lowland rivers. The others, mainly from the left side, originate from the Ural Mountains and are rapid and cold.

The flow regime of most Kama rivers is characterized by a distinct spring flood from snow melt, rain-caused floods in summer–autumn, and low constant flow (140–160 days) in winter (Kuzin, 1960; Agapitova, 1975; Balkov, 1978; Komlev and Chernykh, 1984). Highest discharge occurs during peaks in the spring flood, and averages 70–80 $L\ s^{-1}\ km^{-2}$ in the north, 50–55 $L\ s^{-1}\ km^{-2}$ in the south, and 85–100 $L\ s^{-1}\ km^{-2}$ in the far steppic south due to intensive snow melting. In mountainous areas of the catchment, peak discharge can reach 150–200 $L\ s^{-1}\ km^{-2}$, except in karstic areas. Low discharge occurs in winter, and averages 3–4 $L\ s^{-1}\ km^{-2}$ in the north and 0.5–0.7 $L\ s^{-1}\ km^{-2}$ in the south and southwest. Small streams in basins <100 km^2 can be intermittent and go dry in winter.

Numerous reservoirs and smaller impoundments regulate the runoff in most rivers in the Kama catchment. The largest reservoirs in the catchment are the Kamskoye, Votkinskoye, and Nizhnekamskoye on the Kama. Each of these has a high water exchange (Table 2.6). The Kama comprises 48% of the flow of the Volga (Chernyaev, 2000). The average annual discharge of the Kama and Volga is 3750 and 3800 m^3/s, respectively.

2.7.1.4.1 Temperature

The thermal regime of the Kama is seasonal and temperatures are highest in July, averaging 18.8–20.2°C in different parts of the river. Year-to-year fluctuations in temperature are normal, on average >8°C during spring and early autumn and from 4.5 to 7.8°C in midsummer and late autumn. According to long-term records, ice cover along the river occurs around November 3–5 in the upper Kama and November 21–26 in the lower Kama, lasting 142 and 174 days, respectively. Ice breakup occurs between April 16–30 in the lower Kama and April 22–May 1 in the upper Kama.

Thermal conditions in the large reservoirs depend on reservoir morphology and hydrodynamics. In shallow areas of reservoirs with slow water exchange, spring warming of the water is earlier, whereas warming lags about 6–8 days in deep areas of reservoirs with fast water exchange. Surface water temperatures during the ice-free period follow air temperatures in the reservoirs, being highest in late July or early August at 24–28°C. Because of atmospheric circulation, surface temperatures in reservoirs during high-water periods are 2–2.2°C lower than during low-water periods. Thermal stratification usually develops in deep areas of reservoirs during periods of heating with a temperature difference of 3–7°C. Cooling begins in mid-August and is most intensive in September–October. In the reservoirs, average date of temperature transition >4°C occurs between 7 and 29 October, and the average date of ice cover occurs between November 2 and 23. The duration of the ice-cover period lasts from 125 to 171 days.

2.7.1.4.2 Currents

All types of currents known for artificial water bodies can occur in reservoirs of the Kama. Discharge currents and wind drift currents are the most frequent (Devyatkova and Trutnev, 1983). Discharge currents occur throughout the year, whereas wind-drift currents occur only during the ice-free period. Discharge currents are most typical in the upper basin, while wind effects and long waves caused by the irregular discharge

TABLE 2.6 Physicochemical and biological parameters of the Volga River main tributaries based on Litvinov (2002), Belyaeva et al. (2018), and author's original data.

Parameters	Kama reservoirs			River Oka	Sheksna reservoir
	Kamsk	Votkinsk	Nizhnekamsk		
Length, km	300	365	185	1500	167
Mean depth	6.3	8.4	3.3	n.d.	3.9
Water exchange, year^{-1}	4.2	5.8	6.8	n.d.	0.8
Transparency, m	1.2	1.0	1.4	n.d.	0.9
Water T, °C*	23.3	23.6	24.3	22.5	17.5
	22.1	22.0	24.2	22.5	15.8
Conductivity, µSim/cm	456	331	269	552	152
O_2, mg/L*	9.6	10.6	10.1	10.3	9.5
	2.5	4.2	8.9	10.2	8.3
TN, mg/L	0.61	0.93	0.69	n.d.	0.84
TP, µg/L	42	88	47	n.d.	55
CHL, µg/L	18.9	22.6	17.2	n.d.	10.6
Sedimentary CHL + Pheo, mg/g dry weight	77	43	16	n.d.	n.d.
Phytoplankton biomass, g/m^3	4.1	1.9	0.7	9.2	3.6
Zooplankton biomass, g/m^3	1.8	1.0	1.3	0.2	1.6
Zoobehthos biomass, g/m^2	21	91	n.d.	n.d.	9.7

CHL, chlorophyll; *Pheo*, pheopigments.
*—*surface and bottom above and below the thermocline*.

regime of hydroelectric power stations are common near dams.

Inputs of the Kama and Vishera rivers as well as reservoir levels influence flow velocity in the upper Kamskoye reservoir. High-velocity currents that occur during the spring flood in the upper reservoir range from 120 to 188 cm/s and are similar to those in the upstream river. Current velocity slows to 40–100 cm/s by the end of June and to 10–40 cm/s in late summer early autumn. However, velocity can increase to 60–100 cm/s during floods from rain. Two-ply currents often develop in the middle lakelike part of reservoir. Flow direction and velocity in the upper layer depend upon wind velocity and direction and rarely exceeds 16–18 cm/s. At the same time, currents in deeper layers are relatively stable. Near the dam, discharge currents vary from 45–50 cm/s in spring to 10–15 cm/s in summer and autumn.

In Votkinskoye reservoir, flow velocity also decreases downstream. In spring, velocity is about 1 m/s in the upper reservoir, 0.2–0.5 cm/s in the middle part of the reservoir, and 0.1–0.15 cm/s in the lower reservoir. Velocities are two to three times lower in summer. In the lower Kama below the town of Chistopol' in the Volzhsko-Kamsky reach of Kuibyshev reservoir, discharge velocity depends on the reservoir level but typically decreases downstream from 15–30 to <5–10 cm/s (Znamensky and Chigirinsky, 1978).

2.7.1.4.3 Bottom sediments

Using Kamskoe and Vokinskoye reservoirs as examples, bottom sediments from upper areas of each reservoir to the dam change from sands of different size to silt (Kuznetsova and Rassadnikova, 1983). Dirty sands and erinaceous silts represent an intermediate type of bottom sediment. In the central and near dam parts of reservoirs, gray, brown, and peaty silts are common. Near the dam, these silts look dark gray and almost black because of oil pollution. The layer of deposited silt ranges from 15 cm in the upper reservoir to 30–34 cm in central and near-dam areas. The deepest silt layer, i.e., 80–100 cm, occurs in bottom depressions. No particles are larger than 1 mm and particles 0.5–0.2 mm are most common. The average size of silt particles is 0.005 mm. Silicon acid is a basic component of all sediments, varying from 91% to 97% in sands to 50%–70% in small-size silt particles. Organic matter makes up <3% in sands, 2%–26% in gray and brown silts, and 60% in peaty silts. Discharge from the catchment area along with material from bank processing

TABLE 2.6 Physicochemical and biological parameters of the Volga River main tributaries based on Litvinov (2002), Belyaeva et al. (2018), and author's original data.

Parameters	Kama reservoirs			River Oka	Sheksna reservoir
	Kamsk	Votkinsk	Nizhnekamsk		
Length, km	300	365	185	1500	167
Mean depth	6.3	8.4	3.3	n.d.	3.9
Water exchange, year^{-1}	4.2	5.8	6.8	n.d.	0.8
Transparency, m	1.2	1.0	1.4	n.d.	0.9
Water T, °C*	23.3	23.6	24.3	22.5	17.5
	22.1	22.0	24.2	22.5	15.8
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TP, μg/L	42	88	47	n.d.	55
CHL, μg/L	18.9	22.6	17.2	n.d.	10.6
Sedimentary CHL + Pheo, mg/g dry weight	77	43	16	n.d.	n.d.
Phytoplankton biomass, g/m^3	4.1	1.9	0.7	9.2	3.6
Zooplankton biomass, g/m^3	1.8	1.0	1.3	0.2	1.6
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2.7.1.4.4 Hydrochemistry

The mineralization and chemical composition of the Kama is variable along its course because of different environmental conditions and degree of human activities in the catchment. Soil cover exerts the most significant influence on river chemistry. Thus, a change from podsolic soils absent of soluble salts to dark gray soils of chernozems increases mineralization from the upper catchment to the mouth. Locally, thick deposits of Perm sediments that include soluble salts such as sodium chloride, gypsum, anhydrites strongly influence the chemical composition of the water. In general, the Kama has higher contents of alkaline metals and chlorides than the Volga (Bylinkina et al., 1982a).

