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Dynamics of the water of the Volga section of the Rybinsk reservoir during winter

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DYNAMICS OF THE WATER OF THE VOLGA SECTION OF THE RYBINSK RESERVOIR DURING WINTER /100*

A.S. Litvinov and K.A. Bakulin

In connection with the study of the currents of the Rybinsk Reservoir, the Hydrology Laboratory of the Institute of the Biology of Internal Waters, Academy of Sciences of the USSR, collected and published a certain amount of material on the unestablished regime of the currents in the tail-water of the Uglich Hydroelectric Station (Butorin and Bakulin, 1963; Butorin and Litvinov, 1963). Subsequent observations and special studies, carried out in April, 1963, now enable a more detailed description to be made of the character of the dynamics of the water in this region, in the presence of an ice cover. Inasmuch as the basic aim of the research was to the study of the regime of the currents, the greatest part of the effort was devoted to the change in current velocities along the length of the Volga reach of the reservoir, related to the daily regulatory work of the hydroelectric station.

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* Translator's note: The number in the margin refers to the page number of the original text.

HYDROLOGICAL AND MORPHOMETRICAL CHARACTERISTICS OF THE STUDY AREA

The Volga reach of the Rybinsk Reservoir consists of the tail-waters of the Uglich Hydroelectric Station and represents the well expressed river valley of the Volga. The general direction of the valley is from the south to the north. The boundary of the reach passes along the line Dubets-Rozhnovskii Cape. In accordance with its morphometrical features, the reach may be divided into three sections, the basic characteristics of which are presented in Table 1.

Table 1

The main morphometrical characteristics of the Volga reach of the Rybinsk Reservoir

No of section	With normal back-water level					With 3.5 m lower than normal back-water level (Apr. 1963)				
	Length: km	Area km^2	Mean depth, m	Depth in fairwater: m	Volume km^3	Length: km	Area km^2	Mean depth, m	Depth f'wtr.: m	Volume km^3
1	55	73.6	5.4	14.5-21.5	0.396	55	32.7	6.7	11-18	0.22
2	35	220.2	4.2	19.5-21.5	0.929	35	98	4.2	16-18	0.41
3	17	256.2	5.1	21.5-28.5	1.301	17	151.6	3.8	18-25	0.58
Total	107	550.0	4.8	14.5-28.5	2.626	107	292.3	4.2	11-25	1.21

The width of the first section, with normal back-water levels changes from 500 m in the upper part to 2 km in the lower. The right bank of the Volga is steep and cliff-like, and it constitutes the main bank of the Volga. The left bank is sloping and it consists of the flooded portion of the valley of the Volga. In the lower part of the section the width of the inundated flood-lands is as much as 800 m.

The second section is characterized by a greater width, which increases from Glebovo to Legkovo from 2 to 7 km because of the well-developed inundated left bank flood lands, the width of which reaches 5 km. The steep right bank is subject to wearing away, and the low-lying left, to being boggy. A series of islands are situated in the central and lower parts of the section (Radomskii, Khokhotinskii, Koprinskii, Tryas'e and Shumorovskii Islands). /101

The third part of the reach consists of a bay of about 15 km width, which is directly bounded by the central part of the reservoir. The bottom relief is complex. A significant part of the area is occupied by shoal waters with a depth of 2-3 m.

The Volga reach receives a number of creeks and rivers, information on which is given in Table 2.

Table 2

Hydrographical net of the Volga reach

Tributary	Inflow bank	Distance from hydroelectric station, km	Area of reservoir, km^2
Korozhechna	Left	4.5	1730
Yukhot'	Right	35	1810
Uleima	"	35	716
Sutka	Left	70	552
Il'd'	"	70	243

Methodology of observations

Observations with respect to the elements of the currents in the Rybinsk Reservoir, and in particular in the Volga reach, were commenced in 1954 by the Hydrology Laboratory of the Institute of the Biology of Internal Waters of the Academy of Sciences of the USSR. The methods employed and the results of these studies have been published in papers by N.V. Butorin and K.K. Edel'shtein (1961), N.V. Butorin and A.S. Litvinov (1963) and N.V. Butorin and K.A. Bakulin (1963).

In organizing the research of the dynamics of the waters of the Volga reach in April of 1963, on the basis of preliminary surveys of the area, three hydrometric ranges were marked put (fig. 1). The location of the ranges was carried out in accordance with the following considerations: 1) anticipation of the influence of the morphometrical features of the reach on the transformation of the discharge wave; 2) allowance for lateral tributary inflow.

Hydrometric range No. 1 was situated 33 km from the Uglich Hydroelectric Station, near the settlement of Myshkino. The river-bed in the area of the range is straight, trapezoidal in form with a weakly expressed asymmetry. Marked out on the range were five velocity verticals, the locations of which, in transverse section, were at even intervals and with due regard for the nature of the changes in bottom relief.

Range No. 2 was located 22 km below Range No. 1, at Yur'ino. The channel in the area is straight and the transverse profile is of a symmetrically trough-shaped form. Five velocity verticals were marked out.

Range No. 3 was situated at Koprino, 17 km below Range No. 2, and it was co-located with the hydrometrical range on the transit Borok-Koprino, the site at which, for many years, hydrological and hydrobiological research had been carried out by the institute. In view of the complexity of the transverse profile, and to ensure that the most accurate determination could be made of the outflow of water, eleven velocity verticals were established for the range.

The measurement of the outflow of water at all the ranges was carried out synchronously on 16 April, 1963, when the level of the water in the reservoir was 3.5 m lower than the normal back-water level. Altogether, 12 outflow measurements were made, with up to 30 minutes time being expended on each measurement. The measurements were timed to obtain the outflow occuring at 1100, 1200, 1300 and 1400 hours. Depth measurements, measurements of the thickness of the ice, the calculation of the working depths at the verticals and the subsequent calculation of mean velocities and outflows of water were carried out in accordance with the practices of hydrometry.

Utilized to establish the characteristics of the levels regime were the results of observations made at the water measuring stations of the Hydrometeorological Service, at the settlement of Myshkino, the village of Koprino and at Cape Rozhnovskii.The hourly level in the tailwater of the Uglich Hydroelectric station and the outflow of water was obtained directly from the station. The reliability of the figures on the flow through the station raises no doubts, since the accuracy of the calibration of the turbines is evaluated to be within 1-2% (Gavrilov, 1963).

WATER WORKING REGIME AT THE UGLICH HYDROELECTRIC STATION /102

The discharge of water through the Uglich water control point is normally carried out through the hydroelectric station, the maximum discharge capability of which is 1100 m^3/sec. Besides this, if necessary, the release of water can be carried out through a concrete overflow weir, the overall discharge capacity of which is 11,750 m^3/sec. During the navigation season a porion of the water enters the lower reaches through the operation of a one-chamber lock.

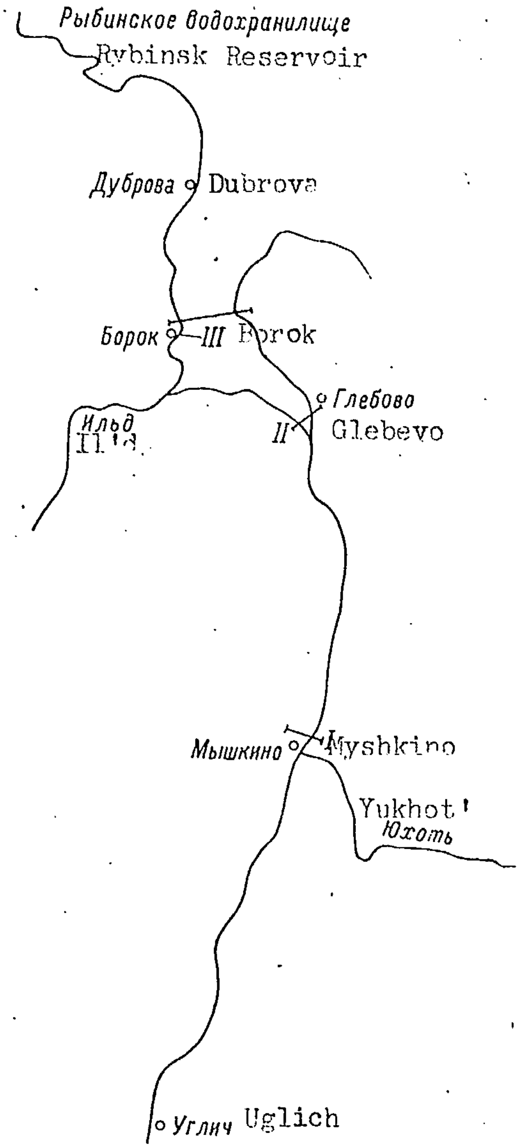

Fig. 1. Location of hydrological sections.

