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NAVIGATION ON THE TAILWATERS OF THE NIZHNY NOVGOROD HYDROPOWER DAM ON THE RIVER VOLGA

Abstract: Ways to optimise discharge control with a cascade of retention dams on the Upper Volga River were identified. The characteristics of the diurnal cycle of navigation depth were described and a restructuring of the timetable for large shipping was proposed.

Key words: Volga drainage basin, navigation, dam lakes.

1. Introduction

The extensive deep waterway system in the European part of Russia is a unique solution playing an extremely important role in both domestic and international river-to-sea transport. The River Volga with its cascade of large dams is the core component of the deep navigable waterway system. However, the failure to fill the Cheboksary reservoir to its design level left sixty kilometres of the Volga River in the tailwaters of the Nizhny Novgorod hydropower dam above the Cheboksary Dam's head of water.

During the 50 years of operation of the Nizhny Novgorod hydropower dam the tailwater reach below the dam suffered irreversible changes with a depth reduction of nearly one meter as a result of the only partial filling of the Cheboksary dam. Similar deformations to the channel reduced navigation depths in the lock chambers and along the shallows of this reach. Dredging is not a solution because it would provoke a further reduction of water level and rule out transit navigation altogether.

As a result of these changes and taking into account the diurnal discharge control, the navigation depth of 3.5 m can only be maintained for 2-3 hours in 24-hour period during the peak navigation season. During the last decade this restricted window for navigation has periodically paralysed the navigation of large cargo ships and modern four-deck passenger cruisers.

2. Research methodology

In the view of the situation, the Volga State Academy of Water Transport has carried out a study of the tailwater regimen of the Nizhny Novgorod reservoir dam at the request of the Russian Ministry of Transport. After a multidimensional investigation of the discharge control with four retention dams on the Upper Volga River, biological studies and mathematical modelling of the river current hydraulics, a large-scale *Programme for the gradual improvement of navigation conditions on the tailwaters of the Nizhny Novgorod dam* was devised.

3. Research outcomes

The research confirmed prospects for the optimisation of the discharge control process using the cascade of dams to ensure that an average diurnal navigational discharge of 1300 $m^3 \cdot s^{-1}$ through the hydropower plant can be guaranteed instead of the design value of 1100 $m^3 \cdot s^{-1}$. By implementing this optimisation the 3.5 meter depth can be maintained for 5-7 instead of two hours in a 24-hour period.

The Hydroprojekt Institute, acting on a commission from the Ministry of Natural Resources, used the study of the Volga College to develop its new *Principles of water resource management on the Rhibinskiy and Gorkovski dams on the Volga River* (Nizhniy Novgorod was formerly known as Gorkiy). This envisaged a larger navigational discharge provided by the hydropower plant. A detailed discharge control dispatching plan was devised to increase the stability of the discharge necessary for navigation. In addition, to ensure effective management of the discharge regimen control during navigation the Academy proposed a system of monthly projections of potential average daily discharge. The projections are based on the control capacity of the Rhibinskiy dam, the largest in the cascade. Taking advantage of the similar operational plan of the average diurnal discharge along the tailwaters of the Nizhny Novgorod hydropower dam, the following formula can be applied:

$$Q_{NNhydro} = \frac{W_{act.\,Rhib.} - 15.61}{t \cdot 0.0000864} + k\sum Q_{proj.side.} - 100 \qquad (1)$$

where: $Q_{NNhydro}$ – mean diurnal navigational discharge of the power plant projected for the following month (during June to November) in $m^3 \cdot s^{-1}$; $W_{act.\,Rhib.}$ – actual total water volume in the regulating Rhibinskiy dam on the last day of the month in km^3; 15.61 – total volume of water in the Rhibinskiy dam below the marked point of the maximum permitted navigational discharge level in km^3; t – days from the calculated date (end of month) until the end of the navigation season (1st November) in days; $Q_{proj.\,side.}$ – projected average side supply of water into the upstream Ivankovskiy, Uglichovskiy, Rhibinskiy, Sheksninskiy and Gorkhovskiy dams, in $m^3 \cdot s^{-1}$; k – loss adjustment factor; 100 – long term average diversion of water from the Ivankovskiy dam into the Moskva Canal, $m^3 \cdot s^{-1}$.