The upper tributaries Veslyana, Lupya, Southern Keltma, contribute hydrocarbonate waters with low mineralization and high Ca content. A distinctive feature of these rivers is the presence of high amounts of iron and organic matter from bogs. Mineralization increases in the Kama below the confluence of the large tributary Vishera. The rivers Yayva and Kosva contribute sulfate-calcium waters to the Kama. The large tributaries Belaya and Chusovaya influenced water chemistry in the middle Kama up to 1954 before construction of Kamskoye reservoir. The Belaya still affects mineralization levels in the lower Kama by doubling the sulfate content.

Waters of the upper Kama are soft and have low mineralization that changes during the year from 32 to 163 mg/L. It ranges from 323 to 120 mg/L during spring and from 120 to 160 mg/L during summer. Anion composition is dominated by HCO (28%–47% equivalent) and SO_4 (2%–18% equivalent). Cations consist of mainly Ca (22%–44% equivalent) and Mg (4%–18% equivalent or 0.2–7.5 mg/L). Na and K content ranges from 1.2 to 6.2 mg/L (1.6%–13% equivalent). Water color and permanganate oxidation are relatively high because of the extensive waterlogged forest cover in the catchment. Color ranges from 130 to 170 Cr–Co degrees during spring high water to 50–80 Cr–Co degrees during summer low water. During summer and autumn floods, it can increase to 110–230 Cr–Co degrees. Permanganate oxidation varies within a year from 5 to 30 mg O/L. Oxygen content is 4–8 mg/L at the end of the ice-cover period and increases to 9–10 mg/L in spring and autumn. Nitrate content can reach up to 1 mg/L.

In the lower Kama, water mineralization and chemical composition are quite different. Ion concentration increases significantly and total mineralization increases from 170 up to 700 mg/L. Prevalence of HCO and Ca decreases as Cl, Na, and K simultaneously increase. Total mineralization and water hardness are higher in the lower reach. The pH values change within a year ~7.0–8.0 becoming slightly higher in summer and lower in at high discharge. Water color decreases at 40–60 Cr–Co degree. Permanganate oxidation is 8–16 mg O/L, and bichromate oxidation is 16–30 mg O/L. Suspended matter influencing water transparency is much higher in spring (on average 22.2 mg/L in the middle and lower Kama) than in summer (7.6 mg/L).

Total nitrogen ranges from 0.6 to 1.5 mg/L in spring to 0.6–1.2 mg/L in summer with mean values of 1.11 and 0.74 mg/L, respectively. Nitrate content in the winter low-water period and during passage of the peaks in high water varies from 0 up to 5 mg/L. Nitrate may go to zero in summer as a result of uptake by plants. A similar picture is observed for nitrite, values ranging from 0.01 to 0.54 mg/L during the annual cycle. Total phosphorus content varies from 22 to 104 μg/L in spring to 20–146 μg/L in summer. Phosphate content varies during the year from 0.005 to 0.065 mg/L (Bylinkina et al., 1982a).

At present, mean transparency in reservoirs of the Kama is near previous values. TN and TP content also fit within the limits of early observations. In the Kamskoye and Votkinskoye reservoirs, there has been a decrease in oxygen content in the bottom waters in summer. Based on chlorophyll content, all three reservoirs of the Kama are eutrophic (Table 2.6).

2.7.1.4.5 Pollution

The reservoirs of the Kama basin are continuously affected by industrial and domestic wastewater. The Kama river itself, the cascade of reservoirs, and most tributaries are characterized by high contents of manganese, copper, iron, and organic matter (Israel' 2006, 2011; Chernogaeva, 2015, 2018). However, cases of contamination by metal compounds on river sections of the Kama, Votkinsky, and Nizhnekamsk reservoirs are not registered. The state of waters in the Kama is characterized as "contaminated" (class 3). The increased content of manganese and iron compounds in water is caused by both anthropogenic and natural factors, including the bed weathering. In general, waters of the Kama are suitable for technical and domestic water supply after treatment and disinfection.

2.7.1.5 Aquatic and riparian biodiversity

The flora and fauna of the Kama is characterized by taxa of bogs, lakes, ponds, and former river-bed water bodies variously connected with the main river channel and consist of typical potamoplankton and rheophyliczoobenthos.

2.7.1.5.1 Plants

The Kama River valley lies in the middle and southern taiga forest biomes that become forest-steppe in its lower reaches (Isachenko and Lavrenko, 1980). Vegetation in the headwater floodplain is characterized by a combination of osiers (*Salix viminalis, S. acutifolia*), and dark coniferous (*Picea abies* x *P. obovata, Abies sibirica*) and paludal (*Alnus incana, Betula pubescens, Salix myrsinifolia, Picea abies* x *P. obovata*) forests. In the middle Kama, this vegetation also includes broad-leaf and mixed broad-leaf forests of *Quercus robur* and *Tilia cordata*. Osier-beds and oak forests dominate in the lower Kama, and black alder (*Alnus glutinosa*) forests are widespread in the near terrace floodplain. Meadows now inhabiting deforested areas in the upper Kama are dominated mostly by small gramineous communities of *Festuca rubra* and *Agrostis tenuis*. Meadows in the middle Kama are covered by gramineous communities of *Alopecurus pratensis, Phleum pratense, Agrostis gigantea, Festuca pratensis*. In the lower Kama, narrow-leaved sedge (*Carex acuta*) is most common (Lipatova, 1980).

Osier-beds are common along the river banks, and aquatic vegetation is most developed in the Kama reservoirs. In reservoir bays, both semi-submersed vegetation of mostly *Phragmites australis, Typha angustifolia, T. latifolia, Glyceria maxima, Equisetum fluviatile*, and submersed plants represented by communities of yellow pond-lilies (*Nuphar lutea*), water lilies (*Nymphaea candida*), different pondweeds (*Potamogeton perfoliatus, P. pectinatus, P. lucens, P. natans*) and other hydrophytes (*Ceratophyllum demersum, Myriophyllum spicatum, Stratiotes aloides*) are abundant. Aquatic flora in the lower Kama reservoir is represented by 93 species of macrophytes.

2.7.1.5.2 Algae

Prior to regulation, phytoplankton of the Kama consisted of typical potamoplankton with abundant algal flora (Tauson, 1947). Bacillariophyta made up 235 species, Chlorococcales 131 species, Cyanophyta 65 species, Chrysophyta 9, Dinophyta 9, Euglenophyta 8, and Volvocales 5 species. Rhodophyta consisted of a single species, *Chantransia chalybea* Fries. *Melosira varians* Ag., *Aulacoseira. granulata* (Ehr.) Sim., *A. italica* (Ehr.) Sim., and *A. italica* var. *tenuissima* (Grun.) Sim., *Diatoma tenuis* Ag., *Synedra ulna* (Nitzsch) Ehr., *Asterionella formosa* Hass, *C. placentula* Ehr., *Navicula cryptocephala* Kütz., and *N. radiosa* Kütz. were most common. Representatives of *Aulacoseira, Asterionella*, and *Cyclotella* caused major algal blooms. Species such as *C. meneghiana* Kütz., *Diatoma vulgaris* Bory, *Fragilaria crotonensis* Kitt., *F. capucina* Desm., *Cocconeis pediculus* Ehr., and *Nitzschia acicularis* W.Sm. were less abundant. The mean density of the diatoms during summer was $1.13-4.52 \times 10^6$ cells/L. Green algae consisted of the genus *Gloeococcus, Pediastrum, Scenedesmus, Dyctiosphaerium*, and *Monoraphidium*. The blue-greens *Anabaena, Aphanizomenon*, and *Microcyctis* were locally abundant in summer.

Seven periods in phytoplankton development could be distinguished over the annual cycle (Shtina, 1968). Phytoplankton were almost absent in winter. In early spring, diatoms begin developing and attain high abundance along with other taxa in late spring. Many bottom forms can be found in the plankton. All groups of algae reach high abundances in early summer, and a single peak of phytoplankton of $11-13 \times 10^6$ cells/L can be observed in August. In early autumn, diatoms again become common, and a decrease in phytoplankton occurs later.

Presently, 242 taxa of algae have been recorded in the reservoirs of the middle Kama, including Bacillariophyta with 88, Chlorophyta 96, Cyanophyta 31, Euglenophyta 10, Chrysophyta 8, and Cryptophyta and Dinophyta 9. The community structure of phytoplankton remains relatively similar over time, although dominant groups differ during the year as well as from year to year (Tretyakova, 1989). Bacillariophyta, mostly *Aulacoseira italica*, comprising up to 10^7 cells/L, are most abundant in spring and blue-greens, numbering 5×10^5 cells/L, are most common in autumn. Mean phytoplankton biomass during 1975–82 ranged from 1.16 to 2.34 g/m^3, being dominated by Bacillariophyta (72%–92%), Cyanophyta (2%–10%), and Cryptophyta and Dinophyta (4%–8%).

2.7.1.5.3 Zooplankton

Zooplankton of the Kama before regulation consisted of 186 species, >60% represented by the Rotatoria (Tauson, 1947). Species such as *Asplanchna priodonta* Gosse, *Filinia longiseta* (Ehrenberg), *Polyarthra dolichoptera* Idelson, and *Keratella cochlearis* (Gosse) were most common, although the cladoceran *Bosmina longirostris* (O.F.Müller), the copepods *Mesocyclops leuckartii* (Claus), and *Thermocyclops oithonoides* (Sars) were also abundant.