The average annual flow of water past the Uglich Hydroelectric Station range, during the first years of the existence of the Rybinsk Reservoir, consisted of 360 m^3/sec (maximum 471 and minimum 309 m^3/sec). In the years following (from 1948 to 1963), the average annual flow of water consisted of 394 m^3/sec (9.4% higher than the flow figure given in the work of Byurig)* and varied from 244 to 610 m^3/sec.

Since the volume of the Uglich Reservoir is not large by comparison with the volume of the annual average outflow (the working volume of the reservoir is 0.809 km^3, the average annual volume of inflow is 13.5 km^3, so that the coefficient of the volume is equal to 0.06), and since the reservoir does not accomplish a full seasonal regulation

* Translator's note: Transliterated.

of the outflow of the Volga, the variations of the average annual outflow through the Uglich Hydroelectric Station basically reflect the process of the inflow into the reservoir.

Thus, the volume of water discharged through the station depends, in the long run, on the wetness of the year.

The regime of the disharge of water through the Uglich station during the course of the year is characterized by its considerable instability, and depends on the reserves of water, weather forecasts and the coverage of energy consumption loads (Balagurov, 1957). The average monthly discharge through the station varies within the limits of 4.3 to 30.3% of the annual discharge. During the fall-winter period the average discharge consists of 5.2-6.7% of the annual. In the individual years considerable variations are noted in the distribution of discharges during the year, which, in the main, are related to the hydrometeorological conditions of the year.

In addition to the annual and monthly variations in the discharge /103
of water, the unevenness of flow through the Uglich center during the day has a strong influence on the hydrodynamic regime of the tail-water of the hydroelectric station. Inasmuch as the operating regime of the station depends on meeting the demands of the electrical network (Balagurov, 1957), and since the energy requirements vary widely during the course of a day, the hourly passage of water through the hydroelectric station is extremely uneven.

During the fall-winter period (from September to February) the hydroelectric station works at peak capacity, due primarily to the inflow

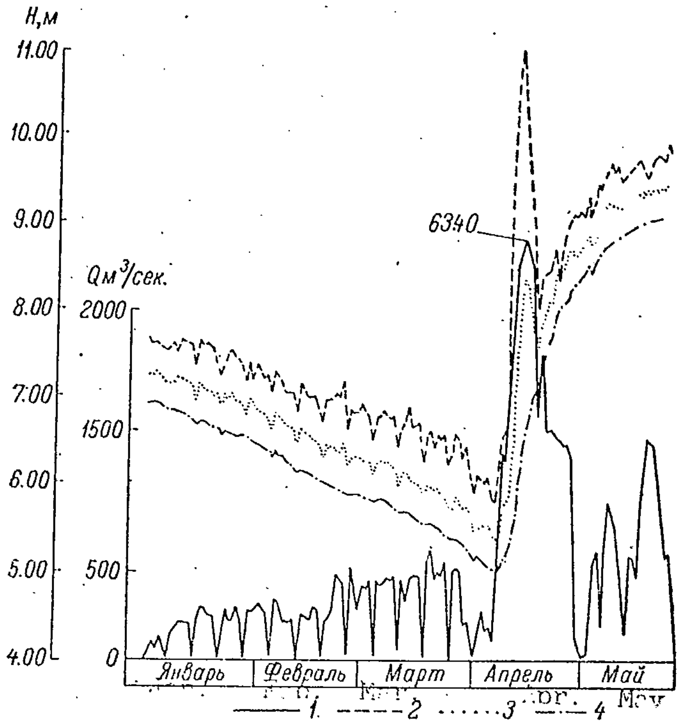

Fig. 2. Chronological graph of the changes in the level of the Volga reach and the expenditure of water through the Uglich Hydroelectric Station.
1 - average daily expenditure of water through the Uglich HES;
2 - average daily level in the tail-water of the HES;
3 - average daily level at Myshkino;
4 - average daily level at Koprino.

and partial working off of the reservoir.The average daily discharges vary from 200 to 400 m^3/sec. The duration of operation of the hydro-elctric station consists normally of 2.5-4 hours. With the commencement of operation of the Uglich Hydroelectric Station, the amount of water worked off into the tail-water grows, in a short period of time, from 4 (expenditure of water on filtration) to 1100 m^3/sec (expenditure at full load). In the middle of March operations begin to prepare the Uglich Reservoir for the passage of high water, and it is discharged to the limit mark, depending on the forecasts of the spring high-water floods.

In connection with this the duration of the operation of the hydroelectric station increases to 12-18 hours per day. The average daily expenditures of water grow to 500-800 m^3/sec.

The daily alteration of the maximum and minimum discharges is disturbed on the non-working days when the hydroelectric station does not work as a result of the decrease of the load in the electric power system. The entry of water into the tail-water on such days is determined, during the winter period, by filtration or by small non-working discharges. The days of minimal discharge are readily noted on the hydrograph of the average daily expenditure of water through the Uglich Hydroelectric Station for the year 1963, presented in fig. 2.

In April of 1963, observations were made during the period in /104
which the Uglich Reservoir was being prepared for the processing of the spring high-water flood. From 1 to 16 April the average daily discharge of water through the hydroelectric station increased from 130-160 to 500-530 m^3/sec, and on 17 April, the discharge of the spring high water began through the Uglich centre. On 16 April, the hourly expenditure of water through the station varied from 390 to 884 m^3/sec. The average daily discharge consisted of m^3/sec.

Water levels

The water levels regime of the Volga reach of the Rybinsk Reservoir is basically determined by the working of the water by the Uglich water control complex. This relationship is most clearly notable during the winter period, when there is practically no variation in the level related to the action of the wind on the water surface. In connection with the fact that on Sundays the hydroelectric station does not operate due to the decrease of the load in the electrical distribution system, periodic decreases in the level of the Volga reach resulting from the emptying of the reach are clearly observed against the background of the general lowering of levels. The amplitude of these fluctuations at the Uglich Hydroelectric Station reach 40-50 cm (fig. 2). With increasing distance from the station this influence on the fluctuations of the level gradually diminishes, and in the vicinity of Myshkino their amplitude consists of 20-25 cm, while at Koprino (70 km from the hydroelectric station), it does not exceed 5-10 cm.

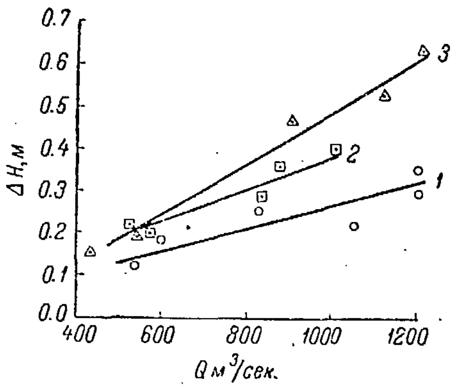

Fig. 3. Dependence of the height of the direct positive wave at the Uglich HES on the discharge and and the level of water in the tail-water.
1-where level of tail-water is 1.8 m below normal backwater level; 2-... 2.6 m below NBL; 3-.... 3.1 m below NBL.

Clearly detectable in the Volga reach, besides the weekly fluctuations, are intra-diurnal fluctuations in the level which are caused by the passage of discharge waves generated by the daily regulation of releases of water through the Uglich Hydroelectric station (Litvinov, 1968). Long waves, generated in the tail-water of the hydro-electric station as a result of the release of water through it, depending on their direction of movement, are usually divided into direct (moving with the current) and reverse (moving against the current, and depending on their form, are divided into positive (rising waves) and negative (falling waves) (Egiazarov, 1937; Arkhangel'skii, 1947).

