Chapter 14
Dynamics of Water Levels in the Gorky Reservoir (Russian Federation) During the Spawning Period and Its Influence on the Area of Spawning Grounds and Natural Reproduction of Limnophilic Fish Species

L. M. Minina and A. E. Minin ⓘ

Abstract On the base of geographic information systems (GIS) the relationship between the areas of spawning areas of the Gorky reservoir and water levels were analyses, as well as assess the influence of the dynamics of spawning areas on the efficiency of natural reproduction of limnophilic fish species. The boundaries of 54 spawning areas of the Gorky reservoir have been digitized and georeferenced using Landsat satellite images. For the first time for the Gorky reservoir, the areas of spawning grounds were calculated at different water levels and formulas were obtained for the dependence of the areas of spawning grounds on the water level. It is calculated that the area of spawning grounds for the lower river, lakes, and dam sections of reservoir at different water levels can change by 1.2 times, the area of the Kostroma spill—by 1.7 times. The dynamics graph of the water levels of the Gorky reservoir in the flood in years of different water content, as well as the interannual dynamics of spawning areas and the number of fingerlings are presented. It is shown that the course of the water level in the Gorky reservoir during the spawning period is usually favorable for the processes of natural reproduction of fish due to the stability of the levels during the spawning period. No correlation was found between the degree of flooding of the spawning grounds and the number of fingerlings, which can be explained by the relative constancy of water levels during spawning in the interannual dynamics, or by the insufficient volume of materials from the fry surveys.

Keywords Gorky reservoir · Water level · Landsat satellite images · Spawning grounds · Efficiency of natural fish reproduction

L. M. Minina (✉) · A. E. Minin
Nizhny Novgorod Branch of Russian Federal Research Institute of Fisheries and Oceanography, Moskovskoe Shosse St. 31, 603116 Nizhny Novgorod, Russian Federation
e-mail: lmminina@yandex.ru

14.1 Introduction

Impact of regulation of the Volga river on the state of aquatic biological resources turned out to be predominantly negative (Chavychalova and Fomin 2018; Shakirova et al. 2012). The main reason that prevents the formation of significant commercial fish stocks in reservoirs is considered by many authors to be an unfavorable level regime, leading to a reduction in flooded spawning areas and, as a consequence, a decrease in the efficiency of natural fish reproduction (Chavychalova 2013; Shakirova et al. 2012; Stolbunov 2016; Vasilchenko and Ponomarev 2017; Vasiliev et al. 2016). It was determined that the flooded areas of spawning grounds can vary several times depending on the water level (Katunin 2014; Vasiliev et al. 2016). In this regard, it is relevant and valuable to obtain quantitative data on the influence of the level regime of reservoirs on the size of spawning areas and on the efficiency of natural reproduction of fish in reservoirs.

The Gorky reservoir, located on the border of the Upper and Middle Volga, was formed as a result of the regulation of the Volga river flow by the dam of a hydro-electric power station, filling was completed in 1957. The area at a normal retaining level (84 m of the Baltic system) is 144.8 thousand hectares (Minina and Minin 2021). The reservoir belongs to the type of plain-river water bodies with seasonal flow regulation (Avakyan et al. 1979). The water level depends on the surface runoff and the operating mode of the Nizhegorodskaya hydroelectric power station, as well as the upstream Rybinsk hydroelectric complex. The area of shallow waters from 0 to 2 m is 45.5 thousand hectares (31%). The Gorky reservoir is a fishery reservoir of regional significance for four constituent entities of the Russian Federation (Yaroslavl, Kostroma, Ivanovo and Nizhny Novgorod regions). Up to 1000 tons of fish are caught annually in the reservoir, of which the catch of limnophilic fish species is about 76%. Since 2008, there has been a tendency to increase the catch volume of limnophilic fish species and, accordingly, the total fish catch (Nizhny Novgorod branch of VNIRO 2021).