Presently, the zooplankton community totals ~200 species consisting of Cladocera (30%), Copepoda (20%), and Rotatoria (50%) (Kortunova, 1983,1985; Dementieva, 1985). The most abundant crustaceans are *Daphnia galeata* Sars, *Diaphanosoma orghidani* Negrea, *D.* gr. *brachyurum* (Lievin), *Chydorus sphaericus* (O.F. Müller), *Bosmina longirostris* (O.F. Müller), *Bosmina* (*E.*) cf. *crassicornis* (Lilljeborg), *Mesocyclops leuckarti* (Claus), *Thermocyclops oithonoides* (Sars), *T. crassus* (Fischer), *A. americanus* (Marsh.) and alien species *Heterocope caspia* Sars and *Eurytemora caspica* Sukhikh et Alekseev. Rotifera such as *Asplanchna priodonta* Gosse, *A. henrietta* Langhaus, *Conochilus hippocrepis* (Schrank), *C. unicornis* Rousselet, *Conochiloides coenobasis* Skorikov, *Euchlanis dilatata* Ehrenb., *Pompholyx sulcata* Hudson, *Collotheca pelagica* (Rousselet), species of genus *Polyarthra*, *Synchaeta* and *Keratella* are also common. The abundance of southern thermophilic species *Diaphanosoma orghidani*, *Thermocyclops crassus*, *Conochiloides coenobasis* and *Brachionus diversicornis* (Daday) has increased noticeably since 2010.

Five alien species, the brackish water invaders from the Caspian and Azov seas, were first discovered in the Kama in summer 2015 and 2016 (Lazareva et al., 2018a). The copepods *Heterocope caspia* Sars, 1897 and *Eurytemora caspica* Sukhikh et Alekseev 2013, common in all three Kama reservoirs, penetrated up to 59°N. The Caspian cladocera *Cercopagis pengoi* (Ostroumov, 1891) in small numbers was found in the mouth of the Kama (Kuibyshev reservoir) as well as in the upper part of Votkinsk reservoir (mouth of the Nytva River, 57°53′ N) and the dam site of Kama reservoir near the city Perm (58°26′ N). The Caspian cladocera *Cornigerius maeoticus* (Pengo, 1879) and Mediterranean copepod *Calanipeda aquaedulcis* Kritschagin, 1873 was found only in the mouth of the Kama at latitude 55° N.

Zooplankton biomass is made up mostly of Rotatoria (>60%) from May to June and Crustacea from July to September. Mean zooplankton biomass varies from 0.9 to 4.6 g/m^3 (Kortunova, 1983,1985; Dementieva, 1985; Kortunova and Galanova, 1988). The abundance of zooplankton can reach up to 2.7 $million/m^3$ and 25.5 g/m^3 in July in shallow areas in the upper and middle reaches of the river. Long-term records in Sylva bay of Kama reservoir showed increases in zooplankton biomass from 1.4 g/m^3 in 1957 to 2.3 g/m^3 in 1978. At present the summer zooplankton biomass decreased to 0.4–4 g/m^3.

2.7.1.5.4 Zoobenthos

Before regulation, zoobenthos in the Kama was similar to that in the Volga and Oka rivers. The first information on zoobenthos for the entire Kama under natural conditions and without any anthropogenic impact such as from hydropower stations was in 1925 (Bening, 1928). Later, 296 taxa were recorded (Tauson, 1947): among them Spongia with 1 species, Coelenterata 1, Nematoda 67, Oligochaeta 25, Hirudinea 6, Mollusca 20, Ostracoda 15, Isopoda 1, Amphipoda 6, Mysidacea 1, Decapoda 1, Plecoptera 4, Ephemeroptera 28, Trichoptera 17, Hemiptera 2, Odonata 1, Hydracarina 10, Bryozoa 1, and Diptera 89 including 84 species of Chironomidae. The most frequent chironomids were *Chironomus* f.l. *semireductus*, *Beckidiazabolozkyi* Goetgh. *Tanytarsus* gr. *gregarius*, *Polypedilum* gr. *nubeculosum*, *Procladius*, and *Ablabesmyia* spp. (Gromov, 1951). Nematods were the next most speciose, including the wide spread species *Dorylaimus stagnalis* Dujar., *D. chrysodorus* Bast., *Ironus tenuicaudatus* de Man., and *Plectus cirratus* Bast, and were especially numerous in tributary mouths. The most common oligochaetes in the middle Kama included *Nais behningi* Mich., *Propappus volki* (Mich.), *Tubifex newaensis* Mich., and *Limnodrilus hoffmeisteri* Clap. (Svetlov, 1936).

Before regulation, Caspian crustaceans, i.e., Amphipoda, inhabited the middle and lower reaches of the Kama. *Dikerogammarus haemobaphes* Eich. and the highly abundant *Corophium curvispinum* Sars inhabited pebble substrates, while other species, e.g., *Stenogammarus macrurus* Sars and *Pontogammarus sarsi* Sowin., inhabited sandy and sand-pebble areas. Numerous colonies of *Metamysis strauchi* (Czern.) (Mysidacea) were found in pure sand habitats. The Caspian mollusc *Dreissena polymorpha* (Pallas) was quite abundant in the lower Kama, especially in stone and pebble habitats, and later in 1939, it also occurred in the middle Kama (Bening, 1928; Gromov, 1951).

Presently, macroinvertebrates in the Kama consist of ~280 species and among them Chironomidae make up to ~50%. Three taxonomic groups, i.e., Oligochaeta, Mollusca, and Chironomidae, comprise the most zoobenthos in terms of number and biomass. The most numerous are Chironomidae *Polypedilum nubeculosum* (Meigen), *Cryptochironomus* gr. *defectus*, *Dicrotendiprs nervosus* (Staeger), *Procladius ferrugineus* Kieff *Cladotanytarsus* gr. *mancus* and species of genera *Chironomus*, Oligochaeta *Potamothrix hammoniensis* (Mich.), *Limnodrilus hoffmeisteri* Claparede and *Uncinais uncinata* (Oersted), Mollusca *Viviparus viviparus* (L.), *Dreissena polymorpha* and species of genera *Pisidium*, *Amesoda*, *Henslowiana*.

In the reservoirs of the Kama cascade, 17 species of invaders of the Ponto-Caspian and Ponto-Azov complexes are registered. Among them, there are crustaceans *Dikerogammarus haemobaphes* (Eichwald, 1841), *Pontogammarus robustoides*, *P. sarsi*, *Chelocorophium curvispinum* and *C. sowinskyi* Martynov, 1924, *Corophium curvispinum*, *Paramysis intermedia* (Czerniavsky), *P. lacustris* (Czerniavsky), Baikal amphipod *Gmelinoides fasciatus* (Stebbing, 1899), Ponto-Azov leech *Caspiobdella fadejewi* (Epstein, 1961), mollusks *Lithoglyphus naticoides* Pfeiffer), *Dreissena polymorpha* and *D. bugensis* that penetrated into the Votkinsk Reservoir (Kurina, 2017b). These taxa also are found in zoobenthos of the Volga.

The total biomass of zoobenthos in Kamskoye and Votkinskoye reservoir varies from 7 to 350 g/m^2, more than 90% is of large mussels *Dreissena polymorpha* (Pallas) and *V. viviparus*. Long-term observations showed increases in the abundance of the mollusks *V. viviparus* and *Dreissena polymorpha*. At the same time, Oligochaeta and Chironomidae decreased in biomass. Average zoobenthic biomass in Kamskoye reservoir (2013–17) makes 20.3 g/m^2, and biomass without mollusks is 2.4 g/m^2. Average zoobenthic biomass in Votkinskoye reservoir (2012–17) is 105 g/m^2, and biomass without mollusks is 2.6 g/m^2.

2.7.1.5.5 Fish

Studies of the fishes in the Kama have been carried out for the last two centuries. The first faunistic descriptions did not contain complete information on fish species and differed greatly from modern taxonomy. However, 24 to 43 fish species were recorded from those times.

Before filling of Kamskoye reservoir in 1954, 42 fish species were recorded in the middle Kama. After dam construction in the middle Volga and Kama River, anadromous fish such as lamprey, beluga, Russian sturgeon, two species and one subspecies of herring, sheefish, and Caspian salmon were lost from the fish community. Concomitantly, catfish disappeared and the natural habitat of brook trout was reduced. As a result, only 32 fish species were found in the middle Kama and its tributaries in the 1970s. Further modifications in the fish community were realized with the appearance of chub and Amur sleeper, by natural recolonization of catfish, and invasion of sardelle from the Volga basin. The white-finned gudgeon inhabits a number of lower reaches of tributaries, and brook trout, Volga zander, spine fish, and round bullhead can now be found in fish catches. Presently, there are 42 fish species in the upper and middle Kama.