On discharge, the expenditures of water through the Uglich Hydroelectric Station, during the winter period, can change from 4 to 1100 m^3/sec over a short space of time, and this leads to the occurrence, in the tail-water, of a direct, positive wave. The intensity of the rise in the level, within the first hour after the commencement of the discharge, may reach 50 cm. The subsequent stabilization of the expenditure through the station results in an insignificant rise in the level due to the filling of the tail-water. Figure 3 shows the dependence of the height of the direct, positive wave at the Uglich Hydroelectric Station on the size of the discharge and the level of water in the tail-water. To avoid the effects of the superimposition of waves in developing this relationship, use was made of only the first discharges after the Sunday break in the work of the hydroelectric station, when the level in the tail-water prior to the discharge could be considered as being near to the average level of the reservoir. From the graph it can be seen that the height of the wave increases with the lowering of the level of the tail-water (the level of the Rybinsk Reservoir) and with the increase in the amount of water being discharged, varying from 0.15 to 0.60 m.

The positive wave flattens as it spreads down the tail-water, /105 due to forces of resistance and friction on the one hand, and the increase of the area of the water section on the other, and this results in a significant decrease in its height and a smoothing out of its profile. Because of this the fluctuations of the level at the Koprino range are considerably smaller than at the hydroelectric station and are displaced in phase. The onset of the maximum and minimum levels at the Koprino range lags by 1-3 hours by comparison with the extremes of the levels at the Uglich Hydroelectric Station. With further distance from the hydroelectric station there is an increase in the shift of the time of the onset of maximum and minimum levels and in the duration of their action. In the vicinity of Cape Rozhnovskii (about 100 km from the hydroelectric station) the fluctuations of the level are to be noted only in extreme cases.

Having passed down the Volga reach, the direct, positive wave is reflected from the water mass of the central part of the reservoir (the reflection occurs in the vicinity of Cape Rozhnovskii-Zonal'naya) and then moves upward through the reach in the form of a reverse, negative wave[1].

During a period of decrease of the load on the electrical distribution system, a second perturbation occurs at the hydroelectric station, generated by the sharp decrease in water expenditure, which results in the formation of a direct, negative wave. The level of the water first falls rapidly and then starts to decrease more slowly, commensurate with the emptying of the reach. On the approach to the hydroelectric station of the reverse, negative wave, an additional lowering of the level occurs and a second direct, negative wave is generated. The reflection of both of these waves from the water mass of the central part of the reservoir results in the formation of two reverse, positive waves which, on reaching

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1 On the reflection of a wave from the water mass of a large body of water, the wave changes its sign (Grushevskii, 1962).

the hydroelectric station, cause a rise in the level at the Uglich water measuring station.

Thus, the movement of waves in the tail-water of the hydroelectric station, generated by an individual discharge, forms a full wave cycle, consisting of the following waves: a direct, positive wave; a reverse, negative wave; two direct, negative waves; and two reverse, positive waves. In the event of an absence of subsequent forced perturbations, made necessary by the operations of the hydroelectric station, the next cycle begins with a direct, positive wave. The wave cycle may be most clearly observed during the period of the Sunday decline in the load on the hydroelectric station, when, in the vicinity of the hydroelectric station, the fluctuations of the levels may be followed through three cycles. At the Koprino range however, only the first and second cycles are particularly noticeable (Litvinov, 1968).

The velocity of wave distribution in the Volga reach of the Rybinsk Reservoir, in the section Uglich-Koprino, consists of about 10 m/sec (Litvinov, 1968).

In the course of the daily regulation of discharges of water through the Uglich Hydroelectric Station, as a result of the superimposition of waves, the pattern of the fluctuation of the levels becomes considerably more complex, while the amplitude of the fluctuations at Uglich may increase to 1 m. At the Koprino range the fluctuation of the level, as a rule, does not exceed 0.2 m.

The most notable changes in the level of the Volga reach of the Rybinsk Reservoir are observed during the period of the passage

of spring high-water floods. Since the average daily discharge of water through the Uglich Hydroelectric Station increases by 10-15 times during this period, the rate of the rise of the level of the hydroelectric station tail-water may reach 260 cm/day, while the rise of the mean level of the reservoir, during this period of filling, rarely exceeds 20-30 cm/day, and only in exceptional circumstances reaches 70 cm (Butorin and Litvinov, 1963). As a result of this, significant short-term rises are observed in the Volga reach. Thus, in the second ten-day period of /106
April, 1962, the level at Uglich rose by 5 m during a period of five days (from 10 to 15 April), while the level of the reservoir, during the same period, rose by only 97 cm. The excess of the level at Uglich over the level of the central part of the reservoir, at the moment of its maximum rise, consisted of 4.03 m. During the low-water year of 1963, the excess of the maximum level at Uglich over the level of the central part of the reservoir, at time of passing spring waters, was considerably less and consisted of 1.69 m.

The duration of sharp rises in the level normally is 3-5 days. With the decrease of discharges of water through the station in the course of a like period of time, the level falls rapidly (fig. 2). The magnitude of the decrease in the level at the city of Uglich in high-water years may be as much as

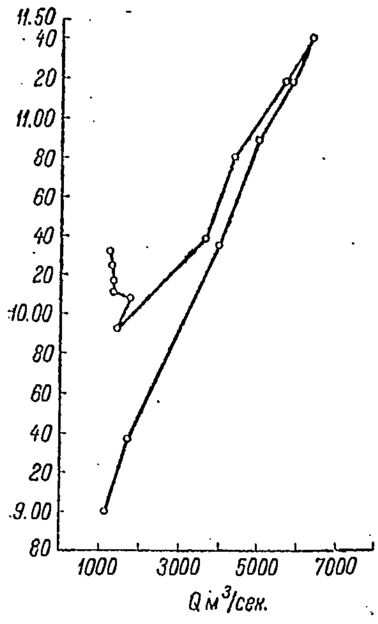

Fig. 4. The curve Q=f(H) in the tail-water of the Uglich HES during the period of passing spring high-water floods.
Ordinate - level, m.

3 m, after which it again rises as a result of the continued filling of the reservoir. The rise and fall of the level of the Volga reach, as described above, is followed at the water measuring stations at Uglich and Myshkino. Relative to this, at the time of maximum discharges through the hydroelectric station in high water years and years of average wetness, the level at the city of Uglich may be significantly higher than the maximum full level of the reservoir. The alteration of levels at the water measuring station at Koprino reflects more the character of the rise of the mean level of the reservoir (Butorin and Litvinov, 1963).

Figure 4 presents a graph of the relationship Q=f(H) for the region of the Uglich water control centre for the period of the passage of the spring high-water floods for the year 1962. From the graph it can be seen that during the rise in the level and during the initial period of fall, a phenomenon which is customary in the case of high-water freshets is to be observed, that is, the same volumes of water pass through when the levels are low as during a fall in the level. With a decrease of the discharge of water through the hydroelectric station the curve for the fall diverges from the curve for the rise (as distinct from uncontrolled rivers), and at discharges of 1200-1600 m^3/sec and a tail-water level approximately 2 m lower than the normal back-water level, the relationship between the levels and the expenditures of water is disturbed. The subsequent change in level then reflects the overall filling of the Rybinsk Reservoir.

Inclination of the water surface

In the Volga reach of the Rybinsk Reservoir permanent inclinations of the water surface are lacking. Since the tail-water of the Uglich

Hydroelectric Station is under the influence of the head of water of the reservoir throughout the course of the year, the level in the Volga reach remains horizontal and coincident with the mean level of the reservoir in the absence of external perturbing forces.

The main external forces which disturb the dynamic equalibrium of the level and result in the formation of longitudinal gradients in the reach, are the discharges of water through the Uglich Hydroelectric Station and the action of the wind on the water surface. In winter, when the surface of the water is isolated from the direct action of the wind by ice cover, the main cause of the formation of longitudinal gradients is the periodic discharge of water through the Uglich Hydroelectric Station.

With the development of the direct, positive wave at the moment /107
of water discharge, as a result of the rapid rise in the level, the formation takes place of positive gradients in the water surface (directed in the direction of the normal inclination of the Volga current). The maximum magnitudes of the positive gradients occur at the time of passage, at the Uglich water measuring station, of the crest of the direct, positive wave.

With the cessation of discharges and the development of the direct, negative wave, a rapid fall of the level at Uglich occurs which leads to the formation, in the Uglich-Koprino section, of a negative gradient, directed opposite to the normal inclination, the magnitude of which increases with the approach to the hydroelectric station of the reverse, negative wave.