According to the nature of the hydrological regime and morphometry in the Gorky reservoir, 5 sections are distinguished (from top to bottom along the Volga river): the upper river, Kostroma spill, middle river, lake and dam. The upper river section is located from the Rybinskaya HPP dam to the city of Kostroma. The hydrology and morphology of the site have changed little compared to the period before the formation of the reservoir, the shallow water zone is limited. The Kostroma spill is a lake-type reservoir formed as a result of the flooding of the Kostroma lowland, it contains a significant proportion of shallow waters from 0 to 2 m (80%). The shallow zone (depths from 0 to 2 m) of the mid-river section, stretching from the city of Kostroma to the mouth of the Yolnat river inclusive, is very limited (5.5 thousand hectares, 25.4%). The lake section is located from the mouth of the Yolnat river to the settlement of Katunki, Nizhny Novgorod region, has significant extensions in river mouths. The area of its shallow waters is 17.3 thousand hectares (23.9%). The dam section is characterized by fluctuations in the water level depending on the releases

of the Gorkovskaya HPP; the shallow waters in it are 2.1 thousand hectares (11.3%) (Postnov 2013).

The middle river, lake and dam sections are of great importance for the reproduction of fish. Here there is about 70% by the number (63% by area) of the spawning sites of the reservoir. Spawning grounds in this part of the water area are floodplain coastal areas, bays, estuarine areas of rivers, as well as shallow waters around the islands and off the coast. By the nature of the water regime and the development of forage aquatic organisms, the Kostroma spill is an extremely important area for the reproduction and feeding of juveniles and adult fish of the Gorky reservoir.

Geographic information systems (GIS) are used to determine the boundaries of spawning areas, their digitization and geographic referencing, as well as to determine their areas (Kalyuzhnaya e al. 2017; Komarova and Filonenko 2015; Tyurnin 2007; Zolotukhin and Hodger 2007). Mapping of spawning grounds in GIS is most often carried out using data from remote sensing of the Earth from space (space images). The advantage of satellite images is their availability and the possibility of high measurement accuracy (Kalyuzhnaya et al. 2017). However, works on comparing data on water levels from hydrological observation posts and areas of spawning grounds determined from satellite images are extremely rare and absent for the Gorky reservoir.

14.2 Materials and Methods

The aim of the work was to establish, using satellite images, the relationship between water levels and areas of spawning grounds of the Gorky reservoir in the spring–summer period, as well as to assess the impact of changes in spawning areas on the amount of replenishment of limnophilic fish species, forming the basis of ichthyocenosis. To achieve the goal, the following tasks were set:

– search and selection of Landsat satellite images;
– GIS mapping of spawning areas by the method of interpretation of satellite images;
– joint analysis of diverse data (numerical—values of water levels and spatial—digitized spawning areas);
– identification of factors influencing the efficiency of natural reproduction of limnophilic fish species of the Gorky reservoir.

With the help of GIS, the boundaries of the spawning grounds of the Gorky reservoir were digitized and geographically linked (see Fig. 14.1), while the list of spawning grounds in Appendix No. 6 to the Fishing Rules for the Volga-Caspian fishery basin (2019) was taken as a basis. Additionally, the analysis included spawning grounds recommended for inclusion in the list of spawning grounds of the Fishing Rules by departments of state control, supervision and protection of aquatic biological resources in Ivanovo and Nizhny Novgorod regions.