During the two centuries of observation, fish composition in the Kama changed little, although significant modifications occurred in structure of communities. As in earlier times, the Ponto-Caspian freshwater species make up most of the species being dominated by bream, white-eye bream, blue bream, silver bream, rudd, asp, bleak, chub, sneep, sabrefish, belica, and chub.

The boreal plains complex is made up of pike, golden, and silver crucian, roach, ide, dace, gudgeon, lake minnow, tench, spined loach, perch, and ruff. The boreal submountain complex consists of beeper, brook trout, grayling, riverine minnow, loach, and bullhead. The upper tertiary plain complex includes starlet, sazan, catfish, loach, zander, and Volga zander. The remaining fish taxa are represented by one to three species. The burbot comprises the freshwater Arctic group, sardelle, spine fish, and round bullhead form the Ponto-Caspian sea group, the Amur sleeper forms the Chinese plain group. Currently, the ichthyofauna of the Kama is represented by 44–48 species from 14 to 15 families and 10 orders. In three large reservoirs (Kamskoye, Votkinskoye, and Nizhnekamskoye), only 27–30 species are typical. It is in reservoirs that fishing is mainly conducted. In the last decade, catches in each reservoir varied from 250 to 380 tons. The main commercial species are bream, scab, pikeperch, roach and pike.

2.7.1.6 Management and conservation

There are 12 administrative regions with a total population of over 29 million in the Kama catchment. Among them, >10 million (~40%) inhabit the adjacent riverine floodplain. The catchment area is rich in minerals and several thousand mines are active here. Ferrous and nonferrous metallurgy, coal industry, oil processing, and engineering and chemical industries thrive in the catchment. Forests occupy about 14 million ha of the catchment area. Kama reservoirs, similar to the Volga reservoirs, were founded for multipurpose goals of water supply, water transport, and timber rafting, among others. Industrial and municipal discharge from river-side cities are the main sources of pollution.

Three reserves and two national parks are found in the Kama catchment (Sokolov and Syroechkovsky, 1988, http://www.nparks.ru, http://oopt.aari.ru/oopt, http://www.sevin.ru/natreserves/, http://visimskiy.ru/). The Basegi Reserve (1982, 380 km^2) and the Vishera Reserve (1991, 2412 km^2) are situated in the Perm' oblast, the Visim Biosphere Reserve (1971, 335 km^2) in Sverdlovsk' oblast. The Nizhnyaya Kama National Park (1991, 262 km^2) is situated along the Kama River in the Tatarstan Republic near the city Naberezhnye Chelny, the Nechkinskiy National Park (1997, 207 km^2) in the Udmurtia Republic.

The Visimsky biosphere reserve (1946, 335 km^2) is located in the western part of the Middle Urals in the upper reaches of the river Chusovaya (left inflow of Kama). The reserve is included in the world network of biosphere reserves in 2001. The territory represents a single forest located within the low-ridge landscape area on the axial part of the Ural ridge with altitudes from 400 to 700 m. Here passes the zone of hybridization of spruce (*Picea obovata* Ledeb. and *P. abies* (L.) H.Karst.), as well as the southwestern boundary of the continuous distribution of Siberian pine (*P. sibirica* Du Tour). Flora of vascular plants counts 495 species, fungi 877 species, bryophytes 147, lichens 234. Rare plant species (27 species) with forest orchids *Epipogium aphyllum* Sw., *Calypso bulbosa* (L.) Oakes, *Corallorhiza trifida* Chatel., *Dactylorhiza viridis* (L.) R.M. Bateman et al., *D. maculata* (L.) Soo., *D. fuchsia* subsp. *hebridensis* (Wilmott) Soo, *Goodyera repens* (L.) R. Br., *Hammarbya paludosa* (L.) Kuntze, *Neottia cordata* (L.) Rich., *Listera ovata* (L.) R.Br., etc., included in the Red Data Book of the Russian Federation. Fauna of vertebrates is typical of the Middle Urals. The mammalian fauna with 48 species includes the brown bear, wolf, wolverine, lynx, badger, Siberian weasel, ermine, mink, otter, European beaver. There are about 180 bird species, 4 amphibian and 5 reptilian species, 14 fish species. On the territory of the reserve, there are 17 Red Book species of animals: amphibian Siberian salamander *Salamandrella keyserlingii* Dybowski, reptilian brittle spindle *Anguis fragilis* L., birds golden eagle *Aquilla chrysaetos* L., eagle-owl *Bubo bubo* (L.), passer-owl *Glaucidium passerinum* (L.), hawk-owl *Surnia ulula* (L.), bearded owl *Strix nebulosa* Forst., Chiroptera species Myotis dasycneme Boie, *Eptesicus nilssonii* Keyserling & Blasius, etc.

The Vishera Nature Reserve is located in the northern Ural in the basin of the Vishera River (left inflow of Kama) and occupies a single Vishera drainage area. The Nature Reserve includes ranges of the Ural axial zone with a part of the main Ural watershed (Oshe-Nyer Range), intermountain meridional depressions and the foothills of the Ural west-facing slope. The mountain middle-taiga spruce-fir forests dominate in the plant cover of the Reserve. Elfin woodland and tall grass sub-alpine meadows are well developed in the sub-golets zone (i.e., the zone below the bald mountains), which as height increases are replaced by mountain heathlands with low mountain cypress, dwarf birch (*Betula nana* L.), and willow thickets. In the golets zone, between 850 and 1000 m asl, mountain tundras are common; and higher than 1000 m asl, cold deserts occur. The flora comprises 460 vascular plant species, including two rare ones (*Calypso bulbosa* (L.) Oakes and *Minuartia helmii* (Fisch. ex Ser.) Schischk.). The fauna comprises 35 mammalian species, 147 avian species, and 8 fish species. The wolf, fox, brown bear, sable (the largest population in the Perm' Region), ermine, moose, and wild reindeer are common. Among rare and endangered bird species, one can find the osprey *Pandion haliaetus* (L.), golden eagle *Aquilla chrysaetos* L., white-tailed eagle *Haliaetus albicilla* (L.), peregrine falcon *Falco peregrinus* Tunst., and black stork *Cyconia nigra* L. The fish fauna comprises grayling *Thymallus thymallus* (L.) and taimen *Hucho taimen* (Pallas).

2.7.2 The River Oka

2.7.2.1 *Introduction*

The Oka (Photo 2.4 C) is a relatively large river in Russia, and one of the two largest tributaries of the Volga. The origin of its name is not exactly known, although the most likely are the Lithuanian word "aka" meaning "spring" or Finnish word "joki" meaning "river." Before Slavic colonization, the upper Oka was inhabited by Baltic tribes (polekhi) and the middle and lower Oka by Finnish tribes (meshchera, muroma). Sites of Stone Age man were discovered on the left bank of the Oka between the Dmitriyevy Mountains and Murom. In 15th–16th century the river acted as the defense line of the Moscow State against Tatar raids from the south.

2.7.2.2 *Paleography of the catchment*

The present Oka catchment was formed in the post-glacial period. The catchment occupies the central part of the Russian plain that is covered by a layer of sedimentary rocks. Within the Moscow syncline, this sedimentary layer exceeds 3000 m in depth. Lowlands, at <200 m asl, occupy a large part of the catchment. Devonian and carboniferous deposits lying near the surface in the upper catchment strongly influence the chemistry of the Oka. Devonian deposits are composed of mainly limestone and dolomite, and inclusions of gypsum and anhydride in some places.

2.7.2.3 *Physiography, climate, and land use*

The source of the Oka is in the Central Russian upland at 226 m asl (SrednerusskayaVozvyshennost') and the lower river flows though the Oka-Don lowland. The Oka essentially flows through the geographical center of the European part of the Russian Federation. The river is 1500 km long with a catchment area of 245,000 km^2. The northwest part of the catchment lies in the subzone of mixed coniferous-broad-leaf forests and the southeast part along the boundary of the steppe and forest-steppe zones. Forests occupy 5%–25% and agriculture >50% of the catchment area (Yablokova, 1973). The climate of the catchment is continental-temperate and is similar to that of the middle Volga. Mean air temperature in January ranges from −11°C in the north to −9°C in the south; and from 17 to 20°C, respectively, in July. Annual rainfall averages 450–680 mm, decreasing from northwest to southeast.

2.7.2.4 *Geomorphology, hydrology, and biogeochemistry*

The Oka flows from west to east. Headwaters of the river are in the forest-steppe black earth (chernozem) lands of the Kursk province. Headwaters are fed by underground springs from Devonian deposits. Banks of the upper Oka are steep, and its width up to Kaluga varies from 60 to 160 m. Its right bank is for the most part higher than the left. From its headwaters, the Oka enters an area of coal mining, changing its direction at right angles several times. In this section, together with its tributary Ugra, the river flows through the Central Russian upland and chernozem forest-steppe zone.