The subsequent decrease in the negative gradients and their transformation into positive occurs on the approach to the hydroelectric station of the reverse, positive wave, and it is during the passage of the crest of this wave that the positive gradients reach their greatest magnitude. Thus, positive gradients are to be observed in the Volga reach during the passage of positive waves (rising waves), and negative, during the passage of negative waves (falling waves). Diagrammatically presented in figure 5, are stop-action longitudinal profiles of the

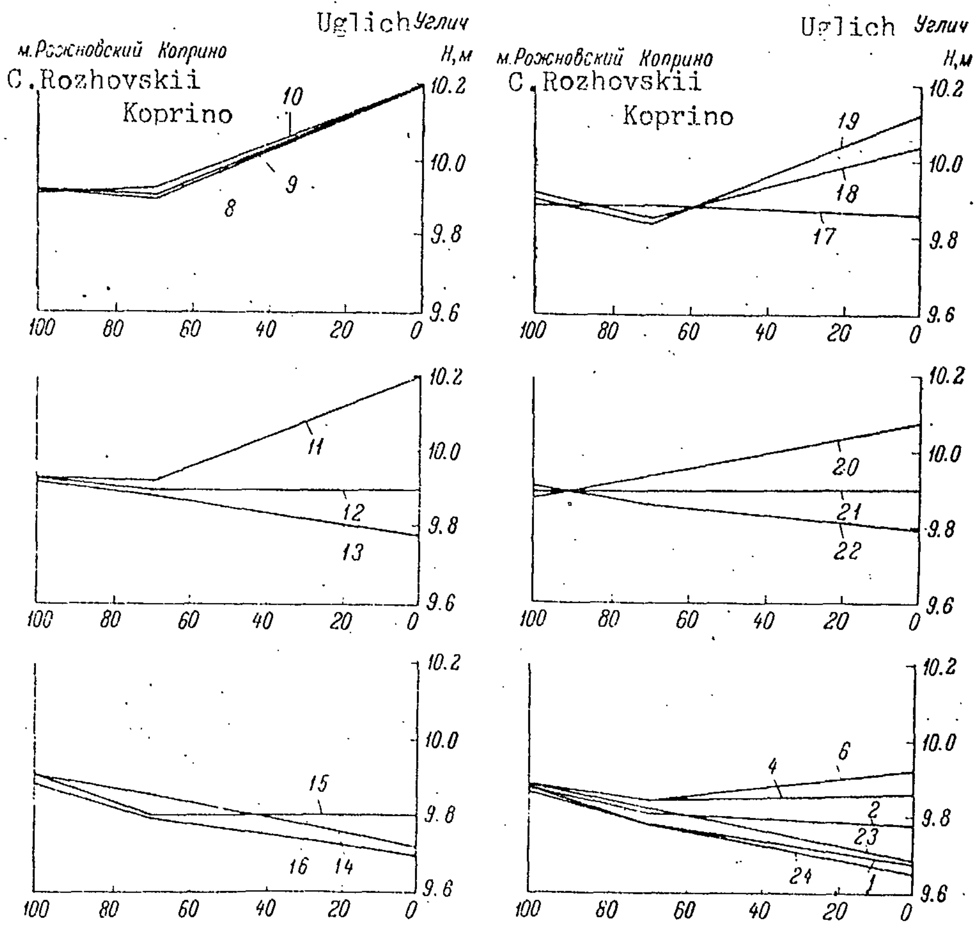

Fig. 5. Diagrammatic stop-action profiles of the water surface in the Volga reach, from 0800 hours, 25 January to 0600 hours, 26 January, 1963. Figures on curves - hours of the day.

surface of the water in the Volga reach of the reservoir. The time span between two maximum values of gradients of the same sign, in the absence of further discharges (for example, on Sundays), is equal to the period of a full wave cycle and, on the average, consists of 10 hours (Litvinov, 1967). /108

The absolute value of the maximum positive and negative gradients depends on the measure of the level in the reservoir and the magnitude of the water discharges, and changes in the course of the winter from 0.005 to 0.008°/oo and from 0.002 to 0.005°/oo respectively. Towards the end of the winter period, due to the lowering of the level of the Volga reach resulting from the winter usage of the water of the Rybinsk Reservoir, a tendency is noted towards an increase in the gradients of the water surface for discharges of the same magnitude. Thus for example, the curve connecting the minimal corresponding levels between the station of Koprino and Uglich (fig. 6)shows that, during the course of the winter, the average excess of the minimal level at Koprino over the minimal level at Uglich consists of about 10 cm. With a lowering of the level in the Volga reach to 9.3 m and lower, the difference in the corresponding levels increases.

The maximum gradients in the water surfaces of the Volga reach of the reservoir are observed during the period in which the spring high-water floods are being passed through the Uglich Hydroelectric Station. As it has already been noted, the surface of the water is constantly distorted during this period as a result of the intensive discharge of water. The duration of this period depends mainly on the wetness of the year and on the average is of 10-15 days (Table 3). The magnitude of the gradient during the period of maximum discharges of water through the hydroelectric station in high water years may reach 0.05-0.06°/oo, that is, exceeding the gradients caused by normal discharges by 7-8 times. In low water years, on the other hand, the maximum gradients normally do not exceed 0.02-0.03°/oo.

Comparing the gradients of the surface of the water in the sec- /109
tion Uglich-Koprino, occurring in the course of the daily regulatory work of the Uglich Hydroelectric Station with the every day inclinations of the River Volga in this same section, we see that, as a result of the significant increase of the level after the filling of the Rybinsk

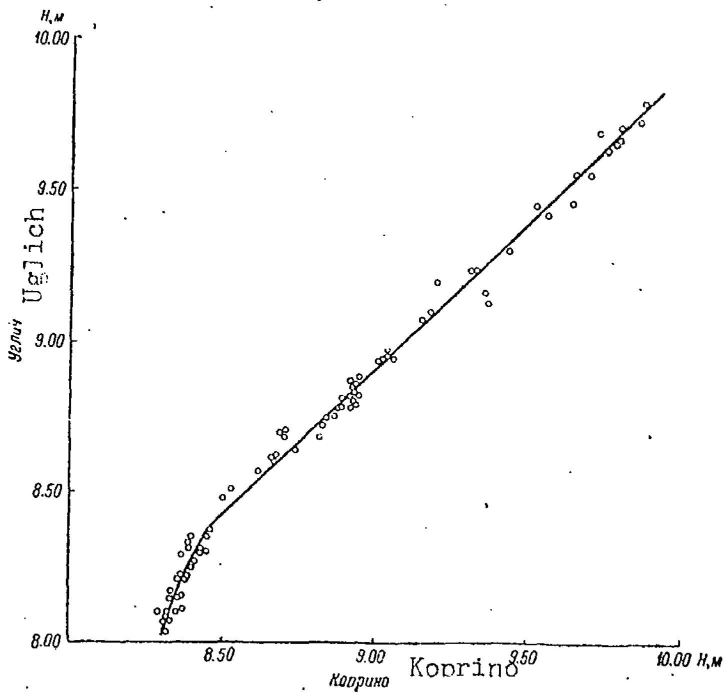

Fig. 6. The curve of minimal corresponding levels between the stations at Koprino and Uglich.

Table 3

Average daily longitudinal gradients of the water surface in the section Uglich-Koprino

High water year 1962		Low water year 1963		High water year 1936		Low water year 1937	
Date	Grad. °/oo	Date	Grad. °/oo	Date	Grad. °/oo	Date	Grad. °/oo
5 IV	0.001	15 IV	0.006	10 I	0.083	10 I	0.073
10 IV	0.009	20 IV	0.009	20 II	0.074	20 II	0.071
15 IV	0.052	22 IV	0.024	10 IV	0.091	20 III	0.072
16 IV	0.043	24 IV	0.015	20 IV	0.113	30 III	0.092
18 IV	0.017	26 IV	0.004	30 IV	0.061	1 IV	0.094
20 IV	0.003					10 IV	0.075

Reservoir, the maximum positive gradient is 10 times smaller than the normal, at a time when the expenditure of water on discharge through the hydroelectric station, during the winter period, increases by 8-10 times in comparison with the normal. Only during the passage of the spring high-water floods in high water years do the maximum gradients (in the section) approach the magnitude of the ordinary gradient, though 1.5-2 times smaller than the ordinary gradient observed in high-water floods.