Mapping of spawning grounds was carried out by the method of visual interpretation and digitization of the coastline using satellite images from Landsat 5, Landsat
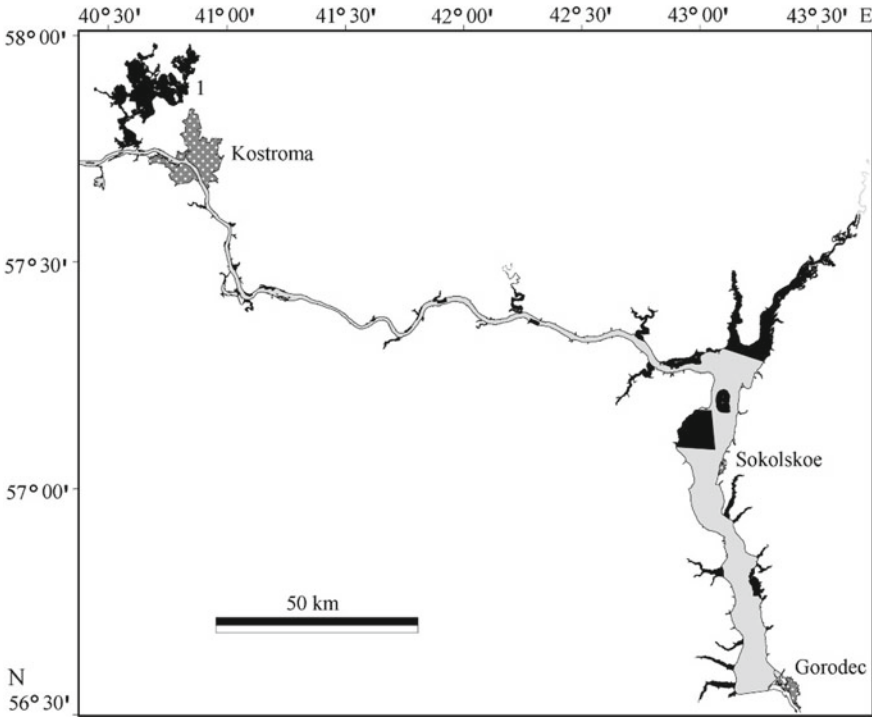
Fig. 14.1 Location of spawning areas of the Gorky reservoir (Kostroma spill, middle river, lake and dam sections): gray solid fill—Gorky reservoir, black fill—spawning grounds (1—Kostroma spill). *Source* Compiled by the authors

7 and Landsat 8 satellites (the resolution of channels in the visible part of the spectrum is 30 m/pixel). The boundaries of the spawning grounds included areas with depths from 0 to 3 m; the depths were determined using a vector map of the depth distribution of the Gorky reservoir (Nizhny Novgorod branch of VNIRO 2013).

To digitize the boundaries of spawning areas, satellite images from the USGS Global Visualization Viewer (2021) were used. The material for the study was 23 sets of Landsat satellite images for the water area of the lower river, lake and dam sections of the Gorky reservoir for 2004–2009, 2011, 2014–2020 during the spawning period (from April 8 to June 15). In the absence of a space image that completely covers the studied area, pairs of images were used for the same date, or differing in time of creation by 1–6 days, while the difference in water levels on the date of creation of the images was no more than 6 cm. 2 space images were analyzed and 3 sets of two images of the lower river, lake and near-dam areas, taken in April, 4 images and 9 sets of two images—in May, 3 images and 2 sets of two images—in June.

The Kostroma spill, which has peculiar conditions (features of origin and hydrological regime, predominance of shallow waters, exceptional feeding possibilities)

(Zelikman 1965), was considered separately from other areas. To assess the areas of the Kostroma spill at different water levels, 28 satellite images were used for the spawning period of 2002, 2004–2011, 2013–2019. We used 8 satellite images taken in April, 13 images—in May and 7 images—in June.

The water levels for the lower river, lake and dam sections are taken according to the data of the hydrological station in the settlement of Sokolskoye in the Nizhny Novgorod region, for the Kostroma spill—according to the data of the station in the city of Kostroma. The data on water levels corresponding to the time of creation of each satellite image was obtained from the archive located in the portal of the Center for Registry and Cadastre (2021). When the water levels differed on the dates of the photographs of one pair, their values were averaged.