Downstream from the confluence with the Moksha River, the Oka leaves the coal-mining area and enters a region of Upper-Jurassic sandstones. Here the right bank, "Ryazan' side," is high and undercut, whereas the left bank, "Meshchera side," is low, wooded and boggy. A wide bottomland of vast coniferous forests lies on the Meshchera side with a base of impervious Jurassic clays covered with layers of sand. The "Ryazan" side is forest-poor and incised with gullies that stretch to the Pronya confluence. The Oka then turns north and then acutely southeast. The middle Oka transverses the Kasimovskaya limestone ridge made up of carboniferous rocks. Downstream from its confluence with the Moksha, the river flows north and then northeast to its mouth. Here the left side is bounded by the Dmitriyevy and Bolotovy Mountains and the right by the historically significant, coniferous-forest lowlands of Murom. Downstream of the city Murom, the left bank lowers and the right is composed of Permian marls and gypsums. Downstream from the city Pavlov is the steep Gorbatovskaya bend where the tributary Klyazma enters from the left. Between the tributary and Gorbatovskaya bend, the Oka runs through a wide depression called Oka gate. Further downstream, the left bank is low, whereas the right-bank borders the Dyatlovy Mountains. At the confluence of the Oka and Volga sits a large industrial and cultural center, the city Nizhni Novgorod.

The total number of rivers and streams in the catchment is >19,000, and about 1600 of these are >10 km (Yablokova, 1973). Left-side tributaries drain mixed coniferous-deciduous forests of sod-podzolic soils of different grain sizes mixed with alluvial soils in floodplains and bog-podzolic soils in poorly drained areas. Right-side tributaries drain forest-steppe where soils are mostly gray forest soils and leached chernozems. Floodplains on the right side of the river are heavily tilled.

The flow regime of the Oka has a pronounced spring flood, and summer and winter low flows with periodic floods from rain events. Spring runoff contributes on average 58% (April–May), winter 14% (January–March, December), and summer-autumn 28% (June–November) to annual discharge. Minimum discharge usually occurs in February (Yablokova, 1973). Mean annual discharge is 39.3 km^3, maximum 58.3 km^3, and minimum 21.6 km^3. Maximal mean monthly discharge in May is 12,500 m^3/s, a minimum of 827 m^3/s occurs at a mean annual discharge of 1240 m^3/s. Average annual discharge ranges from 4.9 $L\,s^{-1}\,km^{-2}$ in the upper Oka to 5.4 $L\,s^{-1}\,km^{-2}$ in the lower river, or 0.98–600 m^3/s, respectively. Year-to-year fluctuations in discharge before the Volga was regulated showed irregular cycles of 3–5 year long high-water periods (i.e., 1905–09, 1915–17, 1926–29) and 3–11 year long low-water periods (i.e., 1910–14, 1918–25, 1934–45, and 1948–50) (Yablokova, 1973).

2.7.2.4.1 Temperature

The highest water temperature in the river is in July, averaging 21°C and ranging from 18.5 to 24.6°C. The river begins to freeze-over in late November early December and lasts on average 125–140 days. Ice thickness varies on average 45–60 cm but can reach 95 cm in some years. In the upper river near the city Orel, the Oka is ice-free on average 235 days (early April to late November) and 210 days in its lower reach between Murom and Nizhni Novgorod.

2.7.2.4.2 Biogeochemistry

The lower Oka belongs to the hydrocarbonate-calcium group. Water mineralization is high (Table 2.6) due to direct contact of surface waters with carbonates and inputs of highly mineralized ground waters. Mineralization is 260–570 mg/L during most of the year, decreasing to 130–140 mg/L in spring during high flows. From the source to its mouth, mineralization continuously increases due to dissolution of surface Dyas deposits, transition of podzolic-sandy soils in the north to gray podzolic soils of forest-steppe and rich chernozems in the south, and a decrease in rainfall from north to south concomitant with an increase in evaporation rate. Mineral content is mainly from SO_2 and Ca (Alekin, 1948). A dominance of HCO is clearly pronounced in the anion composition of the water, representing from 40 to 45% equivalent in the upper river (by Orel) to 26–35% equivalent in the lower river (by Nizhni Novgorod). In contrast, sulfates increase from 5 to 8% equivalence in the upper river to 15–20% equivalence in the lower river. Water pH during the ice-free period is 6.2–8.1 and highest in summer. Average turbidity ranges from 1400 g/m^3 in the upper river to 190 g/m^3 in the low river (Yablokova, 1973). Low water color (15–25 Cr–Co degrees) is observed during winter. Water oxidization changes from 2 to 8 mg/L in summer to 4–19 mg/L in spring due to organic matter inputs from melting snow. Dissolved oxygen varies significantly during the year but is satisfactory for hydrobionts (Table 2.6). Total nitrogen content averages 1.49 mg/L (Alekin, 1948; Zenin, 1965). Total phosphorus content at the mouth varied from 0.208 to 0.304 mg/L, total nitrogen from 1.80 to 3.21 mg/L, and carbon from 5.7 to 11.8 mg/L. Bottom sediments are composed of mostly small particles <1 mm to 5–10 mm pebbles, although sands dominate (Yablokova, 1973).

In comparison with the late 1960s–1980s, in the first decade of the 21st century there was an increase in the mineralization of water masses (by 1.6 times), in the content of sulfates (2.2–4.8 times) and alkaline earth metals (calcium in 1.4–1.7 times, magnesium in 2.2–4.0 times). In addition, the color of water, the content of dissolved carbon dioxide, organic matter (COD, BOD), mineral nitrogen, and total phosphorus decreased but the share of mineral forms of phosphorus in its total content increased by 1.5–1.8 times. All these changes indicate a transition of the waters in the lower reaches of the Oka River from hydrocarbonate to hydrocarbonate-sulfate class. This section of the river is still characterized as an eutrophic-hypertrophic water body with a high level of anthropogenic impact (Okhapkin et al., 2015). The state of water in the Oka River varies from "polluted" (class 3) in the upper reaches to "dirty" (class 4) in the Moscow region and downstream to the mouth. Typical pollutants are organic substances; compounds of copper, iron, and zinc; phenols; petroleum products; ammonium; and nitrite nitrogen. An increased level of pollution is noted in the water area of industrial centers (Israel' 2006, 2011; Chernogaeva, 2015, 2018).

2.7.2.5 *Aquatic and riparian biodiversity*

2.7.2.5.1 Plants

The Oka River valley lies in the broad-leaf forest biome (Isachenko and Lavrenko, 1980). The floodplain is vegetated by a combination of osiers (*Salix acutifolia, S. triandra, S. viminalis*), black poplar (*Populus nigra*), white willow (*Salix alba*), elm (*Ulmus laevis*), oak (*Quercus robur*), and black alder (*Alnus glutinosa*) mixed with meadows. Widely distributed are original Beckmannian (*Beckmannia eruciformis*) meadows (Isachenko and Lavrenko, 1980). Riverbanks are covered by a prevalence of *Salix triandra* and *S. viminalis*. Aquatic vegetation is most diverse in the headwaters, although well-developed communities are found in numerous former river-beds in the lower river comprising semi-submersed plants (*Phragmites australis, Typha angustifolia, Scirpus lacustris*) and submersed plants (*Nuphar lutea, Nymphaea candida, Potamogeton perfoliatus, P. pectinatus, P, lucens, P. natans, Ceratophyllum demersum*, and *Myriophyllum spicatum*). Water-chestnut (*Trapa natans* s. l.) of different forms also is widely distributed in these former river-beds.

2.7.2.5.2 Phytoplankton

Phytoplankton of the Oka River that has been studied since the 1920s (Pavlinova, 1930; Yesyreva, 1945,1968; Mokeeva, 1964; Kuzmin and Okhapkin, 1975; Vodeneeva, 2000; Okhapkin et al., 2014), nowadays includes 648 species, varieties and forms that is 1.7 times more than given earlier (Tockner et al., 2009). The green algae (292 taxa), diatoms (170 taxa), euglenic (58 taxa), and blue-green algae (54 taxa) form the basis of the list of species. The most numerous genera listed earlier are *Scenedesmus, Trachelomonas, Nitzschia, Aulacosira, Stephanodiscus, Dinobryon, Navicula, Phacus, Chlamydomonas, Kirchneriella*, while the genera *Euglena, Closterium, Oocystis* and *Surirella* were added in the recent period. Taxonomic richness peaks in July–August during warm water temperatures with a pronounced increase in the diversity of green algae. Diversity is much lower in spring and autumn (Okhapkin, 1981; Pautova et al., 2013).

Seasonally, phytoplankton biomass peaks in summer and at times in autumn, then decreases to 1–2 g/m^3 or more in September–October and <1 g/m^3 before the river freezes over. Biomass can reach 50 g/m^3 during algal blooms. Diatoms dominate total biomass, and small-celled green algae, mainly *Chlorococcales*, also are common. A bloom of *Stephanodiscus* (*S. hantzschii* Grun., *S. minutulus* (Kьtz.) Cleve et Möller, *S. invisitatus* Hohn et Hellerman, *S. agassizensis* Hek. et Kling.) usually occurs in spring after ice-out. The biomass of *Cyclotella meneghiniana* Kütz. as well as the diversity and biomass of *Chlorococcales* increases in July–August.