Currents

Observations in the Volga reach, conducted over a period of years, have shown that the currents in this section of the reservoir have a periodic character (Butorin and Litvinov, 1963). Their regime is determined, in the main, by the working expenditure of water from the Uglich Reservoir. Since the discharges of water through the Uglich

Hydroelectric Station have sharply expressed seasonal variations, the regime of the currents also varies significantly throughout the course of the year. Inasmuch as the surface of the water is isolated by ice cover from the direct action of the wind in winter, and since the Uglich Reservoir is worked intensively during the period, only outflow currents occur in the Volga reach.

Studies have indicated that the maximum current velocities occur in the region of the Uglich Hydroelectric Station and that these gradually diminish with increasing distance from it. The decrease in current velocities takes place primarily because of the increase of the water section. The absolute magnitude of the velocity of the current depends on the expenditure of water through the Uglich Hydroelectric Station and it varies widely. With discharges of water through the hydroelectric station of 1100-1200 m^3/sec the maximum current velocities along the length of the reach consisted, in March of 1963, of 45 cm/sec at Myshkino, 35 at Yur'ino, 30 at Koprino and 10 cm/sec at the outlet of the Volga flow into the central part of the reservoir at the former city of Mologa. The fact of the considerable weakening of flow with distance from the hydroelectric station is also evidenced by the fact that at 70 km and lower, discharges with maximum expenditure rates of up to 400 m^3/sec no longer generate noticeable velocities of current.

The peculiarities of the regime of the currents in the Volga reach of the reservoir can be readily observed from the data of the synchronous surveys carried out throughout the length of the reach in 1963, and which are presented in figure 7.

With the commencement of the discharge of water and the formation of a direct, positive wave, noticeable current velocities also appear in the Volga reach. Relative to this fact, the current does not /111 occur throughout the length of the reach at the same moment, but rather after a time lag which increases with the increase in the distance from the hydroelectric station. The magnitude of this time lag depends on the velocity of distribution of the wave. Thus for example, noticeable velocities of current in the region of Myshkino appear 1 hour after discharge, at Koprino, after 2-3 hours.

The duration of the existence of a current in the Volga reach depends on the duration of the discharges of water through the hydroelectric station. With increasing distance from the hydroelectric station, a measure of increase in the duration of the existence of the current occurs. This condition is due to the fact that the discharge wave flattens with increasing distance from the hydroelectric station and the same volumes of water take longer to pass through any given range. With average durations of discharge of 1-4 hours at the beginning of winter, the duration of the current at Koprino consists of 1.5-5 hours. During the period of the pre-spring working of the Uglich Reservoir, in its preparation for the passage of spring high-water floods, the duration of the discharges of water increases. Accordingly, commencing in March, the duration of the current increases to 6-8, and on individual days, to 18 hours (fig. 7). As a rule when the duration of the current exceeds 10 hours, two peak maximum velocities are observed, as a result of the changes in the expenditure of water through the

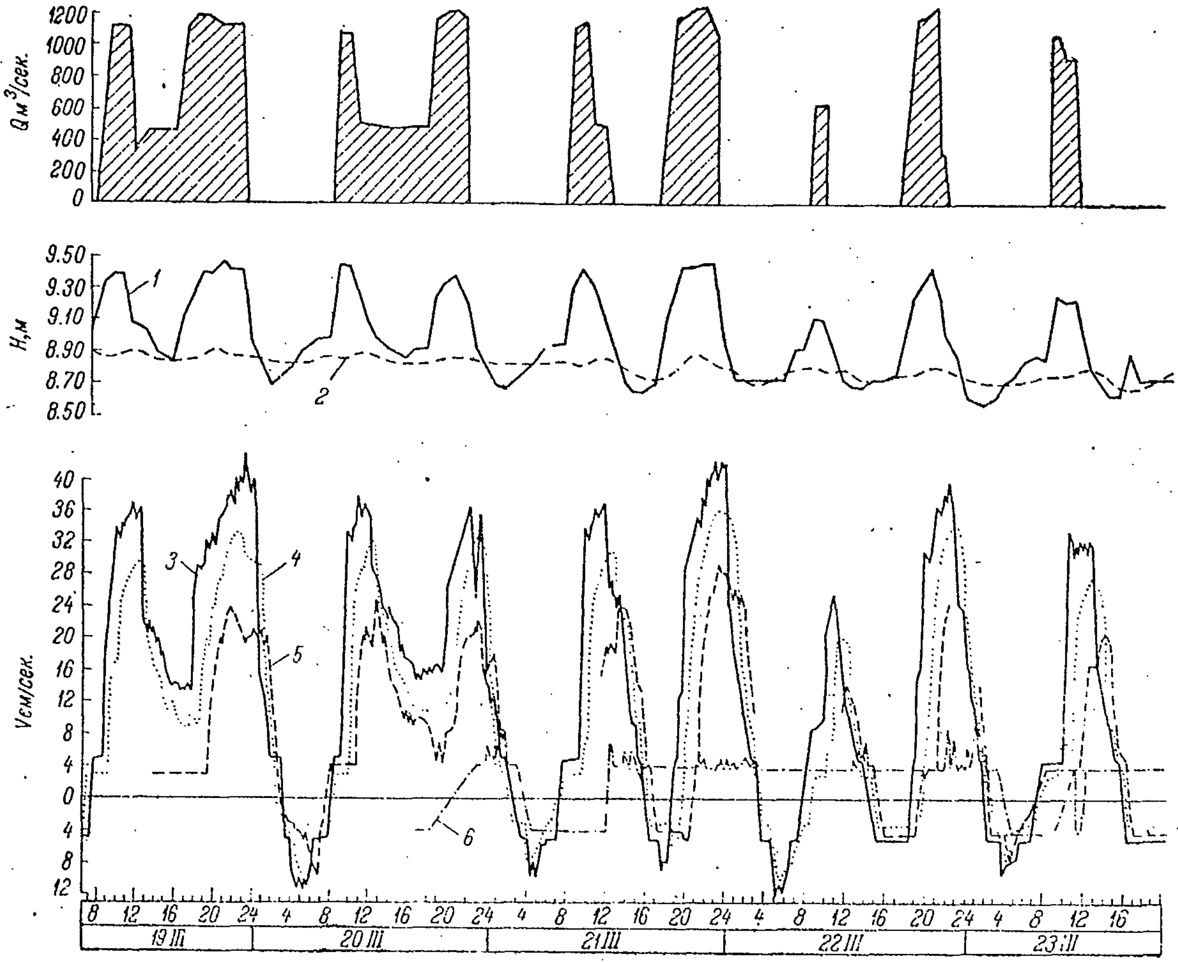

Fig. 7. Composite graph of the changes of the levels and current velocities in the Volga reach and the expenditures through the Uglich GES, from 19 to 23 March, 1963.

1 - change of the level at Uglich; 2 - change of the level at Koprino; 3 - current velocity at the river village of Myshkino; 4 - current velocity at Yur'ino; 5 - current velocity at Koprino; 6 - current velocity at the former city of Mologa.

hydroelectric station. In the process of the development of the current during the daily regulation of the discharge of water through the hydroelectric station, and as a result of the superimposition of discharge waves, the time required for the increase of velocities to the maximum is greater, in some cases, than the time span of decrease, and in other cases less.

The absolute magnitude of the velocity of the current in the Volga reach of the reservoir depends not only on the magnitude of the maximum expenditure of water through the hydroelectric station, but also on the level of water in the reservoir and on the duration of the maximum discharge, that is, on the volume of water discharged through the hydroelectric station.

For example, in December-January, 1961/62, as distinct from the data presented for the very same absolute magnitude of maximum discharge rates of water, but for shorter durations and with a higher level of the reservoir, the velocities of the current at Koprino consisted of 12-18 cm/sec. The lowering of the level of the Volga reach as a result of the winter working down of the Rybinsk Reservoir leads to a decrease in the area of the water flow section and to an increase of the gradients of the water surface. Thus, for a decrease in the level of 2 m in the region of Koprino, the area of the water section is decreased by 52% (Table 4).

