Mathematical modelling of water turbidity in the water body

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\textbf{Abstract.} Suspended solids spreading in water reservoir is pre-defined by morphometry of the latter, inflow and outflow location, solids ingress with inflow and meteorological conditions. Configuration particulars of Kuybyshev water reservoir and its large elongation over longitude lead to irregular turbidity spreading and irregular unit flow of sediment. Represented spreading map of max. water turbidity values in Kuybyshev water reservoir is built at hypothetic initiation of bed solid stirring processes in water area. The acquired spreading map of max. water turbidity enables assessing of water areas with the most adverse hydrodynamic conditions that can form the basis to issue further recommendation on actions connected to dredging or damping.

1. Introduction

Suspended solids are mineral and organic substances (particles of clay, sand or silt) and different microorganisms present in water in suspended state. Suspended solids concentration (or water turbidity) in water body pre-defines water transparency and, accordingly, light penetration, warmup intensity, as well as sorption processes and photosynthesis intensity. All these affect to water quality and activity of aquatic organisms. The article [2] considers details of the nature of increased suspension concentrations impact to aquatic wildlife of water reservoir. In addition, the [2] notes that, depending on duration of increased turbidity period, “fallout of some links in food chain and ecosystem degradation can occur” [2]. However, “along with negative mechanic effect to water bodies ecosystem, suspensions play the role of transporter and carrier of highly toxic pollutants” [3].

All this pre-defines the research actuality of space-time patterns of water turbidity spreading over the territory of water reservoir for different hydro-meteorological conditions. Analysis results of turbidity data and data acquired following the mathematical simulation form unconditional basis to solve current actual issues of wastewaters rationing and for planning various hydrotechnic events in the water objects [5]: “before evaluating the anthropogenic effect on water turbidity of stream flows, one shall consider domestic parameters of turbidity and its variability” [5].

Currently, the observations of water reservoirs turbidity behavior are irregular and often complicated under conditions of extreme hydro-meteorological phenomena: stormy winds, intense and high flood periods, high waters etc. Accordingly, mathematic simulation enables evaluation of space-time patterns of water turbidity spreading in water area under numeric experimental conditions, when reproducing different adverse hydro-meteorological scenarios. The results of such simulation can be useful both in evaluation of water quality in reservoir and planning water-related activities.
2. Materials and methods

Kuybyshev water reservoir is the biggest in Volga Cascade. It is formed by shutting down the course of Volga River 6 km downstream of the City of Togliatti in autumn, 1955. The reservoir was filled within three stages. In 1957, water level of reaches projected Baltic datum of 53.0 m. After construction of Cheboksary and Nizhnekamsk HPP the water-surface area of the reservoir has reached 5,900 km², and its total capacity at normal headwater level (NHL) amounted to 58.0 km³. Total length along flooded channel of Volga River is 510 km and biggest width is 27 rm. Cheboksary and Nizhnekamsk water reservoirs provide basic water supply of Kuybyshev water reservoir.

Starting from 1958, Togliatti Hydro-Meteorological Station has provided water turbidity observations in Kuybyshev water reservoir: in open part each decade and in lateral hydrological sections on monthly basis. High water mobility degree is typical for Kuybyshev water reservoir and this leads to unbalanced condition of water turbidity within a year. By degree of water saturation with suspensions, turbidity values can be close to zero and reach up to 50 – 100 g/m³ [1]. Thus, suspended sediments content in open part of water area in winter period does not exceed 5 – 15 g/m³. In the period of spring high waters, suspended sediments content increases up to 30 – 60 g/m³ and in summer and autumn decreases up to 10 – 20 g/m³ [8].

Suspended sediments spreading along the length and cross-section of water reservoir is not uniform. Increased sediments content is observed on underwater shore slopes, on flow deep stream and in surface layers. Such dynamism is typical for any season and different operational conditions of water reservoir. Turbidity behavior changes abruptly, when severe storms appear on water body. In this time, water saturation degree increases significantly, with several times increase acquired average data.

