The application of geometric models for the study of hydrological regime of protected shallows in reservoirs

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Abstract. This study considers the possibility of using geometric models in the study of individual elements of hydrological regime in different types of protected shallows in the Upper Volga reservoirs. Three types of models were chosen and verified. The formulas for calculating the bathygraphic curves of geometric figures approximating the beds of protected shallows are determined. Classes with different morphometric characteristics are identified using non-hierarchical cluster analysis for each type of shallows. Model calculations of areas and volumes of shallows are carried out depending on seasonal changes in water level, as well as estimates of thermal content, average monthly water balance and water exchange in the shallows.

1. Introduction

Open and protected shallows are the two main types of the littoral zone determining the abiotic and biotic structure of coastal ecosystems. Protected shallows are becoming particularly important for biological production in the littoral zone where the processes of water self-purification are especially active, aquatic and semi-aquatic plants develop intensively, phytophilous fish concentrate for spawning, juvenile fish feed and grow [1]. The functioning of shallows’ ecosystems is determined by their hydrological regime to a large extent. At present, along with expensive instrumental methods used to study the hydrological regime elements in shallow waters [2], there is a number of one- two- and three-dimensional mathematical models for assessing water quality and ecological status of water bodies. It should be noted that the effect of macrophytes on current velocity and flow regime is included in the hydrodynamic block of models for shallow lakes and reservoirs [3–6]. Simple geometric models can be used as an alternative to complicated complex mathematical models, to study general hydrological patterns of water bodies and their individual parts [7–9].

The aim of this study is to evaluate the possibility of using geometric models for the study of thermal regime, water balance and water exchange in certain types of protected shallows of the Upper Volga reservoirs, considering seasonal water level fluctuations.

2. Materials and methods

273 different types of protected shallows (bays, shallow areas behind islands, pocket-type shallow areas) in the Upper Volga reservoirs were studied [10]. Morphometric parameters of shallows – length ($L$, m), average width ($B$, m), width along the boundary line between shallow and open (channel) part of the reservoir ($B_0$, m), maximum depth along this line ($H_0$, m), average depth of the shallows ($\overline{H}$, m),
surface area \((F, \text{m}^2)\), \(z\) – variable water level and volume \((W, \text{m}^3)\) – were calculated using nautical charts, field survey data and «SAS Planet» software package. Hydrometeorological information on the reservoirs was taken from the information system on water resources and water management of river basins of Russia [11, 12].

The water balance of shallows, except for precipitations on water surface and evaporation, was calculated according to the formula: \(\sum Q_{\text{in}} - \sum Q_{\text{out}} = \pm \Delta W\), where \(\sum Q_{\text{in}}\) is total input, \(\sum Q_{\text{out}}\) – total output, \(\pm \Delta W\) is the change of water reserve in the water body for the estimated time period. Rivers’ inflow was excluded: \(\sum Q_{\text{in}} = \pm \Delta W\), i.e. we only considered water inputs or outputs caused by fluctuations in the reservoir level. Znamensky’s model was used to calculate water exchange in shallows [13, 14]: \(K_{\text{exc}} = \frac{\Delta W}{\bar{W}}\), where \(\Delta W = W_{\text{end}} - W_{\text{start}}\). \(W_{\text{end}}\) is the volume at the end of the month, \(W_{\text{start}}\) is the volume at the beginning of the month, \(\bar{W}\) is the mean monthly volume of water.

Change in the thermal content of shallows is calculated according to the formula: \(\pm \Delta \theta = c_p \rho (W_{\text{end}} \bar{T}_{\text{end}} - W_{\text{start}} \bar{T}_{\text{start}})\), where \(c_p\) is the heat capacity of water, 4190 J/(kg°C); \(\rho\) is water density, 1000 kg/m³; \(\bar{T}_{\text{end}}, \bar{T}_{\text{start}}\) are the mean water temperatures at the end and beginning of the estimated time period correspondingly [8]. A second-order polynomial is used to approximate seasonal changes in water temperature. The heating phase, when water temperature increases from its minimum values in May to maximum in July, is calculated according to the formula: \(T = -64.2 + 0.81 \tau - 0.002 \tau^2\), and the cooling phase (August-September): \(T = 112.3 - 0.55 \tau + 0.002 \tau^2\), where \(\tau\) is the number of days since January 1 [15]. Microsoft Office Excel 2007 and Statistica 10 software packages were used for statistical evaluation of hydrometeorological data.

3. Results
Initially, 16 geometric shapes were selected for the approximation of shallows’ morphometry. A truncated trapezoidal prism, a truncated triangular prism and a wedge were chosen of these 16 shapes for bays, pocket-type shallow area sand shallow areas behind islands, respectively (figure 1) based on the results of verification using «SAS Planet». Mean relative errors of \(F\) account for 0.1%, and of \(W\) – 7.3% in all of the reservoirs. Formulas for \(F = f(z)\) and \(W = f(z)\) (bathymetric curves) are determined for each of the three geometric shapes (table 1).

![Figure 1](image)

**Figure 1.** Geometric shapes approximating the bed of shallow waters: a – bays, b – pocket-type shallow areas, c – shallow areas behind islands.

