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Formation, movement and alteration of the water masses of the Gorky reservoir

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FORMATION, MOVEMENT AND ALTERATION OF THE WATER MASSES IN THE GORKY RESERVOIR

Every inland body of water, including reservoirs, represents one of the phases of the entire drainage process. This process consists of the movement and interchange of water masses, each possessing definite properties such as temperature, density, composition and concentration of dissolved and suspended substances, etc (Muraveyski, 1960). This process of drainage is both a quantitative and qualitative phenomenon, and therefore full knowledge of it can only be acquired by simultaneous investigation of both aspects of this single process. The interconnection between them is best reflected in reservoirs, because the distribution of water masses having diverse qualities and the rate of change of their properties

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are closely related to the conditions of regulation of water balance and water exchange in these man-made water bodies.

With reference to, and in view of the above, the Hydrology Laboratory of the Institute of Biology of Inland Waters of the Academy of Sciences of the USSR, under the leadership of N. V. Butorin, in 1960 undertook investigations of the water masses of the Upper Volga reservoirs. The present work is a part of this program; in it the results of three years of study on the water masses of the Gorky reservoir are summed up.

The construction of the Gorky hydroelectric development near Gorodets and the filling of the reservoir up to the full supply level (FSL) was concluded in spring of 1957. The main purpose of this hydro-installation was utilization of the Volga flow for energy and transportation (Neporozhnyi and Filakhtov, 1960). It represents a fourth and final phase of the Upper Volga hydroelectric station series.

The Gorky reservoir is a markedly elongated and relatively narrow body of water formed as a result of flooding the floor of the Volga Valley and a number of its tributaries. The backwater extends from the Gorky dam, along the Volga up to the Rybinsk hydroelectric station and along the largest tributary of the reservoir, the Unzha, to a point 65 to 70 km from its former mouth. The reservoir is 434 km long; its average width is approximately 3.5 km; maximum width is 16 km. The surface

area is 1570 km^2, and volume 8.7 km^3 at normal retaining level. The reservoir is one of the ten largest reservoirs in the European part of the Soviet Union but it is the most shallow: its average depth is 5.5 m, the maximum depth being 22 m at the dam in the Volga channel. By means of this reservoir seasonal control of the run-off is provided and depths indispensable for navigation maintained not only at its head near Rybinsk, but also at the not yet controlled stretch of the Volga below the Gorky hydroelectric generating station. A characteristic feature of the reservoir as one of the links in the series of water bodies, is a high degree of run-off control from its drainage basin. The Rybinsk and other reservoirs of the Upper Volga strongly alter the inflow into the water from 4
2/3 of its catchment area, both qualitatively and quantitatively. The reservoir has a great number of tributaries, differing in their water chemistry, whose contribution forms approximately 40% of the incoming portion of the annual water balance of the reservoir.

The Gorky reservoir is one of a number of the most thoroughly investigated from the hydrological and biological point of view in the Soviet Union. This is why we consider it possible to proceed with a description of methods and the results of investigations of the water masses of this body of water without recapitulating here the general hydrological characteristics of this reservoir. First work in this direction was carried out by A. A. Zenin (1961) who in May and August of 1957 and 1958, made four surveys of the Gorky reservoir, and by V. I. Rutkovskii (1963) who, in July 1960, made a quick survey of the temperature and electrical conductance of the water. These surveys showed a considerable degree of heterogeneity in waters filling the lake part of the reservoir. The authors explained the nature of the distribution of chemical and physical characteristics over the water area, by the presence of waters of various origin within the reservoir, that come from the Rybinsk reservoir and from the large tributaries, such as the Unzha, Nemda and others.