The control system has already led to certain improvements in the water level in the tailwaters of the Nizhny Novgorod hydropower dam since its introduction in 2003/2004. Nevertheless, the diurnal regimen of water levels and navigational depths had to be investigated in relation to the fluctuation of electricity generation at the hydropower plant in order to further increase the navigational capacity of the reach in question. Practically, all hydropower plants on large rivers operate in peak regimens, while also regulating the diurnal discharge. As a result of this discharge control regimen, an outfall wave forms, travels down and gradually transforms (flattens) on the tailwaters. An illustrative example of this is the diurnal fluctuation pattern on the tailwater of the Nizhny Novgorod hydropower dam on the River Volga (Figure 1).

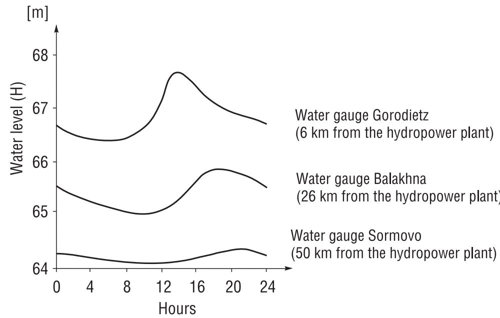

Figure 1. Diurnal water level fluctuation pattern on the Nizhny Novgorod hydropower dam tailwater on the River Volga

Minimum ('disaster') and maximum water levels are observed directly below the plant once in every 24-hour period, respectively around 7:00-8:00 hours and 12:00-13:00 hours.

Frequent water level fluctuations of considerable magnitude cause corresponding changes to the depth both in time and location along the tailwater reach, which materially complicates the navigation conditions. This is why investigation of the outfall wave movement and profile patterns remains a crucial issue. Indeed, the tailwater channel is prone to deformation, which in turn has a considerable influence of the hydraulic properties of the current.

I.V. Yegazarov proposed a formula for the average travelling speed of the wave in a slow-changing non-stable regimen in a prism-section channel:

$$\overline{V} = \sqrt{gT_{ave}}\left(1 + \frac{3}{4} \cdot \frac{h}{T_{ave}}\right) + \overline{V}_0 \quad (2)$$

where: T_{ave} – average initial depth (stabilised regimen); h – wave height, V_0 – average initial current velocity.

There is a fundamental differentiation between the wave travelling velocity and the water flow rate proper in a non-stabilised movement regimen. Field and laboratory investigations by N.I. Makkaveyev (1957) confirmed that the velocity of a wave front is considerably different from the water flow velocity within the body of the wave (Table 1).

Table 1. Hydraulic characteristics below hydropower plant

Distance from hydropower plant [km]	0.20	4.00	12.10	31.10	46.10	77.50
Wave crest velocity [m·s^{-1}]	0.56	1.61	2.90	1.96	1.20	0.85
Average current velocity [m·s^{-1}]	0.42	0.64	0.76	0.79	0.78	0.82

The quoted data show that the velocity of the daily outfall wave near the hydropower plant is much higher than the average current velocities, which difference diminishes with the growing distance from the hydropower plant.

A comparison of Makkaveyev's results with results of Yegazarov's formula shows that the calculated wave velocity is nearly twice as high as that observed in a laboratory. The difference may be explained by the fact that in one of the estimations the wave velocity was considered in a smooth prismatic channel with rectangular section. It is obvious that at the crest of the outfall wave water level increases, as does channel depth. Taking into account the longitudinal profile of a flattened-out outfall wave along the tailwaters and a relatively low intensity of the discharge changes at the hydropower plant, the zone of increased depth and its timing may be of significance. In spite of this, the actual wave speed turns out to be entirely comparable with the speed of cargo ships on the navigationally complicated shallow stretches. This circumstance ought to be used in steering large ships along the hydropower plant tailwater at the time of depth deficit when the water level is low.