The next step includes the classification of each type of shallow waters according to their characteristics \((L, B_0, H_0)\) using a non-hierarchical cluster analysis (the k-means method). As a result, each type of shallows is assigned to one of the two classes with minimum and maximum horizontal dimensions. Then, in accordance with the formulas from table 1, we calculate the areas and volumes of shallows by their clusters depending on the seasonal water level fluctuations. Further analysis of the water level regime has revealed seasonal deviations from the normal impounded water level in the
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Ivankovo, Uglich, Rybinsk and Gorky reservoirs ranging from 0.08 to 2.7, 0.11 to 2.99, 0.42 to 3.06 and 0.0 to 1.34 m, respectively (figure 2).

Table 1. Formulas of dependences $F = f(z)$ and $W = g(z)$ for protected shallows of different types.

| Parameter          | General formulas                              | Local formulas                              |
|--------------------|-----------------------------------------------|---------------------------------------------|
| Area $S_x$         | $S_x = \frac{L}{H_0^2} (H_0 - z)[B_0(H_0 - z) + bz]$ | $S_x = \frac{B_0}{5H_0^2}L(H_0 - z)(5H_0 - 3z)$ |
| Volume $W_z$       | $W_z = \frac{L}{6H_0^2} (H_0 - z)^2[2B_0(H_0 - z) + b(H_0 + 2z)]$ | $W_z = \frac{1}{5}L B_0 (H_0 - Z)^2(2H_0 - z)$ |

Pocket-type shallow areas (truncated triangular prism)

| Area $S_z$         | $S_z = \frac{B_0}{H_0^2}L(H_0 - z)^2$ |
|--------------------|---------------------------------------|
| Volume $W_z$       | $W_z = \frac{1}{3H_0^3}LB_0 (H_0 - Z)^3$ |

Shallow areas behind islands (wedge)

| Area $S_z$         | $S_z = \frac{B_0}{H_0^2}L(H_0 - z)[L(H_0 - z) + L_1z]$ | $S_z = \frac{B_0 L}{5H_0^2}L(H_0 - z)(5H_0 - z)$ |
|--------------------|-----------------------------------------------------|
| Volume $W_z$       | $W_z = \frac{B_0}{6H_0^2} (H_0 - z)^2[2L(H_0 - z) + L_1(H_0 + 2z)]$ | $W_z = \frac{B_0 L}{15H_0^2} (H_0 - z)^2(5H_0 - z)$ |

Note. Local formulas for bay sand shallow waters behind islands are derived under the assumption that $b = 0.4B_0$ and $L_1 = 0.8L$.

Depending on their horizontal dimensions, the volumes of shallows vary largely from $0.012 \cdot 10^6$ to $7.56 \cdot 10^6$ in bays, from $0.013 \cdot 10^6$ to $33.9 \cdot 10^6$ in shallow areas behind islands and from $0.013 \cdot 10^6$ to $12.8 \cdot 10^6 \text{m}^3$ in pocket-type shallows. The results of the calculations show that the average annual coefficient of water exchange in shallows, conditioned by only the water level fluctuations, is very small (0.37–0.6 – in the Ivankovo and Uglich, 0.48–0.95 – in Rybinsk and 16–0.3 – in Gorky reservoirs).

Figure 2. Seasonal deviations from the normal impounded water level in the Ivankovo (1), Uglich (2), Rybinsk (3) and Gorky (4) reservoirs.

The temperature conditions in shallows are determined by their morphometric characteristics, water inputs and outputs during the reservoir filling and summer-fall drawdown periods. The water received by the shallow areas warms up unevenly. In general, the variation in water temperature is seasonal,
and it closely following the changes in air temperature. Our calculations show that, depending on the horizontal dimensions of shallows and seasonal water level fluctuations, their thermal content in May–October changes from 0.3–4.5 to 28–323 in the Rybinsk Reservoir and from 2.3–7.9 to 83–462 $10^6\text{MJ}$ in Ivankovo, Uglich and Gorky reservoirs.

4. Discussion

Small shallows ($L - 744–1193$, $B - 133–270$ $\text{m}$) account for 77% and large protected shallows ($L - 2250–3766$, $B - 450–880$ $\text{m}$) – for 23% of the total number of shallow water areas in the reservoirs. According to the reservoirs’ operation practices, the drainage of shallows in the Ivankovo and Uglich reservoirs occurs in February – March, in the Rybinsk Reservoir – from August till March and in the Gorky Reservoirs shallow waters are not drained completely. In spring, water fills shallow areas fast enough. This process ends by the end of May – beginning of June when the normal impounded water level is reached. It should be noted that 25% of shallow waters in the Ivankovo Reservoir, 33% in the Uglich Reservoir and 61% in the Rybinsk Reservoir are drained during the drawdown period prior to flood time. The annual dynamics of filling and draining of protected shallow water areas are presented in table 2.