Materials on quantitative indicators of reproductive success of limnophilic fish species (bream *Abramis brama* (L., 1758), pike *Esox lucius* L., 1758, roach *Rutilus rutilus* (L., 1758), common carp *Cyprinus carpio* L., 1758, asp *Leuciscus aspius* (L., 1758), crucian carp *Carassius auratus* (L., 1758), rudd *Scardinius erythrophthalmus* (L., 1758), tench *Tinca tinca* (L., 1758), silver bream *Blicca bjoerkna* (L., 1758), blue bream *Ballerus ballerus* (L., 1758)) were collected during seine surveys (by drag and fry seine) in the studied sections of the Gorky reservoir in 2002, 2006, 2010, 2011, 2014, 2016–2020.

14.3   Results

The graph of changes in the water levels of the Gorky reservoir during the spawning period in years with different water availability is shown in Fig. 14.2.

Based on the results of decoding the Landsat satellite images, they digitized and linked to the geographic grid of coordinates of the border of 53 spawning areas of the middle river, lake and dam sections of the Gorky reservoir, as well as the Kostroma spill. 23 variants of the area of spawning grounds of the middle river, lacustrine and near-dam sections were determined at different water levels, 28 variants of the area of the Kostroma spill (see Fig. 14.3).

The regression dependence of the area of spawning grounds in the middle river, lake and dam sections of the Gorky reservoir on the water level was obtained:

$$y = 2360.5858 - 58.6976\,x + 0.3693\,x^2 \tag{14.1}$$

where: y is the area of spawning grounds, thousand hectares;

x is the water level at the Sokolskoye hydrological station, m.

The dependence of the area of the Kostroma spill on the water level is expressed by the following formula:
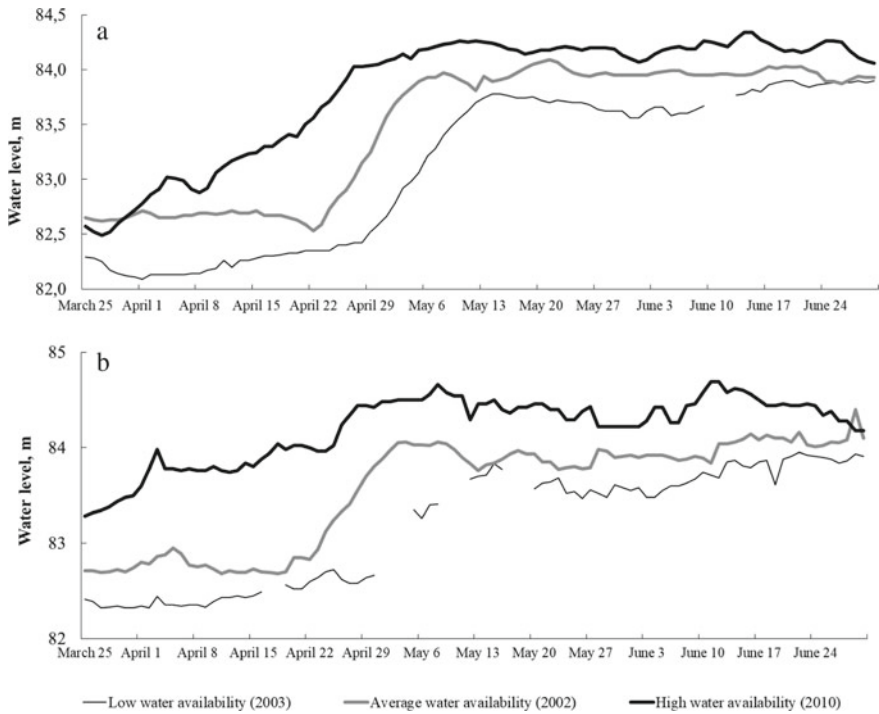
$$y = 24016 - 576.37\,x + 3.4603\,x^2 \tag{14.2}$$