In early records (c.1920s), with few anthropogenic impacts on the river, diatoms *Melosira* = *Aulacosira, Fragilaria, Asterionella* together with *Chlorococcales* dominated the algal community and phytoplankton biomass was ~1 g/m^3. In the first decade of the 21st century, with a noticeable change in the external conditions that affect the formation of phytoplankton, its composition at the level of large taxa remained unaltered. However, there was an increase in the diversity of Centrophyceae (up to 40 species, varieties and forms) (Okhapkin et al., 2010; Genkal et al., 2012; Genkal and Okhapkin, 2013), gradual expansion into the Oka alcocoenoses and components of marine and brackish-water–freshwater complexes *Actinocyclus normanii* (Greg.) Hust., *Contricridra weissflogii* (Grun.) Stachura-Suchoples et Williams, *Cyclotella ambigua* Grun. emend. Genkal, *C. choctawhatcheeana* Prasad emend. Genkal, *C. marina* (Tanimura, Naguto et Kato) Ake-Castillo, Okolodkov et Ector, *Stephanodiscus delicatus* Genkal, *S. volgensis* Genkal et Korneva, *Thalassiosira faurii* (Gasse) Hasle, and *T. incerta* Makarova emend. Genkal et Okhapkin, while retaining values of *Skeletonema* species that appeared in the second half of the 20th century. The abundance of *Stephanodiscus hantzschi, S. invisitatus, Aulacoseira ambigua* (Grun.) Sim., *Cyclotella meneghiniana, Stephanodiscus neoastraea, A. granulata, C. meduanae* Germ., *Thalassiosira incerta* is high. Together with *Chlorococcales*, these species form the basis of the dominants and subdominants of plankton communities (Okhapkin et al., 2014,2016b); most are indicators of eutrophic conditions.

In the early 21 century, the average phytoplankton biomass fluctuated within the range of 5.6–12.7 g/m^3 during the growing season characterizing the current trophic status of the Oka River as eutrophic. The species, indicators of a high trophic degree and high water saprobity are still predominant. The diversity and importance of marine and brackish-water diatoms have increased, as has the overall productivity of plankton.

All this is a direct result of intensive eutrophication of the river and warming of the climate.

2.7.2.5.3 Zooplankton

Zooplankton of the river consists of more than 100 species of Rotifera (over 50% taxa), Cladocera (about 35%), and Copepoda. Most of these are eupelagic cosmopolitan species widely distributed in running waters of the temperate zone. However, the periodic input the water from the Gorky reservoir into Oka estuarine zone causes the appearance of limnophilic species.

The most common species among Rotifera are representatives of the genus *Brachionus*. Among them, *B. calyciflorus* Pallas has several morphological forms (i.e., *B. c. calyciflorus* Pallas, *B. c. dorcas* Gosse, *B. c. anuraeiformis* Brehm, *B. c. amphiceros* Ehrenberg, and *B. c. spinosus* Wierzejski), *B. angularis* Gosse, *B diversicornis* Daday, *B. quadridentatus* Hermann, *B. urceus* L., *B. leydigi* Cohn, *B. budapestinensis* Daday. The other wide spread Rotifera are *Keratella cochlearis* (Gosse), *K. quadrata* O.F. Müller, *Filinia longiseta* Ehrenberg, *Polyarthra minor* Voigt, and *Asplanchapriodonta* Gosse. Crustacea also have high taxonomic richness and commonly include species *Bosmina longirostris* O.F. Müller, *Daphnia cucullata* Sars, *Diaphanosoma brachyurum* Lievin, *Ceriodaphnia pulchella* Sars, *Chydorus sphaericus* O.F. Müller, *Alona rectangula* Sars, and *Ceriodaphnia quadrangula* O.F. Müller. Copepoda have the least number of species and is mainly composed of *Cyclops kolensis* Lilljeborg, *Mesocyclops leuckarti* Claus, *Thermocyclops oithonoides* Sars, *Eudiaptomus gracilis* Sars, and *E. graciloides* Liljeborg.

The invasive species *Kellicottia bostoniensis* Rousselet, a rotifer of North American origin, and *Diaphanosoma orgidani* Negrea, crustacean of the Ponto-Caspian fauna, have been found. Species *Euchlanis dilatata* Ehrenberg, *Bosmina coregoni* Baird, *Leptodora kindtii* Focke, and *Heterocope appendiculata* Sars belong to the limnophilic components of the Oka plankton (Shurganova and Maslova, 2010). Specifically, *Rotaria rotatoria* Pallas and *Daphnia pulex* Leydig. are indicators of organic pollution. Seasonal dynamics of zooplankton in the Oka estuary area is characterized by a single-vertex curve of abundance and biomass caused mainly by development of the rotifers *Brachionus calyciflorus* Pallas in the second half of June. Despite the differences in hydrometeorological conditions in different years, the overall picture of zooplankton seasonal dynamics is generally preserved (Shurganova et al., 2015).

2.7.2.5.4 Fish

The Oka, being unregulated by dams, has a rheophilous complex of fish species. Icthyofauna include 35 species, 9 of these are typical rheophils. The river has a self-reproducing population of sterled sturgeon. Common fish species in the middle and upper Oka are gudgeon, ide, dace, rudd, Volga nase, minnow, bystranka, and zherekh. Today, the icthyofauna has changed due mainly to the disappearance of Caspian anadromous species and much lower abundances of valuable rheophilic species (sterled, large cyprinids and percids). The presence of the Amur sleeper in the Oka basin was first recorded in the 1970s, and now this species can be caught in several sections of the river itself (e.g., around Kaluga). Monitoring catches also show the presence of Asian carp and silver carp in low numbers (<1% of the catch). However, there are no self-reproducing populations of these species in the river, and the main sources of these fish are two reservoirs (Lyudinovskoe and Brynskoe) on tributaries of the Oka where these fish are cultured. The expansion of crucian carp is notable and is consistently in fish catches in the Oka. Its abundance in the region's waterways is growing (Dgebuadze and Slyn'ko 2005).

2.7.2.6 *Management and conservation*

The Oka catchment has a high population density. The river flows though seven administrative units and 11 cities/towns are along its banks. Six of these towns have populations of 100–500,000 and Nizhni Novgorod has over 1,298,000 inhabitants. Industrial and municipal discharge from the cities is the main source of water pollution. The Oka is navigable and is a part of the water network connecting Moscow with the Volga region. Water monitoring of the Oka is under regional control, and the water quality is satisfactory. However, its use for water supply is possible only after proper purification (Yablokova, 1973). Three biosphere reserves and one national park (Meshcherskiy, 1992, 1030 km^2) are located within the Oka catchment (http://oopt.aari.ru/oopt).

Zablotsky Priokcky Terraced State Wildlife Biosphere Reserve was founded in the Moscow region in 1945 and occupies 50 km^2. About 143 bird species, 62 mammal species, 980 species of plants, 133 species of mosses, 138 species of lichens, and 699 species of fungi are registered in the reserve (http://oopt.aari.ru/oopt, https://pt-zapovednik.ru/). Plants of different climatic zones from south taiga to steppe are found here, as well as the southern limit of fir. There are eight rare plants listed in the Red Data Book of Russia, and *Cypripedium calceolus* L., *Orchis militaris* L., *Orchis ustulata* L., *Fritillaria meleagris* L. are among them. The bat *Myotis dasycneme* Boie and European bison *Bison bonasus* L. are entered in the Red List of the International Union for Conservation of Nature. The reserve has had a European bison farm since 1948.

Oksky State Wildlife Biosphere Reserve was established in 1935. It occupies 557 km^2 and is in southeast

Meshera in the Ryazan province. The reserve is one of the 14 world reserves labeled in UNESCO documents and awarded the diploma of Council of Europe (Sokolov and Syroechkovsky, 1989; Belko, 2004, http://oopt.aari.ru/oopt). More than 880 species of higher plants, about 198 species of mosses, and 140 species of lichens grow in the reserve. About 60 species of mammals, about 260 bird species, 11 species of amphibians, 6 species of reptiles, and 39 fish species live here. In the Red Data Book of the Russian Federation, rare representatives of the Orchid family, i.e., *Cypripedium calceolus* (L.), *Neottianthe cucullata* (L.) Schltr., and *Orchis militaris* L. are noted. Some 29 species of animals living in the reserve are included in the Red List of International Union for Conservation of Nature, 42 species in the Red Book of Russia. The first Russian Central Ornithological Station and farms for rare species of crane, rare birds of prey and pure-blooded European bison *Bison bonasus bonasus* L. were established in the reserve. Up to 1000 individuals of the rarest animal species, desman *Desmana moschata* L., are recorded from water bodies in the reserve.

Mordovia State Reserve, 321 km^2, was established in 1935 in the Moksha River (left tributary of the Oka), the catchment of Mordovia Republic. Coniferous forests grow here with trees up to 350 years old. The flora is represented by more than 1000 species of plants (749 vascular plants, 77 mosses, and 83 lichens). Some 59 species of mammals and 194 bird species live in the reserve (Sokolov and Syroechkovsky, 1989, http:/www.comzapovednik).