Table 2. The percentage of filling of protected shallows relative to their volume at the normal impounded water level.

| Type of shallow waters | Month |  
|------------------------|-------|
|                        | I     | II   | III  | IV   | V    | VI   | VII  | VIII | IX   | X    | XI   | XII  |
|                        |       |      |      |      |      |      |      |      |      |      |      |      |
| Ivankovo Reservoir     |       |      |      |      |      |      |      |      |      |      |      |      |
| Bays and Pocket-type shallow areas | 54 | 24 | 0,4 | 27 | 93 | 90 | 82 | 78 | 77 | 81 | 86 | 74 |
| Shallow areas behind-islands | 64 | 37 | 4,3 | 40 | 95 | 93 | 87 | 84 | 83 | 86 | 90 | 81 |
| Uglich Reservoir       |       |      |      |      |      |      |      |      |      |      |      |      |
| Bays and Pocket-type shallow areas | 57 | 30 | 0 | 12 | 91 | 86 | 80 | 77 | 74 | 74 | 75 | 68 |
| Shallow areas behind-islands | 67 | 42 | 2 | 23 | 93 | 89 | 85 | 83 | 80 | 80 | 81 | 76 |
| Rybinsk Reservoir      |       |      |      |      |      |      |      |      |      |      |      |      |
| Bays and Pocket-type shallow areas | 2,3 | 0,3 | 0 | 1,8 | 55 | 67 | 52 | 33 | 19 | 11 | 10 | 7 |
| Shallow areas behind-islands | 9 | 3,8 | 2 | 8 | 65 | 75 | 63 | 46 | 31 | 22 | 20 | 16 |
| Gorky Reservoir        |       |      |      |      |      |      |      |      |      |      |      |      |
| Bays and Pocket-type shallow areas | 69 | 45 | 21 | 29 | 96 | 97 | 94 | 93 | 91 | 100 | 93 | 84 |
| Shallow areas behind-islands | 77 | 57 | 33 | 41 | 97 | 98 | 95 | 95 | 93 | 100 | 95 | 88 |

As shown in table 2, the filling of bays and pocket type shallows in the Ivankovo and Uglich reservoirs is practically identical. In March, they may dry up completely or have minimum volumes of water. In spring, shallow areas behind islands get filled up to a higher percent of their volume due to greater dimensions. From May to December, all shallows are filled with water to 68–95% of their capacity. In the Rybinsk Reservoir shallows fill up maximum to 67–75% of their capacity in June and then gradually drain in accordance with seasonal water level fluctuations (figure 2). In the Gorky Reservoir, due to insignificant seasonal fluctuations in the water level (figure 2), shallows are filled
with water well enough: minimum to 21–33% in March and maximum to 84–100% of their capacity in May–December.

Regardless of the type of shallows, the highest rate of water exchange is recorded in spring during the period of reservoirs’ filling. Shallow areas behind islands are characterized by the smallest coefficients of water exchange due to their large horizontal dimensions. There is virtually no water exchange caused by water level fluctuations during the summer-fall period in protected shallows of the Ivankovo, Uglich and Gorky reservoirs. The most lotic are shallow waters in the Rybinsk Reservoir because of their gradual drainage for navigation purposes.

In reservoirs with quasi-constant water level (Ivankovo, Uglich and Gorky reservoirs), the major portion of heat is accumulated by shallow waters during the navigation period in May-July (up to 65%), with a maximum in May (56%). As temperatures begin to decrease (late July – August), the thermal content in shallow waters falls by 7% at the constant volume. The loss of heat increases in October up to 43% reaching its maximum in October (60%). In the Rybinsk Reservoir, seasonal water level fluctuations contribute 4–98% in the formation of shallow waters thermal content. In the middle of June it increases by 90%. In summer, the heat loss gradually increases from 7 (late July) to 64% (August-September) despite high water temperatures, due to the beginning of the reservoir draw down. In October, due to significant reduction in water volume and a sharp decrease in air temperatures, the thermal content in protected shallows falls by 77% (table 3).

Table 3. Change in the thermal content of protected shallows in the Upper Volga reservoirs during the open water period (%).

| Period       | Rybinsk Reservoir | Ivankovo, Uglich, Gorky reservoirs |
|--------------|-------------------|-----------------------------------|
|              | Bays and pocket-type shallows | Shallow areas behind islands | All types of shallows |
| May-June     | 94                | 83                  | 56                  |
| June-July    | -10               | -3                  | 9                   |
| July-August  | -40               | -30                 | -7                  |
| August-Sep   | -68               | -60                 | -43                 |
| Sep-Oct      | -79               | -74                 | -60                 |

Note: «−» means loss of heat.

5. Conclusion
A satisfactory approximation of different protected shallows’ beds by certain geometric shapes (a truncated trapezoidal prism, a truncated triangular prism and a wedge) makes it possible to calculate and predict such important elements of hydrological regime as the filling and draining of shallow waters, their water exchange and thermal content in the seasonal aspect. Registration of water level fluctuations allows assessing changes in morphometric parameters of shallows.

Further studies of hydrodynamic processes in shallows (wind and discharge currents, wind waves) with regard to the effects of hydrometeorological factors as well as the reservoir drawdown and filling regimes, will contribute to a better understanding of water balance and thermal characteristics of shallows and make it possible to find interrelations between the hydrological regime and the biotic link of shallows’ ecosystems.

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