Fig. 14.2 The dynamics of the water levels of the Gorky reservoir in the spring–summer period in the years of different water availability: **a** according to the data of the hydrological station in the settlement of the town of Sokolskoye, **b** according to the data of the hydrological station in the city of Kostroma. *Source* Compiled by the authors
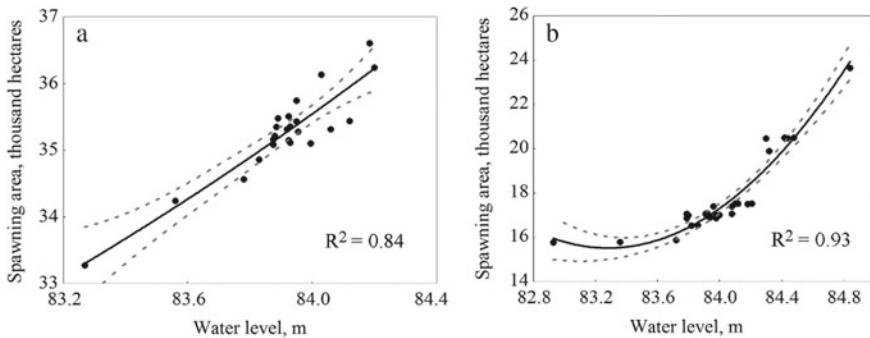

Fig. 14.3 Dependence of the area of spawning areas of the Gorky reservoir on the water level: **a** middle river, lake and dam sections (n = 23), **b** Kostroma spill (n = 28): solid line—regression curve, dotted line—borders of 95% confidence interval for regression curve. *Source* Compiled by the authors
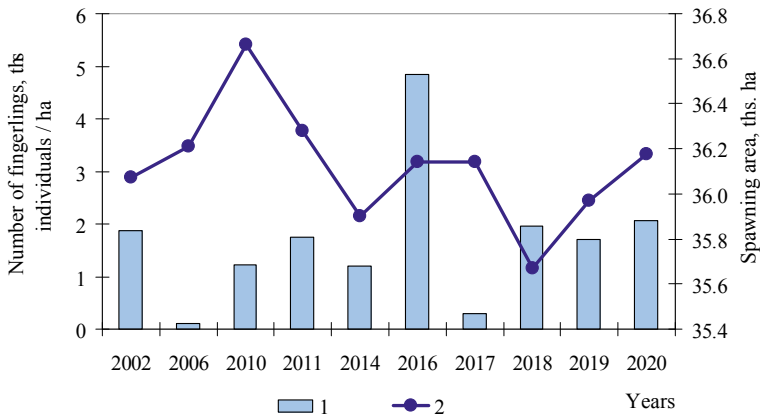
Fig. 14.4 Interannual dynamics of the relative number of fingerlings (1) and the maximum area of spawning grounds (2) of the middle river, lake and dam sections of the Gorky reservoir. *Source* Compiled by the authors

where: y is the area of the Kostroma spill, thousand hectares; x is the water level at the Kostroma hydrological station, m.

The interannual dynamics of the areas of spawning grounds and the number of fingerlings in the shallow waters of the Gorky reservoir is shown in Fig. 14.4.

Evaluation of the impact of the flooding of the Kostroma spill on the yield of fish generations is still not possible due to the small number of measurements of quantitative indicators of the success of fish reproduction.

14.4   Discussion

According to the graph in Fig. 14.2, the dynamics of the water levels of the Gorky reservoir in the flood in different water years is similar. High water in the Gorky reservoir usually begins in early April (median—April 4). After reaching a peak in early May (median—May 4), no noticeable decrease in water level until the winter low-water period, which was also noted by Kozhevnikov (1965, 1974). The absence of a sharp drop in the water level after the peak of high water (see Fig. 14.2) ensures a sufficient duration of flooding of spawning grounds and stable conditions for the development of eggs and juveniles of fish, which is reflected in the stability of the relative abundance of fingerlings in the interannual dynamics (see Fig. 14.4). For other sections of the Volga river it was also noted that the decline rate of the flood wave with an insufficient duration of flooding of spawning grounds is of decisive importance for the productivity of spawning grounds (Taradina and Chavychalova 2017; Zhezmer and Buber 2018).