2.7.3 The River Sheksna

2.7.3.1 *Introduction*

The Sheksna River (Photo 2.4 D), a tributary of the Volga, flows through Vologda province of Russia. Historically, the Sheksna was called Shekhsna, as mentioned in Nestor's chronicle in 1071. The river has served as a waterway from the Volga to Onega, Ladoga. and Velikiy Novgorod. Finnish tribes settled on its river banks. The Sheksna was part of the Marin system, and presently is included in the Volga–Baltic water-way and North-Dvina system. No large towns or major agricultural developments occur in the Sheksna catchment, thus anthropogenic impacts on the river are relatively small. Data presented in this chapter were based mainly on the book *Modern State of Sheksna Reservoir Ecosystem* (Litvinov 2002) and *Hydrometeorological Regime of Lakes and Reservoirs in the USSR* (Vikulina and Znamensky, 1975).

2.7.3.2 *Paleography of the catchment area*

The Sheksna catchment lies in the boreal biographic region and was formed by the influence of glaciation, in particular the Valdai glaciation. However, the main features of the landscape were formed before the Ice Age from erosional processes. The influence of glaciation was manifest in grinding bedrocks from the surface, smoothing benches, and piling loose material in some areas. Young postglacial formations have also developed as a result of processes associated with rivers and lakes.

2.7.3.3 *Physiography, climate, and land use*

The catchment is in the northwest part of the Russian plain with a crystalline foundation formed by Precambrian rocks to depths of 2 km covered by a layer of Paleozoic sedimentary rocks. Most of the catchment is covered by Middle and Upper Carboniferous sediments overlaid by friable Quaternary deposits (Pakhtusova, 1969). The Quaternary deposits are represented mainly by glacial and water-glacial formations of different age.

The catchment encompasses the Belozersk plain and is transected by two undulating ridges in the shape of arcs. One arc, Magersk-Andomskaya, separates the Belozersk plain from the adjacent Onaga depression, whereas the other, Belozersk-Kirillovskaya, arcs around the Beloye Lake depression. South of Belozersk is the Andogsk ridge, formed just before the last glaciation. Altitudes here range from 111 to 304 m asl.

The geographical location of the catchment favors intrusion of arctic, polar (middle latitudes) and, at times, tropical air masses. Arctic air masses bring anticyclonic weather. In winter, air temperature drops sharply, and frosty sunny weather occurs. Frosts are common in spring and autumn (Adamenko and Malinina, 1981). The average annual air temperature is 2 to 4°C. The coldest month is January (February in some years) with a monthly average temperature of −11.9°C, fluctuating from −4.4 to −20°C. In winter, minimum temperatures can reach −46 to −49°C, but thaws occur each year.

Monthly average air temperature in July is 16.7°C. The lowest average temperature recorded in the last 50 years was 13.4°C (1956) and the highest was 20.8°C (1972), although daily values can exceed 30°C. Air temperature remained >0°C for the town of Belozersk for 205 days. The transition to >0°C average daily temperature occurs around April 8 and to <0°C around October 30. The frost-free period lasts from mid-May to mid-September, for 104–122 days. Mean annual rainfall is 632 mm, 422 mm of this between April and October, and 210 mm during winter. Southerly and southwesterly winds prevail during the year (41% of the time), and northerly winds are more frequent during the warmer months, especially May–June. The wet climate (50% evaporation rate) and flat relief promote bog development, mainly raised bogs, flat bogs, and transition bogs. The area is mostly waterlogged, although unevenly distributed. On average, marshland accounts for 13% of the catchment, forests 81%, and lakes 10% (Vikulina and Znamensky, 1975).

2.7.3.4 *Geomorphology, hydrology, and biogeochemistry*

The Sheksna catchment is within the middle taiga zone of mostly coniferous forests with some broad-leaf trees. The Sheksna begins in Lake Beloye, flowing then into the Sheksna reach of Rybinsk reservoir. Most of its water originates from snow melt. The catchment area is 19,445 km^2 and lies mainly along the meridian line. The northern boundary is at latitude 60°55′ N and the southern boundary is at 59°30′ N, extending about 300 km from north to south and 180 km from west to east. The lower river is regulated by the dam of Sheksna Hydroelectric Power Station built in 1963 (Bylinkina et al., 1982b). The resulting reservoir also influenced Lake Beloye 120 km upriver from the dam, and the length of the river decreased by about 300 km after Rybinsk reservoir was filled. Its major tributaries include the Kovzha from the west, and Siz'ma, Pid'ma, and BolshoiYug from the east.

2.7.3.4.1 Hydrology

The Sheksna basin is in a zone of excessive moisture, with a mean annual discharge averaging about $9\ L\ s^{-1} km^{-2}$. Rivers in the catchment show significant variation in runoff over the year. On average, spring runoff from snowmelt contributes 50–70% to annual flow, summer–autumn runoff 20–32%, and winter runoff 5–12%. The volume of spring runoff decreases from April to May in rivers with a low ratio of lake surface to drainage area. Maximal spring runoff of rivers in the lacustrine-karst zone occurs in May. Two periods of low runoff, summer–autumn and winter, are typical for rivers in the catchment. Summer–autumn low-flows usually begin in July and ends in September–October, averaging 80–90 days. Winter low water lasts from late November–early December to late March–early April, averaging 120–140 days. The lowest water occurs in February–March. From 1964 to 92, average annual discharge at the Sheksna power station was 160 m^3/s, with a maximum of 184 m^3/s in 1990. A maximum average monthly discharge of 631 m^3/s occurred in May 1992 and a minimum of 22 m^3/s occurred in March 1984. In free-flowing sections of the river, velocity can reach 30–70 cm/s (Vikulina and Znamensky, 1975).

2.7.3.4.2 Temperature

Based on long-term data, ice breakup begins around April 17–27, but as early as March 10–April 5 and as late as April 29–May 7. The incremental increase in temperature in early May is 3.5°C with a maximal incremental increase of 3.6–4.1°C in mid-May. The interannual fluctuation in water temperature ranges from 2.3 to 14°C. The summer warming period lasts until late July when surface temperatures reach 19.6–19.9°C (maximum ~22°C). The autumn cooling period begins in early August, decreasing by about 0.5°C over 10 days. The rate of cooling by late September is 3°C over 10 days. The average date of first ice appearance is November 20, but can be as early as October 26 and as late as January 6.

2.7.3.4.3 Bottom sediments

The filling of the reservoir for the Sheksna Hydroelectric Power Station turned lowland areas into swamps and drowned floodplain forests. A layer of sand deposits formed in the littoral zone up to 2-m water depth from bank and bottom erosion, and a layer of sand with peat particles formed in deeper areas. The peat was derived from flooded swamps of the Sheksna-Sizmensk lowland where floating mats of peat were commonly observed. The bottom of narrow sections is composed of sands, and pebbles, large boulders and clay outcroppings in some places. The sedimentation rate near the dam is 1.5 mm/year on average, varying from 0.6 in the littoral zone to 20 mm/year at deeper depths. Depending on the sediment type, organic matter content ranges from 1.0 to 1.5% in sand, 2.0–2.8% in silt sand, 5.5–10.4% in sand silt, 9.5–15.3% in clay silt, 30–40% in silt peat, and up to 60% in peat silt. Sedimentation rate near the river source is 0.5–0.8 mm/year.

2.7.3.4.4 Hydrochemistry

Hydrochemical conditions in the Sheksna are influenced by surface inflow from the forest zone containing low contents of soluble mineral compounds and high content of humic organic matter. River chemistry is mainly determined by water masses from Lake Beloye. The total salt content ranges from 77 to 135 mg/L in spring, 124–170 mg/L in summer, and 128–173 mg/L in winter. The salt concentration increase is from carbonates and sulfates, as well as groundwater inputs and local tributaries during low flows. Hydrocarbonates dominate waters in the northwest part of the catchment, whereas groundwaters with sulfate, calcium, and magnesium are found in the southeast (Savinov and Filenko, 1965).

Suspended sediments originate from Lake Beloye where high mixing often occurs during the ice-free period. Sediment levels varied from 11 to 57 mg/L before regulation and are similar today (Vikulina and Znamensky, 1975). Suspended sediment levels decrease quickly downstream of the lake. Water transparency is about 1 m, reflecting changes in suspended sediments. COD values equal 34 mg O_2/L, corresponding to ~13 mg/L organic carbon. Dissolved oxygen reaches 92–98% saturation in spring and autumn, while supersaturation is observed in summer. Water color varies from 25 to 185 Cr–Co degrees, being 50–70° on average from the high concentrations of humics. Nutrients are characterized by low total nitrogen and high total phosphorus values, although phosphates are low. The hydrochemistry of the Sheksna has not undergone considerable change since the 1970s.