To assess the Volga's navigation capacity on the tailwaters of the Nizhny Novgorod hydropower dam water level behaviour was investigated at the time of passage of the outfall wave. Field observations were used to calculate the coordinates of the curves of free water surface at the design average daily discharge of 1100 $m^3 \cdot s^{-1}$ (Table 2). Momentary

Table 2. Water levels below the hydropower plant

Observation hour	Water level readout, distance from the hydropower plant		
	6 km	18 km	26 km
0	66.85	66.09	65.58
4	66.41	66.07	65.34
8	66.42	66.07	65.06
12	67.33	66.17	65.06
14	67.66	66.69	65.27
16	67.28	66.90	65.66
20	66.95	66.15	65.76

positions of the free water surface curve were presented along the tailwater longitudinal profile (Figure 2). A adequately rapid increase in the water level during the first part of the day gives way to a more gradual reduction later on.

After earlier extensive dredging the difference in depth between the shallows and short intermittent trenches has been reduced. The river channel was properly 'channelled'. Taking this particular feature into account the location of the planned channel bottom with the approved navigation depth of 3.5 m was presented along the longitudinal profile (Figure 2).

This location of the channel bed, formed as a result of earlier dredging for navigation, corresponds to the current navigation situation. During 'disaster' water levels, which can

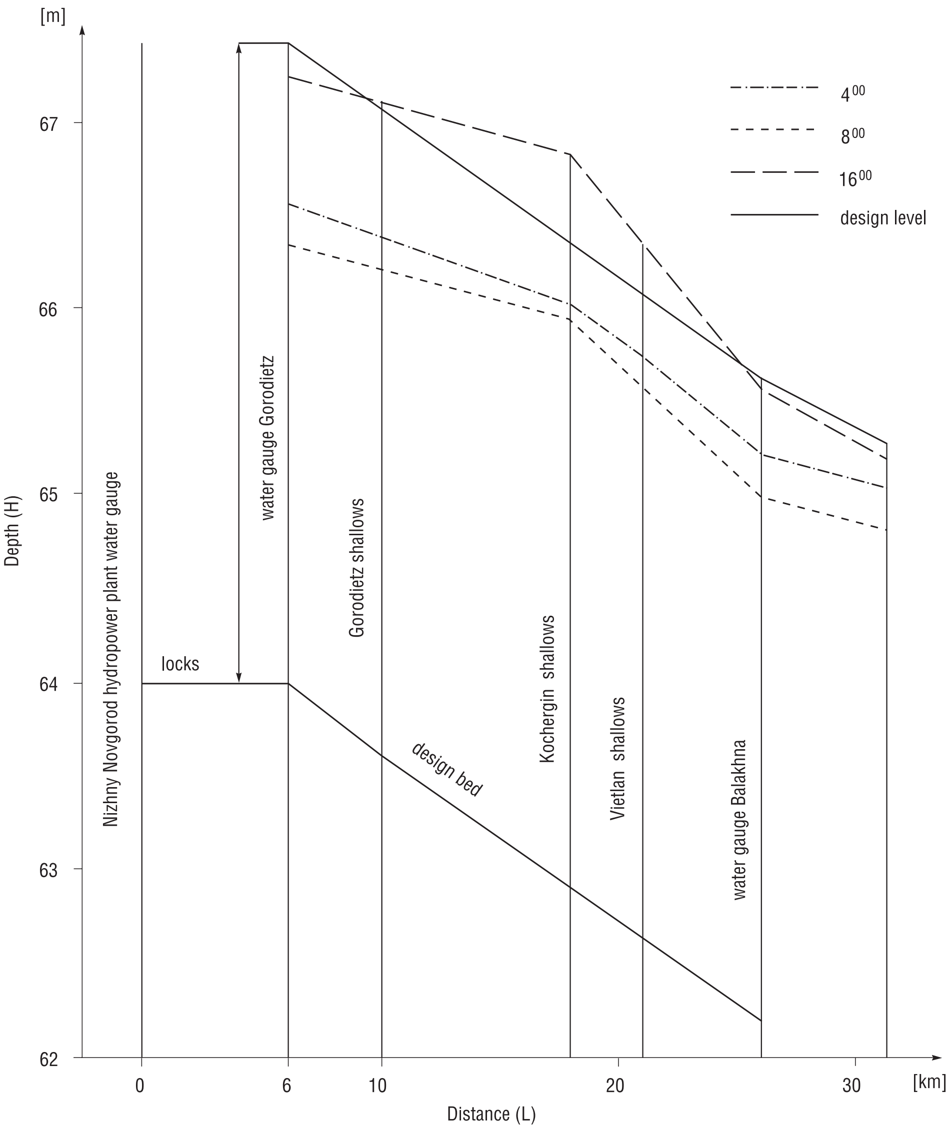

Figure 2. Free water levels at the average mean daily discharge of 1100 $m^3 \cdot s^{-1}$ (30 September 1999)

drop by one meter from the design level, the depth can be as low as 2.6 m at certain times of the day.

By defining a stable channel bed design and specific levels of water surface at particular times, navigation depth projections can be made taking into account their changes along the reach and in time (Table 3).