As per [10], the share of allochthonic suspension for Kuybyshev water reservoir amounts to 10 – 14 % due to intercept of erosion products by Cheboksary and Nizhnekamsk water reservoirs. In view of this, erosion contribution calculations can be neglected, as main part of sediments is autochthonic and only inter-reservoir mass exchange processes accounting solid flow ingress with Volga and Kama Rivers shall be considered.

Kuybyshev water reservoir is a source of industrial and drinking water supply for big number of settlements located within its shore area; among then there are Kazan, Togliatti, Ulyanovsk, Tetyushy, Zelenodolsk, Chistopol, Volzhsk, Novoulyanovsk. Accordingly, hydraulic engineering and dredging works in order to improve shipping routes and water exchange between streams, mining of non-metallic materials lead to water turbidity increase within hydro-dynamic source of stirring and further spreading of turbid water tails in water area. Increased turbidity of water body, as it was mentioned above, negatively impacts to ecosystem of water body, “both its hydrological, hydro-chemical parameters and biological components, including condition of fish feed base, their spawn conditions and, finally, condition of the whole fish stock” [7], as well as complicates water use system. Transport capacity of flow or its maximal suspension-carrying load pre-defines hydraulic variable flow states. Accordingly, evaluation of the fields with maximal water saturation with suspended solids at hypothetic initiation of bed solid stirring processes in water area is of special interest. Such definitions have special values for low stream period, which is distinguished by smallest flow depth and, accordingly, biggest values of turbidity.

At all timelyness of water turbidity monitoring and re-shaping of water bodies’ bed solids, natural observations on big water reservoirs are often complicated and expensive. In this case, numeric simulation of hydrodynamic inter-water body processes, describing two-phase mass transfer in water area can be useful.

The bases of further calculation is formed by “Volna” 3D – hydrodynamic model developed by A.V. Rakhuba [6] and analytic formula for sediment flow [9, 10] and analytic formula for flow transport capacity [9, 10] integrated therein. This simulation system has been already used to evaluate flow sediment and bed solid re-shaping of appurtenance broad of Kuybyshev water reservoir [7]. In this case, it is assumed that independent water flow and sediment flow calculation is permitted in case of insignificant solids concentrations in a flow [11].
3. Results

To calculate spatial turbidity spreading in the water area of Kuybyshev water reservoir, the year of 1969 was accepted as average in water content. Calculations for low water periods and high water were made for stationary conditions at no wind, as well as for low water period at winds observes in summer time of reporting year, NNW and SW winds with average speed of 12 and 10 m/s, respectively [4].

Parameters of analytic formula for sediment flow were calibrated using the observations on vertical lines of Kuybyshev water reservoir [4] for low water period and flood period of 1969 (table 1). Relative variations between calculated $S_{\text{calc}}$ and observed $S_{\text{obs}}$ average vertical turbidity values amounted from 3 to 70%.

See on figure 1 turbidity maps for Kuybyshev water reservoir for low water and high water periods. In low water period, turbidity values do not increase 20 g/m$^3$, moreover, the highest turbidity values falls to relatively shallow-watered northern parts of the water reservoir. Deepwater central and southern parts of water area are distinguished by relatively low turbidity values, from 5 to 10 g/m$^3$. In the period of high waters, transport potential of water increases that leads to increase of suspended solids concentration. The highest turbidity values in northern shallow-watered areas increase 60 g/m$^3$, while for central and southern parts of water reservoir turbidity values fall within 20 – 30 g/m$^3$. Both for low water period and for high water period, lower turbidity values for deep water fluvial part are observed, as compared to adjacent areas.