Thus, these previously taken measurements demonstrated the possibility of investigating the distribution of the physical and chemical characteristics and the dynamics of waters in the reservoir by analysis of the water mass, meaning genetically homogeneous water volumes possessing a number of definite physical, chemical and biological properties (Butorin, 1965 a). The preliminary results of investigating the water masses in the Gorky reservoir were published in a series of articles (Edelshtein, 1965 a, 1965 b, 1966, 1967). The present work provides full data of observations at the reservoir. Its aim is an attempt to show a correlation between the quantitative and qualitative aspects of the process of flow into the reservoir, revealed by the transformation and formation processes of its water masses; to give the characteristics of both inflowing water masses and those formed _in situ_; to determine the pattern of the distribution of these masses in the body of water, and to obtain an idea of the processes of internal water exchange in the reservoir and in its individual parts on the basis of the peculiarities of water mass movement.

The author was helped in the course of observations and office study by the laboratory assistants V. I. Vnuchkova, N. M. Sizova, L. A. Ugarova, and the Moscow State University students S. A. Fil and N. N. Vinogradova. Additional data on the chemistry of the reservoir waters were kindly contributed by F. I. Bezler, N. A. Trifonova and A. V. Fotiev. Of great help in organizing the investigations and during the writing were senior scientific officer N. V. Butorin and Prof. B. B. Bogoslovski. To all of whom the author conveys his deep gratitude.

THE EXTENT AND METHODS OF THE FIELD OBSERVATIONS.

In order to study the water masses of the Gorky reservoir, eleven cruises were organized in 1961-1963 and in the course of these it was possible to carry out 21 hydrological surveys of the body of water with a total number of approximately 1000 stations.

Table 1 shows the dates of collection of the individual data and the extent of the field observations. During the navigational period the cruises were made by the expedition vessels of the Institute of Inland Water Biology of the Academy of Sciences of the USSR; winter trips were undertaken by car (observations were made by trips on foot). In spring, during the break-up period, observations were carried out both directly from on board the ice-breaker "Don" and from the ice in a number of expeditions on foot.

In the navigational period, the chart of each cruise was plotted as follows. During the initial 2 to 4 days the river part of the reservoir was surveyed from the Rybinsk hydroelectric generating station to the Yur'evets, and on the following 4 to 5 days the lake part was surveyed in detail. Three to four days later, an abridged repeat survey of the lake part was undertaken, of one or two days' duration, making it possible to note the changes occurring in the boundaries of the water masses during 7 to 10 days. The cruise was concluded by a repeat survey of the river part of the reservoir from Yur'evets to the Rybinsk hydroelectric power plant. /5

The methods of surveying the river part of the reservoir gradually improved. On the 1961 cruises, observations were made only at a number of stations uniformly distributed along the Volga navigational channel. At these stations a complete hydrological data collection was made, including current measurements. In the course of this it was determined that in the river part of the reservoir, the water mass is in most cases vertically /6 homogeneous, while along the longitudinal axis of the reservoir noticeable ~~changes~~ change in its hydrological characteristics took place. This is why, during the first two cruises in 1962, the number of stations was reduced, but measurements of the temperature and electrical conductance in the surface layer of water began to be taken every second kilometer along the navigation channel; such a method was followed by V. I. Rutkovskii (1963). Thus sharp variations of these characteristics were detected in stretches below the inflow of large tributaries, which are explained by the heterogeneity of the water over the cross-section of the body of water. In subsequent cruises, apart from 4 to 6 key hydrological stations, below the mouths of the major effluents of the river part of the reservoir, the cross-sections were made with frequent (every 100 to 150 m) samplings of surface water in order to measure temperature and electrical conductance Such sections were located at intervals of 8 to 10 km along the whole stretch where the influence of the inflowing waters was traced.

