The structure of currents and water exchange in the overgrowing shallows

S A Poddubnyi, A V Kutuzov and A I Tsvetkov

Papanin Institute for Biology of Inland Waters, Russian Academy of Sciences, Borok, Nekouzskii raion, Yaroslavl oblast, 152742 Russia

spod@ibiw.ru

Abstract. The morphometric characteristics and bottom topography of typical shallows behind the island are characterized. The long-term and seasonal dynamics of the water level in the Rybinsk reservoir during the period from 1947 to 2020 is considered. The periods of fluctuations of the main hydrometeorological parameters in relation to the investigated section of the reservoir are shown. Based on archival and modern observation data on the structure of currents, the patterns of water transport and water exchange in the shallows are investigated, taking its seasonal overgrowth with macrophytes into account.

1. Introduction

The presence of shallows protected from direct hydrodynamic impacts determines the formation of specific habitats of aquatic organisms associated with higher aquatic vegetation (HAV) in the area of lowland reservoirs. The water level regime, wind waves and currents are among the main hydrological factors influencing the spatial distribution of macrophytes and the long-term dynamics of overgrowth in the shallows [8, 9, 12]. At the same time, the bilateral nature of interactions between these dynamic processes and the distribution of HAV should be considered. On one hand, intense wind waves and currents lead to a limitation of the propagation of HAV in the littoral zone [6]. On the other hand, associations of macrophytes create conditions facilitating a change in the wind field over overgrown areas of the slowing down water flow and, accordingly, reduce water exchange rate and flow in the protected shallows [3, 10, 11, 13].

Thus, the aim of the work is to study the features of the structure of currents and water exchange rate within the overgrown shallows of the Rybinsk Reservoir.

2. Materials and research methods

The object of the study was a shallow located behind an island in the Volga reach of the Rybinsk Reservoir [5]. Under modern conditions, at a normal retention level (NRL), the shallow water area is 5.21 km², with a length of 3.8 km and an average width of 1.8 km. Depths from 0 to 2 m occupy 79%, and depths of over 3 m – only 3.6% of the area (figure 1).
Figure 1. The layout of the autonomous buoy stations and currents’ observation sections. 1 – 1976; 2 – 1977; 3 – 1992; 4 – 2016 and 2020; 5 – land above the NRL 101.81 m; 6 – the area of macrophyte distribution in the early June according to satellite data.

Long-term monthly average data on the water level of the Rybinsk Reservoir, the volume of inflow into the reservoir and precipitation on its surface, obtained as a result of regular observations by the Rybinsk hydrometeorological observatory, as well as borrowed from the VNIIGMI – MCD database were used [1, 2].

Shallows’ boundaries were identified according to Earth remote sensing (ERS) satellite data for the period 2015–2020. The contours of the shallow water coastline for different levels of water drawdown in the reservoir were obtained by automated processing of satellite imagery scenes (Landsat – 8 and Sentinel – 2 satellites) of medium spatial resolution (up to 10 m/pixel) in the near infrared optical range.

The speed and direction of the currents were measured using the BPV – 2r recorders in 1976–1977 and by the ACITT in 1992 (archival materials of IBIW RAS). In 2016–2020 the current parameters in the overgrown areas of shallows were recorded using a Sontek Mini ADP acoustic Doppler profiler.

The observations in the deepest part of the shallows (channel) with 2.2 km² area at the NRL were carried out, since its eastern and western parts were completely overgrown with HAV (Figure 1). Seasonally, the open water area of the channel decreased by 60% by the end of summer, to 0.91 km² following the development of macrophytes.

3. Results and discussion

Level regime. The main factors determining the range of water level fluctuations and their frequency in the Rybinsk Reservoir are: the approved values of the water level which limit the useful and spillway control volumes of the reservoir, dispatching rules for regulating the flow by the hydroelectric complex; hydrometeorological and landscape conditions for the formation of runoff in the catchment; morphological features of the bed of the reservoir [7].

The average long-term value of the NRL was 101.47 m (with the project level designated at 101.81 m) over 74 years of the Rybinsk Reservoir operation. The minimum level of pre-flood drawdown (PFD) was observed in March, and in some cases in February reaching a 98.80 m on average. PFD increased gradually over the entire observation period, and after 2004 practically did not fall below 99.00 m (Figure 2).
The maximum depth of the studied shallow at the NRL was more than 3 m, i.e. was below the 98.81 m mark. During the periods of current surveys, the shallow’s water depth varied from 3 m in the second half of May to 1.6 m in the first half of September.