Besides this, under winter conditions, the surface is covered with a sheet of ice which, for a distance of 70 km from the hydroelectric station, is attached firmly to the shore. For this reason the conditions that occur for the passage of discharge waves are those of a pipe,

Table 4

The change in the area of the water section and the velocity of the flow in the region of Koprino with different levels of the Rybinsk Reservoir

Date	Mean level of the reservoir conventional units	Area of the water section, m^2	Maximum expenditure through the HES m^3/sec	Maximum velocity of current cm/sec
10-12 IV 1960	7.30	7858	1050-1150	32-34
1 IV 1961	9.30	11988	1100	18
19 II 1962	9.50	12441	950-1000	16
30 III 1962	8.20	9743	1050-1200	22-26
1-3 IV 1962	8.80	10906	1050-1200	18-20

in which the ice (as one of the walls) creates pressure conditions which, /112 for the same expenditure of water, vary as the area of the water section changes. Thus, a decrease in the area of the water section, in the face of the same expenditure, will result in the increase of the velocity of the flow.

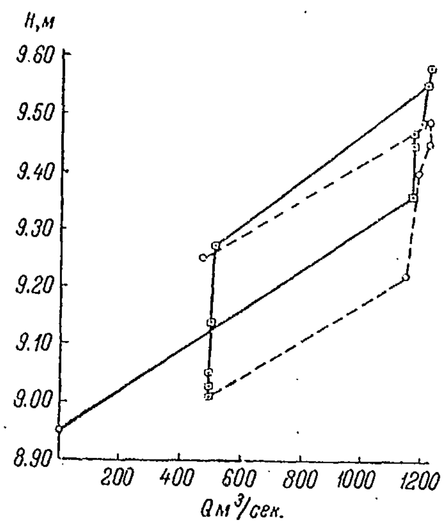

Fig. 8. Curves of Q=f(H) for the tail-water of the Uglich HES, 11 Mar.,1963.

Figure 8 presents the relationship Q=f(H), through hourly levels and expenditures, for one of the discharges of the Uglich Hydroelectric Station. From figure 8 it can be seen that with the commencement of the discharge after the Sunday break in the work of the hydroelectric station and the sharp increase in the expenditures, an intensive rise in the level takes place. Subsequently, with an almost steady expenditure of water through through the hydroelectric station, the level continues to rise noticeably because of the filling of the tail-water. With the decrease of the expenditure of water through the hydroelectric station the level rapidly falls, relative to which, the same expenditures during the fall pass through at a higher level than during a rise, that is, there is a clear expression of the loop which points to the unestablished character of the movement of the water. With the stabilization of the expenditure of the water the level continues to decrease commensurate with the emptying of the tail-water. A subsequent increase of the expenditure elicits the next rise in the level.

In this way, evidently, a phenomenon characteristic of high water freshets takes place at the hydroelectric station; first of all the values of the velocity reach their maximum, then those of the expenditure and finally, those of the level. This is indicated also by N.N. Fedorov (1965) on the basis of the analysis of data on the unestablished movements in the River Tverts. However, with the increase of distance from the hydroelectric station, this regularity is disrupted. The maximum velocities of the current at all three ranges (Myshkino, Yur'ino and Koprino) during discharges of 1-4 hours duration, are normally observed during the fall of the level and not at the moment of its maximum rise, and they are noted initially in the upper ranges and then in the lower. This is related to the fact that part of the volume of water during the period of the rise in the level, commensurate with the distance from the hydroelectric station during the discharge, is expended on the filling of the flood lands, and during the period of the fall, it returns to the main channel. A similar phenomenon leads to the decrease of the expenditure of water passing along the main channel during a rise of the level, and to their increase during a fall (Grushevskii, 1965). Thus, with the increase of the distance from the hydroelectric station, maximum magnitudes are first reached by the values of the level, then the gradients, the current velocities and the expenditures of water.

In the event of discharges through the hydroelectric station which are of longer duration (for example, the evening discharge of 19 Mar., fig. 7) when, after the reflection of the direct, positive wave from the water mass of the central part of the reservoir the reverse, negative wave spreads through the reach, the maximum velocities of the current are observed first at the lower ranges and then at the upper, since the passing of this wave is accompanied by an increase in the expenditure of water at a given range.

The spreading through the reach of the direct, negative wave, generated by the decrease of discharges through the Uglich Hydroelectric Station, followed by that of the reverse, positive wave, leads to a sharp decrease in the velocities of the current and the expenditures of water which can take on negative values (fig. 7); at this point a reversal of the direction of the current takes place. The change in the dir- /113
ection of the current at the village of Koprino commences 3-4 hours after the cessation of the discharges of water and lasts for a period of 20-60 minutes (Butorin and Litvinov, 1963). The maximum velocities of the flow in the reverse direction ar 8-12 cm/sec and are observed, as a rule, in 5-6 hours after the cessation of discharges, that is, at

the moment of the passage along the reach of the reverse, positive wave, the distribution of which is linked to a certain rise in the level and to a decrease in expenditures (Grushevskii, 1962).

The vertical distribution of current velocities and the structure of the velocity fields through the length of the Volga reach may be judged from the data presented in figures 9 and 10. From this data it can be seen that at the ranges at Myshkino and Yür'ino, where there is an almost total absence of inundated flood lands and the flow is confined to the main channel of the Volga, the velocity field covers the whole water cross-section. At the Koprino range, despite the considerable areas of inundated flood lands, the main velocity field still holds to the main channel of the Volga. The flood land areas of the section appear to act only as collecting basins and are practically devoid of through flow. Minor current velocities are to be observed only in the flood lands of the right bank. Similar results for the given range were also obtained in 1962 (Butorin and Litvinov, 1963), though the differences in the velocities of the current were as much as 20 cm/sec.

Examining the change in the structure of the velocity fields with time (from 1100 to 1400 hours, 16 Apr.), it can be seen, that in all three ranges a certain increase in the main current velocities was observed, which on the whole for the range, was expressed in the increase of the area of the section with the maximum velocities.

Analysis of the distribution of current velocities on the deep stream verticals of the ranges (fig. 10) indicates, that the minimum relative (with respect to the mean velocity) change of velocities in the ranges at Myshkino and Yur'ino was observed on the 0.4-0.6 m horizons, where it did not exceed 5%, and the greatest was in the surface and bottom layers. Relative to this, while at the Myshkino range the reconstruction of the flow velocity field leads to a significant (up to 30%) relative decrease of the surface velocity and to an increase (up to 15%) of the bottom velocity, at the Yur'ino range there was observed a constant increase in the surface velocity (up to 15%) and an increase followed by a decrease in the bottom velocity. On the whole though, for the entire observation period, the surface velocity was somewhat higher than that of the bottom (up to 5%).

At the Koprino range the maximum relative change of velocity was observed to be at 1400 hours at the 0.4 m horizon and at the bottom. In the surface layer, as was the case at the Yur'ino range, a minor increase in velocity was noted, but it was 20%, and at 1400 hours 30% lower than the bottom velocity. Thus, despite the fact that the regime of flow was close to that established, there was constant reconstruction of the working curves of the velocities, in the course of which the most significant changes were noted at the surface and bottom horizons. The character of this reconstruction apparently depends on the morphometric features of the channel in a given section and the turbulence of the flow.

Of considerable theoretical and practical interest also is the character of the change of the surface and bottom speed of flow during a period of an intense increase or decrease of current velocities at a given range during the passage of discharges through the hydroelectric station. The data from synchronous observations at the 0.2 and 0.8 m horizons of the channel verticals at the Koprino range, obtained in March, 1962 (fig. 11) with the aid BPV-2-r recorders, indicate that in a period of the intensive increase of velocities during the passage of the direct, positive wave, a significant excess is observed of the absolute magnitudes of the bottom velocities over the surface velocities, /115 that is, on the 0.8 m horizon noticeable current velocities appear 10-20 minutes earlier than on the 0.2 m horizon. Subsequently, with the increase of the velocities to their maximum, an evening out occurs and there is little distinction between the absolute magnitudes of the velocities at the two horizons. During a period of a sharp decrease in the velocities, a reverse picture is observed, that is, as a result of the fact that the current velocities at the 0.8 m horizon begin to diminish sooner than at the 0.2 m horizon, the absolute magnitude of the velocity in the surface layers may be significantly higher than in the bottom layers.

Thus, the bottom layer at the Koprino range reacts more quickly to changes in the regime of discharges than does the surface layer. This is demonstrated more obviously by the change of the direction of the current when the shift in time extends to 40-90 minutes (fig. 11).