The comprehensive survey of the lake area of the reservoir comprised observations on longitudinal sections of the whole series of bays adjacent to river mouths, as well as on transverse sections in the open part of the reservoir from Yur'evets to the Gorky dam. Tests were made in bays along Mera, Zhelvata, Elnat', Nemda, Unzha, Mocha, Yachmen', Sanikhta and Yug, in each of which from 2 to 5 hydrological stations were established. The uppermost of them we endeavoured to place in the zone of wedging-out of the backwater, where there is a constant discharge current. On several minor tributaries, however, such as the Zhelvata, Sanikhta, Yug and others, this did not prove feasible because of obstacles of various kinds: bridges, sinkholes, and shallows. In the wide part of the reservoir, surveys were made along 8 transverse sections (Fig. 1). Permanent hydrological stations were set up in typical parts of cross sections (the former Volga channel, flooded channel edges, floodplain and near the shore areas. Thus, when a detailed survey was conducted in a lake part of the reservoir, the total number of stations reached 60 or 70. In a brief, repeat survey of the lake area, only transverse sections of the open part of the reservoir were subject to observation. Aside from stations, during surveys at individual sections more frequent (every 1 to 2 km) determinations of temperature and conductance of the surface water layers were made, and this permitted us to obtain more specific information on the water mass limits.

At hydrological stations, the vertical distribution of temperature and electrical conductance of the water were determined by the "thermoKappameter"[1] (Ershova and Edel'shtein, 1966) and water transparency and colour by the Secchi disc. In addition water samples were taken at the surface and close to the bottom for pH and chemical analyses. The latter were carried out under field conditions and were limited to determinations of total hardness, bicarbonate concentration

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[1] English term is not available (Transl.)

by using standard methods (Alekin, 1954), and also the total amount of strong acids by means of ion-exchange columns (Podgornyi and Fotiev, 1958). In the two last cruises, determination of dissolved oxygen content was undertaken at the surface and at the bottom.

Apart from the hydrological surveys, in the lake part of the reservoir several diurnal stations were established where diurnal variations of individual values of indices of the water masses were observed under various weather conditions, and currents were measured. The technique of this type of observations was devised earlier at the Rybinsk reservoir (Edel'shtein, 1963).

During the winter and spring cruises we were obliged to considerably decrease the number of stations and to limit ourselves to determination of temperature, conductance, colour and pH value.

The hydrological work was associated with regular /8 meteorological observations. In the course of cruises, temperature and humidity of air, direction and velocity of wind, as well as barometric pressure and cloudiness were determined every 2 hours.

INDICES AND METHOD FOR DEFINITION OF WATER MASSES.

The following water characteristics, being easy to determine by rapid analysis under field conditions, were used as indices of water masses in the Gorky reservoir: temperature, electrical conductance,3) transparency, colour, content of bicarbonates and of dissolved oxygen, total hardness and pH value. These characteristics may be conditionally sub-divided into two groups differing in the degree of conservativeness of this or that water mass property. Content of bicarbonates, hardness, electrical conductance and colour may be considered as the most conservative. The conservatism of the first two characteristics state of potassium carbonate equilibrium, the relative stability of which is connected with a lowering of the normal calcium carbonate saturation in waters of the reservoir and its tributaries (Moricheva, 1965). As HCO_3', Ca'' and Mg'' ions predominate in the chemical composition of the reservoir water, and relative changes in this composition are slight (Zenin, 1964), the electrical conductance value depends mainly on the concentration of these ions, and is a sufficiently conservative characteristic as well. Fortunatov (1959) proved in detail the possibility of using colour as an indicator of water origin in reservoirs. Thus, the characteristics of the first group barely change their values as long as the water mass remains in the reservoir, and because of this they may serve as good indicators of the water origin and alteration

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3) Here and henceforth on, the term "electrical conductance" is used to mean the relative electrical conductance of water determined by using the Pleissener Table (Pleissener, 1909) at a temperature of 18°C and expressed in micro-siemens/cm (1μ mho/cm= 1.10^{-6} ohm^{-1} cm^{-1}).

as a result of intermixing with other water masses.

Temperature, transparency, pH and oxygen content must be assigned to the second group of characteristics. They may alter their values considerably as a result of thermal, dynamic, biochemical and other processes occurring within one and the same homogeneous water volume. These characteristics are an indication of water mass alteration due to weather conditions, morphology and water exchange in individual areas of the body of water. As previously pointed out, such a division of the water characteristics is largely conditional because in individual cases the characteristics of the second group may be fairly good indicators of derivation of the water masses (for instance the water temperature in early spring and late fall, transparency and pH in periods of rain-induced freshets, winter oxygen content, etc.).