| Vertical number | Locality | Sediment discharge $G_{\text{calc}}$, g/s·m$^2$ | $S_{\text{obs}}$, g/m$^3$ | $S_{\text{calc}}$, g/m$^3$ | Flow rate $v_{\text{obs}}$, m/s | Flow rate $v_{\text{calc}}$, m/s | Depth $h_{\text{calc}}$, m |
|-----------------|----------|---------------------------------|-----------------|-----------------|----------------|----------------|----------------|
| Low water period |          |                                 |                 |                 |                |                |                |
| 66              | v. Vyazovye | 3.86                         | 15.4            | 15.0            | 0.17           | 0.254          | 7.93           |
| 50              | t. Tetushi  | 0.47                         | 11.7            | 12.9            | 0.06           | 0.036          | 16.92          |
| 63              | v. Undory   | 0.31                         | 14.7            | 14.1            | 0.08           | 0.022          | 9.87           |
| 5               | v. Klimovka | 0.35                         | 21.0            | 12.4            | 0.10           | 0.029          | 37.81          |
| 1               | t. Toliatti | 0.65                         | 9.02            | 12.2            | 0.16           | 0.054          | 39.77          |
| Spring flood    |          |                                 |                 |                 |                |                |                |
| 68              | v. Vyazovye | 33.21                        | 28.5            | 53.1            | 0.44           | 0.64           | 11.2           |
| 50              | t. Tetushi  | 4.57                         | 33.0            | 29.3            | 0.14           | 0.16           | 18.8           |
| 60a             | v. Undory   | 4.14                         | 40.4            | 50.0            | 0.05           | 0.08           | 11.6           |
| 88              | v. Klimovka | 1.50                         | 11.4            | 11.2            | 0.20           | 0.13           | 39.4           |
| 1               | t. Toliatti | 1.76                         | 5.93            | 10.1            | 0.29           | 0.17           | 41.3           |

Figure 2 provides maps of unit flow of sediment (g/(s·m$^2$)) in low water period in wind conditions of specified directions. In line with acquired results, NNW wind facilitates more intense water area stirring in its central and northern parts. The values of unit flow of sediment exceed 2 g/(s·m$^2$). For SW wind, the highest values fall to pool stage extensions in central part of water reservoir, while in southern part the values of unit flow of sediment amount to approx. 0.5 g/(s·m$^2$) in average.

Maximal water turbidity field, i.e. hydrodynamic potential for maximal suspensions content in water for the whole Kuybyshev water reservoir area is calculated for low water flow at stationary calculation regime. Figure 3 provides the map of maximal water turbidity spreading in the whole area of Kuybyshev water reservoir. As can be seen from figure 3, the highest turbidity levels fall to the smallest depths in the northern part of water reservoir and amount to 300 g/m$^3$. The lowest turbidity...
values fall on deep water southern part of water reservoir and its central part, appurtenance broad and amount to 100 – 200 g/m³.

Figure 1. Maps for Kuybyshev water reservoir for low water (a) and high water (b) periods, g/m³.

Figure 2. Maps of unit flow of sediment (g/(s·m²)) in low water period in wind conditions of specified directions – NNW 12 m/s (a) and SW (b) 10 m/s.
4. Conclusion

It is obvious that suspended solids spreading in water reservoir is pre-defined by morphometry of the latter, inflow and outflow location, solids ingress with inflow and meteorological conditions. Configuration particulars of Kuybyshev water reservoir and its large elongation over longitude lead to irregular turbidity spreading and irregular unit flow of sediment. The values of suspended solids concentration in northern and southern parts of the water reservoir vary two or three times. The values of unit flow of sediment in the area in severe wind conditions vary by a decade.

Represented spreading map of maximal water turbidity values in Kuybyshev water reservoir is built at hypothetic initiation of bed solid stirring processes in water area. This result is not of specific value for low stream period, which is distinguished by smallest flow depth and, accordingly, biggest values of turbidity. The acquired spreading map of maximal water turbidity enables assessing of water areas with the most adverse hydrodynamic conditions that can form the basis to issue further recommendation on actions connected to dredging or damping.

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