During a reversal of the current (that is, on the passage past the range of a reverse, positive wave) the time of the appearance of noticeable velocities at the 0.2 and the 0.8 m horizons is approximately the same, but the absolute magnitude of the velocity of the surface layer,

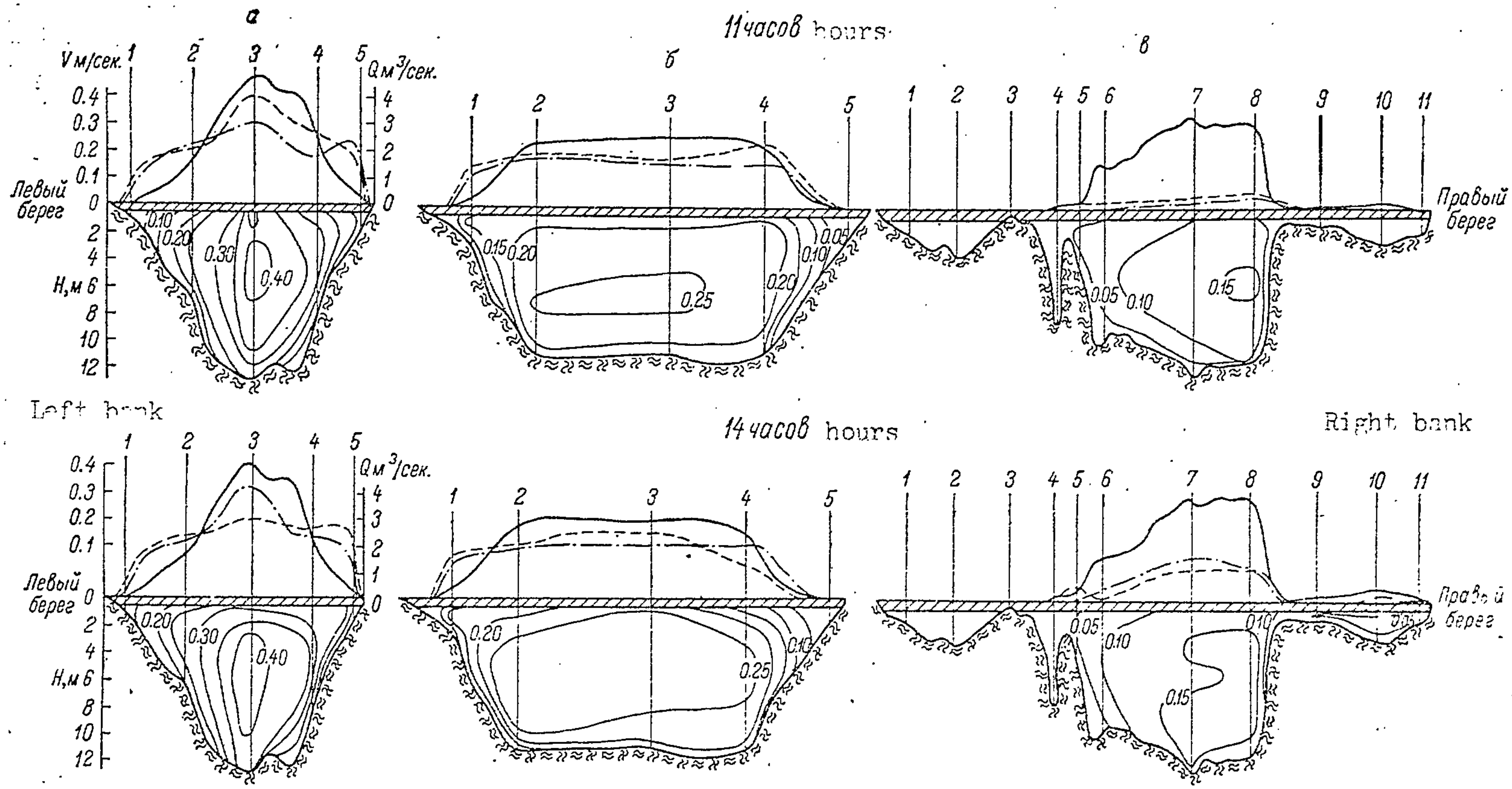

Fig. 9. Structure of the velocity fields in the Volga reach, 16 April, 1963.

a - range No. 1; b - range No. 2; c - range No. 3.
Arabian numerals - numbers of stations; solid line - elementary expenditure of water; dotted line - surface current velocity; broken line - mean current velocity; shading - thickness of ice; isolines indicate current velocities, m/sec.

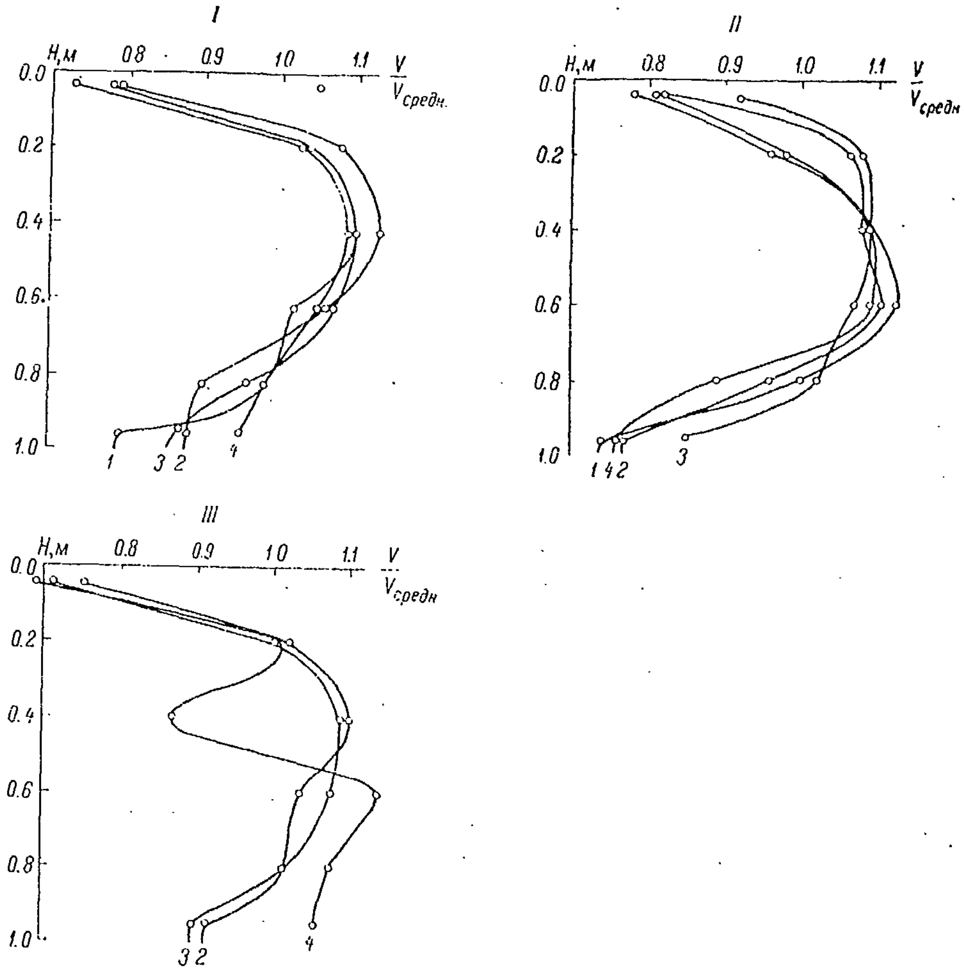

Fig. 10. Vertical distribution of relative velocities of the current (relative to the mean on the vertical), on the deep stream verticals of stations 1 - 3, 16 April, 1963.
1 - for 1100 hours; 2 - for 1200 hours; 3 - for 1300 hours; 4 - for 1400 hours.