2.7.3.5 Aquatic and riparian biodiversity

2.7.3.5.1 Plants

Much of the Sheksna floodplain is inundated by waters of the Sheksna and Rybinsk reservoirs. The banks of the reservoirs are mostly covered by meadows or osier-beds of *Salix cinerea*, *S. triandra*, and *S. viminalis*. Osiers also cover the banks of most islands, although low parts of islands and low banks are covered by *Phalaroides arundinacea*, *Glyceria maxima*, *Carex acuta*, and hygrophilous and marsh motley grasses. Aquatic vegetation in running waters of the reservoirs is poor, mainly communities of clasping-leaf pondweed (*Potamogeton perfoliatus*) and reed (*Phragmites australis*). Vegetation in bays and shallows of the reservoirs is more diverse. Here, dominate clasping-leaf pondweed and reed, but also swamp horse-tail (*Equisetum fluviatile*), broad-leaf cattail (*Typha latifolia*), star duckweed (*Lemna trisulca*), bur-reed (*Sparganium emersum*), manna-grass (*Glyceria maxima*), Old-World arrowhead (*Sagittaria sagittifolia*), and water milfoil (*Myriophyllum spicatum*) are common. Aquatic vegetation in the Sheksna reservoir is represented by only 97 macrophyte species (Litvinov 2002).

2.7.3.5.2 Algae

Since 1955–95, 904 species (1123 species, varieties and forms) of phytoplankton were recorded in the Sheksna reservoir (Korneva, 2015). Diatoms show high seasonality in the reservoir. In contrast to the Volga reservoir, a spring peak in phytoplankton biomass is less pronounced. In spring, *Stephanodiscus minutulus S. agassizensis*, *Aulacoseira islandica*, *Asterionella Formosa* dominate. Total biomass increases in summer when diatoms and cyanobacteria (blue-greens) are predominant. The phytoplankton composition is mainly composed of *Aulacoseira granulata*, *A. subarctica*, *Cyclotella radiosa*, *Tabellaria fenestrata*, *Asterionella formosa*, *Stephanodiscus binderanus*, *S. agassizensis*, *Aphanizomenon flos-aquae*, *Microcystis aeruginosa*, *M. wesenbergii* and species of genus *Anabaena*. In the summer of 1990, the abundance of nonheterocystus cyanobacteria *Gloeotrichia echinulata* (J.S. Smith) P. Richt, *Microcystis holsatica*, small-celled cryptomonads (*Chroomonas acuta*), and the euryhalyne diatom *Actinocyclus normanii* increased (Litvinov 2002). Of note is the presence of large-celled diatoms of *Cymatopleura* and *Gyrosigma* in Sheksna reservoir. The change in community structure of phytoplankton in Sheksna reservoir during the last few years is similar to those observed in the Volga reservoir. Average annual phytoplankton biomass during the ice-free period from 1955 to 1977 ranged from 0.8 to 4.9 g/m^3 with maximal values in 1965 and 1976. In 1994–95, biomass did not exceed 4 g/m^3.

2.7.3.5.3 Zooplankton

Zooplankton consists mainly of Cladocera, Copepoda, and Rotatoria, with about 120 species. Crustacea make up 60% of the species and constitute >90% of the biomass. *Bosmina coregoni gibbera* (Schoedler), *B. longispina* Leydig, *B. crassicornis* P.E. Müller, *Daphnia galeata* Sars, *D. cucullata* Sars, *D. cristata* Sars, *Diaphanosoma brachyurum* (Lievin), *D. orghidani* Negrea, *Mesocyclops leuckarti* Claus, *Thermocyclops oithonoides* (Sars), *Eudiaptomus gracilis* Sars, *Heterocope appendiculata* Sars, *Limnosida frontosa* Sars, *Leptodora kindtii* (Focke), and *Bythotrephes longimanus* Leydig are most common. Small organisms, i.e., *Conochilus unicornis* Rousselet, *C. hippocrepis* (Schrank), *Keratella cochlearis* Gosse, and *Kellicottia longispina* Kellicott are numerous; Rotifera, making up to 50,000/m^3. Nonnative species of *Cyclops scutifer* Sars and *Asplanchna herricki* Guerne that belong to the northern lacustrine complex probably came from water bodies of the catchment from 1960 to 80. The southern species, *Diaphanosoma orghidani* Negrea, found in 2005 likely came from the upper Volga, it numbers about 2000/m^3. Average zooplankton abundance during May–October is 40,000/m^3 and biomass is 0.7 g/m^3. Highest values (156–235,000/m^3 and 2.8–4.0 g/m^3) are usually observed in June–July in the lower river.

2.7.3.5.4 Zoobenthos

Presently, 170 species of macrozoobenthos have been found in the flooded channel of the Sheksna (Bakanov 2002). The majority, up to 83% of the total, is made up by chironomids (60 species), mollusks (40), and oligochaetes (37). Oligochaetes *Tubifex newaensis*, *T. tubifex*, *Limnodrilus hoffmeisteri*, *L. udekemianus* Claparide, *Potamothrix hammoniensis*, and *P. moldaviensis*; chironomids *Chironomus plumosus*, and *Procladius choreus*; mollusks *Dreissena polymorpha* and large representatives of Pisidiidae, the genus *Amesoda* and *Sphaerium* dominate zoobenthos numbers and biomass.

The highest biomass of macrozoobenthos at 145–200 g/m^2 was found near the dam at a depth of 18–22 m. The chironomid *Chironomus plumosus* and oligochaete *Tubifex tubifex* made up most of the biomass (about 75%). Only one species under danger of extinction, mollusk *Anisus vorticulus*, was not included in the fauna list of macroinvertebrates in the Sheksna. Along the entire river, the nonindigenous Baikal amphipod

Gmelinoides fasciatus was the single representative of crustacean (Bakanov 2002). In 2005, average macrozoobenthos biomass in the Sheksna reservoir was about $6\ g/m^2$, while upstream of Cherepovets, in the river with flowing water it was $0.5–3.6\ g/m^2$. In 2016–17, the average biomass of macrozoobenthos increased to $9.7 \pm 2.2\ g/m^2$, its main share (76%) was made up of larvae of chironomids with a dominance of *Chironomus plumosus*.

2.7.3.5.5 Fish

Ichthyofauna of the Sheksna traditionally was of a mixture of rheophilous species (pike, perch, roach, ide, ruffe, bleak) and limnophilous species coming from Lake Beloye. The first marked decrease in the number of species and their composition was observed in 1896 after the dam that separated Lake Beloye from the upper Volga basin was built, leading to the disappearance of Russian sturgeon, beluga, sterled, and sazan. In 1970s, the number of species was 29, 25 in the 1980s, and 24 species are presently observed in catches. The following species are no longer observed since 1970s: minnow, grayling, zanthe, wels catfish, chudskoi whitefish, ludoga whitefish, smelt and river lamprey. Tench, eel, and peled were observed at single times. In the 1980s, these species along with belica and loach have disappeared, and elets, chub, crucian carp, spined loach and bullhead became rare. In the 1990s, these latter species became extinct and white-eye bream, rudd, gudgeon, ide, and zherekh were counted as rare. Now the ichthyofauna is made up of limnophilous fish species. Before Sheksna was regulated, commercial catches were about 5 tons, dominated by pike. At present, the annual catch equals 100 tons and the dominating species is bream.

2.7.3.6 Management and conservation

Anthropogenic stressors in the Sheksna are few. There are a number of diffuse pollution sources along the banks, diffuse runoff, and navigation effects. Water quality is estimated as "pure" according to microbiological tests, and the water is mesotrophic according to chlorophyll and β- or α–β mesosaprobic. Poor water quality is apparent only at local sites. The Sheksna is monitored by a regional ecological service net, and the water chemistry has not changed in the last 40 years.

The Russkiy Sever National Park (1992, $1664\ km^2$) is located in the Vologda Region at Sheksna catchment within the Belozersko-Kirillovskaya Mountain Ridge between lakes Beloye, Vozhe, Kubenskoye, and Sheksna Reservoir. Natural conditions here are very diverse due to the complex landscape of the territory. On the Park's territory, there are historical–cultural monuments of world significance: Kirillo-Belozersky, Feropontov, and Goritsky monasteries, and the Nilo-Sorskaya hermitage. The border between middle and southern taiga forests goes along the edge of the Park's territory. Spruce, pine, birch-spruce, and birch-aspen forests prevail. Along the rivers and streams, on the lake-side terraces the grass-gramineous meadows are spread, having appeared in the place of forests. The great diversity of flora is determined with a combination of taiga, arctic, Siberian, and European species. The northern border of oak, hazel, maple, lime areas lies in the Park. More than 500 vascular plant species were recorded, including the rare forest orchids (*Cypripedium calceolus* L., *Ophrys insectifera* L., *Epipogium aphyllum* Sw., *Dactylorhiza baltica* (Klinge) Nevski, etc.). The fauna of the National Park comprises 228 vertebrate animals, including 48 mammalian species and 161 avian species. Rare are osprey *Pandion haliaetus* (L.), white-tailed eagle *Haliaetus albicilla* (L.), golden eagle *Aquilla chrysaetos* L., Greater Spotted eagle *Aquilla clanga* (Pall.), eagle-owl *Bubo bubo* (L.), peregrine falcon *Falco peregrinus*Tunst., etc. (https://parkrusever.ru/category/natur).

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