Analysis of the degree of flooding of spawning grounds, carried out using satellite images and a regression model (14.1), showed that the total area of spawning grounds in the middle river, lake and dam sections of the Gorky reservoir in the spring varies depending on the water level within the following limits: minimum—30.92 thousand hectares, maximum—37.02 thousand hectares (at water levels, respectively, 82.19 and 84.36 m; the minimal and maximal water levels are determined according to the Center of the Register and Cadastre for 2002–2021). The possible range of variation in the spawning areas of the middle river, lake and dam sections of the Gorky reservoir in the spring is 1.2 times. The areas of the Kostroma spill can vary 1.7 times: the minimum is 15.8 thousand hectares, the maximum is 26.3 thousand hectares (at water levels of 82.93 and 85.09 m, respectively). Kozhevnikov (1965) indicated the area of the Kostroma spill equal to 26 thousand hectares.

No correlation was found between the number of fingerlings of limnophilic fish species in the middle river, lacustrine, and dam sections of the reservoir and the maximum area of spawning grounds. In contrast to the Gorky one, for the Cheboksary reservoir, a noticeable positive relationship was established between the number of fingerlings and the average area of spawning grounds—the Spearman correlation coefficient is 0.65 at $p = 0.01$ (Minina et al. 2021). Perhaps this is due to the insignificant range of variation in the areas of spawning grounds of the Gorky reservoir at different water levels (by a factor of 1.2). The spawning grounds of the Cheboksary reservoir can increase in area by 1.7 times (Minina et al. 2021). This difference is probably determined by the fact that the area of the Gorky reservoir is characterized by less variability depending on the water level, in contrast to the Cheboksary one (Minina and Minin 2021). Also, one of the reasons for the lack of correlation between the number of juveniles and the area of spawning grounds in the Gorky reservoir may be the insufficient amount of data on juvenile surveys ($n = 10$). In the work of Klevakin with co-authors (2012), it is indicated that at different values of the maximum water level of the Gorky reservoir, the total number of fingerlings can differ by 36–211 times.

Further research can help to obtain a formula that allows predicting the amount of natural reproduction of fish based on known water levels and areas of spawning areas determined from them, which will allow forecasting of fish stocks and will help to determine the optimal values of the total allowable catch and recommended catch.

14.5   Conclusion

The total area of spawning areas of the lower river, lake and dam sections of the Gorky reservoir can increase by 1.2 times with an increase in the water level, the area of the Kostroma spill—by 1.7 times.

The obtained formulas for the dependence of the areas of spawning grounds on the water level can be used to predict the degree of flooding of spawning grounds in specific years.

Stabilization of the water level of the Gorky reservoir after reaching the peak of the flood waters ensures the preservation of the water availability of the spawning grounds, which favorably affects the success of the natural reproduction of fish. The lack of correlation between the breeding efficiency of limnophilic fish species of the river, lake and dam sections of the Gorky reservoir and the area of spawning grounds may be explained by insignificant differences in the values of spawning areas at different water levels, or by the lack of data on juvenile surveys.

The method of reconstructing spawning areas from satellite images in coordination with data from hydrological observation posts makes it possible to compare the amount of fish recruitment directly with the areas of spawning areas, and not with water levels.

Due to the geographic referencing in GIS of the boundaries of spawning areas, discrepancies in the interpretation of their descriptions in the Fishing Rules and localization on the terrain have been eliminated, proposals have been prepared for amending the Fishing Rules, indicating the coordinates of the boundaries of the areas, which will enhance the effectiveness of their protection.

The conducted studies help to use fish stocks without harming fisheries and the environment in four regions of the Russian Federation and contribute to the development of sustainable fishing in the Gorky reservoir.

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