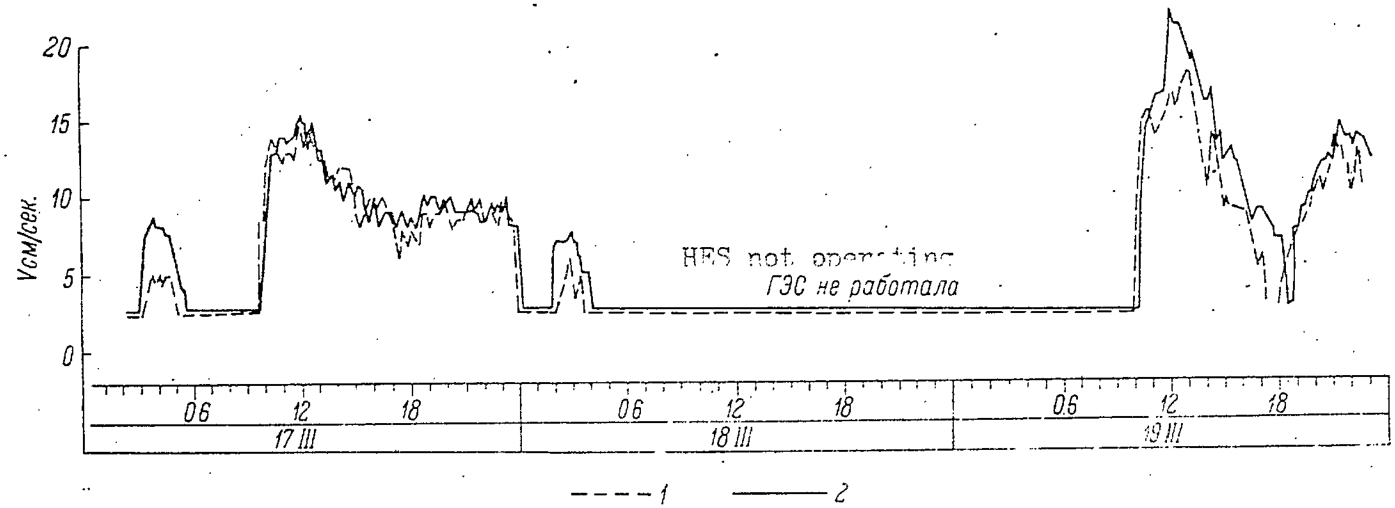

Fig. 11. Composite graph of changes of velocity and direction of current in the surface and bottom layers in the region of Koprino.

1 - 0.8 m horizon ; 2 - 0.2 m horizon.

both during a period of drastic change and at the time of maximum velocities, is significantly higher. Besides that, it is also interesting to note the fact that during the period of the Sunday break in the work of the hydroelectric station, when the velocities of the current at the Koprino range fall below the sensitivity of the recorders and the movement of water can only be detected by the change in the direction of the current, the stability of the current direction at the 0.8 m horizon is greater than at the 0.2 m horizon. /117

Material, currently existing in the literature, on the research of the velocity field of flow in the head portion of a discharge wave, is extremely contradictory. Even though the data presented in the present study agrees with the laboratory research of the structure of the velocity field, carried out by G.F. Fedorov (1960), it is essential to note that the laboratory work of A.N. Shabrin (1964) and the field studies of the State Hydrological Institute on the River Tverts (Fedorov, 1965) give contradictory results, that is, these authors come to the conclusion that during the passing of the head portion of a discharge wave, the working curves of the distribution of velocities do not undergo significant changes. N.N. Fedorov indicates that the restructuring of the curves of velocities takes place only when the mean velocity takes on an almost constant value. In the course of this restructuring the relationship of the surface and bottom velocity, and the mean on the vertical, can deviate up to 20-25%, which also agrees with our data.

Table 5 presents the results of the calculations of the expenditures of water based on the observations made at the ranges at Myshkino,

Table 5

Calculational data for expenditures of water on 16 April, 1963
with the mean level throughout the reach 3.51 m below normal back-water level

Indexes	Uglich HES				Myshkino				Yur'ino				Borok-Koprino			
	Hours															
	11	12	13	14	11	12	13	14	11	12	13	14	11	12	13	14
H, m convent'nl	8.73	8.75	8.73	8.75	8.53	8.53	8.54	8.54	8.49	8.49	8.49	8.50	8.44	8.44	8.44	8.44
Q, m^3/sec	844	864	864	864	927	945	970	1002	1048	1090	1140	1160	927	1011	1028	1042
F m.** channel,* m^2	--	--	--	--	--	--	--	--	--	--	--	--	110	--	--	--
F, surface ice, m^2	--	--	--	--	185	185	185	185	425	425	425	425	1578	1578	1578	1578
F, trough of main ch*, m^2	--	--	--	--	3005	3005	3005	3005	5130	5130	5130	5130	8926	8926	8926	8926
F, total, m^2	--	--	--	--	3190	3190	3190	3190	5555	5555	5555	5555	10614	10614	10614	10614
V, mean, m/sec	--	--	--	--	0.31	0.31	0.32	0.32	0.20	0.21	0.22	0.23	0.10	0.11	0.12	0.12
V, maximum m/sec	--	--	--	--	0.42	0.43	0.43	0.44	0.26	0.27	0.29	0.29	0.16	0.18	0.19	0.18
B, m	--	--	--	--	405	405	405	405	680	680	680	680	2150	2150	2150	2150
H, mean, m	--	--	--	--	7.9	7.9	7.9	7.9	8.2	8.2	8.2	8.2	4.94	4.94	4.94	4.94
H, maximum, m	--	--	--	--	13.0	13.0	13.0	13.0	11.8	11.8	11.8	11.8	12.7	12.7	12.7	12.7

**Translator's note: Transliterated.

* Translator's note: Speculative.

Yur'ino and Koprino. It was noted earlier that the measurements were carried out during expenditures through the hydroelectric station close to the established discharge regime. During the period of observations the measurements, from 1100 to 1200 hours, increased by only 20 m^3/sec, which, for an initial discharge of 844 m^3/sec, constitues 2.5%.

From the table it can be seen that at the Myshkino and Koprino ranges the measured expenditures of water at the beginning of the obser- /118 vations exceeded those at the hydroelectric station range by 10%, and that towards the end of the observations, this difference increased to 22%. At the Yur'ino range though, the increase in expenditure consisted respectively of 22 and 34%, relative to the expenditure at the hydroelectric station range. It is most likely that the increase of the expenditures at the Myshkino and Koprino ranges takes place as a result of tributary inflow. The somewhat higher expenditure at the Yur'ino range might have been linked to the presence of a local back-water, generated by the artificial narrowing of the channel which decreased the area of the water section by approximately 30%.

In conclusion, let us dwell on the water exchange in the Volga reach of the Rybinsk Reservoir. Since the average annual outflow through the Uglich water control point consists of 13.5 km^3, relative to which 6.3 km^3 of that goes through in the spring period, then in the course of 10 months the average monthly outflow volume consists of 0.7 km^3. The volume of the Volga reach on the other hand, at a level 2 m below normal back-water level, is equal to 1.7 km^3. From this it follows that, in the course of the 10 month period, the Volga reach changes over fully in 2.4

months. During the spring period though, (from 20 April to 20 June), when the average monthly outflow volume increases to 3.1 km^3, the exchange of the water mass in the reach takes place in approximately 16-17 days.

Conclusions

1. Observed in the Volga reach of the Rybinsk Reservoir are seasonal, weekly and daily fluctuations of the level. The seasonal fluctuations are linked to the change of the mean level of the reservoir and reflect the character of the relationship between the inflow and the discharge of water over an extended period of time. The weekly and daily fluctuations of the level are caused by the routine of the working of the water through the Uglich Hydroelectric Station. The weekly fluctuations are related to the periodic breaks in the operation of the hydroelectric station on non-working and pre-holiday days, while the daily fluctuations are generated by the passage of discharge waves resulting from the daily regulation of the flow of water through the station.

2. Permanent gradients in the water surface of the Volga reach are lacking during the winter period, though, as a result of the passage of discharge waves, periodic distortions of the water surface occur. Relative to this, during the passage of positive waves (rising waves), positive gradients occur, and during the passage of negative waves, the gradients are negative. The absolute magnitude of the gradients depends on the level of the reservoir and is 10 times smaller than the normal inclination of the Volga.

3. The current regime is determined by the water working regime

of the Uglich water control point and changes throughout the year. The absolute magnitude of the velocity depends on the expenditure of water through the hydroelectric station, the level of the Rybinsk Reservoir and the volume of the discharge.

4. During a period of the rapid increase of velocities (on the passage of a direct, poistive wave) it is observed that the absolute magnitudes of bottom velocities exceed those of the surface, while during a period of the sharp reduction of velocities, the absolute magnitude of velocity in the surface layer may be significantly higher than in the bottom layer.

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