Currents and water exchange rate. To determine the main factors that form currents in the protected shallows, statistical processing of time series of the current velocity obtained at the ABS in different parts of the shallow (figure 1) as well as wind speed and flow volume through the Uglich HPP was carried out. Fluctuations in the synoptic scale (2−3 and 5−7 days) and local variations (0.5−1 days) were revealed based on the spectral analysis in the wind speed series. The discharge through the HPP was characterized by weekly (5−7 days) and semi-weekly (2.5−3.5 days) fluctuations. In addition, in the high-frequency region of the spectrum, oscillations with periods of 3−4, 6, and 12 hours were clearly distinguished. The spectra of currents were dominated by synoptic oscillations (2−3.5 and 5−6 days), diurnal and semidiurnal oscillations, as well as high-frequency oscillations with periods of 4.5, 6, and 8 hours (figure 3). Regression analysis of the studied series revealed the predominant role of wind in the formation of currents within the shallow (r = 0.5−0.8).

The study of the spatial distribution of currents was carried out on the sections within the shallow water area free from HAV (figure 1). The length of the sections varied from 335 to 730 m at the end of May and from 95 to 216 m in mid-July depending on the degree of development of macrophytes. According to the measurement results, water was transported in the direction of the wind. Due to the insignificant wind effect (1.0−2.2 m/s), the average velocity of water transfer along the longitudinal axis of the shallow was 2.0−3.0 cm/s. The average water discharge rate at the sections varied from 5 to 20 m$^3$/s. The water exchange rate was 0.47−0.67 under the indicated hydrometeorological conditions, i.e. the water in the considered area of overgrown shallow completely changed in 1.5−2 days (table 1).

4. Conclusions
The results of the study showed that wind current prevails within the protected shallow. In some cases, with a weak wind effect, significant water flows through the Uglich HPP, coincidence of the frequency of discharges with wind speed and manifestations of free and forced fluctuations in the water level, the contribution of runoff to the formation of shallow water flow can exceed or be comparable with the contribution of the wind. According to the earlier studies [4], the periods of changes in the current velocity in the Volga reach of the Rybinsk Reservoir are 11.8, 8, 6, 2.5−3 hours. Despite the seasonal overgrowth of the site with macrophytes, its water exchange rate remains quite high.
Table 1. Hydrometeorological characteristics of overgrown shallow water

| Characteristic                                      | Year, month |
|----------------------------------------------------|-------------|
|                                                    | 2016        |
|                                                    | May         |
| Wind direction, °                                  | 316         |
| Wind speed, m/s                                    | 1.0         |
| Current direction, °                               | 140         |
| Current velocity, cm/s                             | 2.2         |
| Average area of transversal section, m²             | 945         |
| Average water discharge rate, m³/s                  | 20          |
| The length of the shallow, m                        | 3800        |
| The volume of water in the studied area, 10⁶ m³    | 3.6         |
| Inflow volume per day, 10⁶ m³                       | 1.7         |
| Water exchange rate                                 | 0.47        |
| The time of water exchange, day                     | 2           |
| Flow rate, km/day                                   | 1.8         |
|                                                    | 2020        |
|                                                    | July        |
| Wind direction, °                                  | 120         |
| Wind speed, m/s                                    | 2.2         |
| Current direction, °                               | 360         |
| Current velocity, cm/s                             | 2.0         |
| Average area of transversal section, m²             | 248         |
| Average water discharge rate, m³/s                  | 5           |
| The length of the shallow, m                        | 3800        |
| The volume of water in the studied area, 10⁶ m³    | 0.9         |
| Inflow volume per day, 10⁶ m³                       | 0.43        |
| Water exchange rate                                 | 0.48        |
| The time of water exchange, day                     | 2           |
| Flow rate, km/day                                   | 1.8         |
|                                                    | 2021        |
|                                                    | July        |
| Wind direction, °                                  | 346         |
| Wind speed, m/s                                    | 1.7         |
| Current direction, °                               | 160         |
| Current velocity, cm/s                             | 3.0         |
| Average area of transversal section, m²             | 578         |
| Average water discharge rate, m³/s                  | 17          |
| The length of the shallow, m                        | 3800        |
| The volume of water in the studied area, 10⁶ m³    | 2.2         |
| Inflow volume per day, 10⁶ m³                       | 1.47        |
| Water exchange rate                                 | 0.67        |
| The time of water exchange, day                     | 1.5         |
| Flow rate, km/day                                   | 2.5         |

Figure 3. Spectra of wind speed (a) and current speed (b) fluctuations on 17.06–08.08, 1977; wind speed (c), discharge through the Uglich HPP (d) and current speed (e) 22.07–20.08.1992
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