Table 3. Variations of navigation depth below hydropower plant

Distance from hydropower plant [km]	Depth for navigation at certain times of the day [cm]							
	8^{00}	12^{00}	14^{00}	16^{00}	18^{00}	20^{00}	22^{00}	24^{00}
6	260	330	340	350	320	300	300	300
18	320	320	350	390	350	320	310	310
22	300	310	340	380	350	330	320	320

The duration of a certain depth, as well as the depth itself, can also be estimated by analysing the changes of the free water surface curve during a 24-hour period. It was established that the greater the depth to be evaluated the shorter its duration. For example the design depth of 350 cm at the design discharge through the hydropower plant is only maintained near the locks for two hours in every 24-hour period.

With a growing distance from the hydropower plant the influence of the fluctuating outfalls from the dam on the water level and on depth patterns somewhat evens out and the duration when the depth is maintained increases to reach four hours at 18-20 km from the hydropower plant.

This navigation situation is determined by the river channel deformations along the tailwater caused by considerable channel bed erosion. The actual duration of various depths is illustrated in the chart (Figure 3).

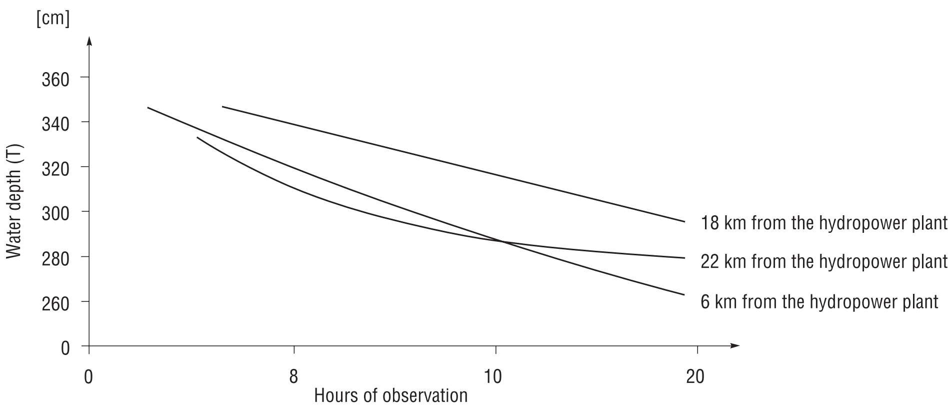

Figure 3. Water depth duration

4. Conclusions

The results of the investigations of the Nizhny Novgorod hydropower dam tailwaters on the River Volga were recommended for use in an operational assessment of the navigation conditions on this reach and for the dispatcher control of large ship movement.

References

Fyodorov G.F. (Фёдоров Г.Ф.), 1966, *Волновые явления и особенности плавания в нижних бьефах гидроузлов*, Транспорт, Москва.

Makkaveyev N.I. (Маккавеев Н.И.), 1957, *Русловые процессы и путевые работы в нижних бьефах гидроузлов*, Труды ЦНИИЭВТ, 12.

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