Representativeness of the water mass characteristic does not depend only on its conservatism. Although sufficiently conservative, such a characteristic cannot be regarded as useful for distinguishing between water masses if the difference between the index value of two or more water masses found in a body of water is not large in comparison with the possible error of method in its value determination. In Table 2 the maximum range of variation of several water mass characteristics is given: R_{max} at moments of the Gorky reservoir surveys, mean error in their determination(ε) and the relationship between the first and the second values (K). The larger the K parameter value the more representative is the characteristic. The least reliable characteristics from the point of view under discussion proved to be transparency, pH, and particularly the total of strong /9 acids. Despite quite high conservatism in SO_4'' and Cl' ions, we were compelled to refrain from using the total strong acids as a characteristic in successive analyses of the water masses in the reservoir, for exactly this reason.

Definition of the water masses in the reservoir was carried out by using a complex method, consisting in analysis of the spatial distribution of all enumerated characteristics in the body of water. The data collected in hydrological surveys were plotted on separate charts for each characteristic. Then isolines were traced at intervals larger than or equal to the possible error of method in measuring the appropriate characteristic. When substantial stratification of any characteristic was noticed during this survey, the charts were plotted for the surface and near-bottom layer, in other cases for the surface water layer only.

On the charts, the areas of water mass distribution were characterized either by an absence or wide separation of index isolines, while considerable "bunching" of them occurred in frontal zones. Obviously, as the tentative limit of two water bodies that line should be accepted which connects the points at which a 50% mixing of adjacent water masses was observed. However, the mass calculation using the mixing formula is quite labour-consuming, therefore the boundary of the water masses, or hydrological front, was traced according to the V. K. Agenorov method (1944). By calculating the horizontal gradient of electrical conductance - the most conservative and representative among all the characteristics being determined - points were defined at which this gradient has a maximum value. The line, or to be more precise, the plane that links such points was accepted as the boundary of the water masses.

On the basis of two hydrological surveys of the lake part of the reservoir, a comparison was made of the location of fronts traced by using the maximum electrical conductance gradient, as well as lines of the 50% mixing of the water masses also determined by electrical conductance. In the overwhelming majority of examples investigated, the front lines determined by these two methods fully coincided and in only some cases did they fail to do so. In analysing these cases, an impression was created that the line of maximum /10
gradients and the line of 50% mixing do not coincide if, in the calculation using the mixing formula, the characteristics of one of the masses are included, this mass being not "pure" but somehow modified due to mixing with the other water mass.

A comparison of the fronts traced for the same two surveys, using maximum horizontal gradients of various characteristics (conductance, bicarbonate content, total hardness, colour) proved their complete identity. Results of these two methodological studies show that the plane joining the points of the maximum values of the conductance gradients may be accepted as the conditional boundary of the two water masses in the Gorky reservoir. It should be noted that tracing boundaries between two geographical complexes (in bodies of water between two water masses) by using the maximum gradient of a characteristic is wide-spread not only in oceanography (Agenorov, 1944; Muromtsev, 1953) but also in the study of landscapes, when, in mapping, the location of a natural boundary has to be determined. (Armand, 1955).

INITIAL WATER MASSES.

The waters which initially make up the water mass of the Gorky reservoir are provided by the Rybinsk reservoir (later it will be referred to as the Volga water mass), and by the discharges of tributaries. Atmospheric precipitation on the surface of this body of water, the surface and groundwater run-off constitute little more than 2 to 3% of the intake of the annual water balance in the reservoir, and, as a result, their part in modification of the reservoir water masses is insignificant. While investigating the stream flow regime and physical and chemical properties of the initial water masses at the inflow ranges compared with the reservoir, we do not discuss their formation in detail in this book.

A number of works by N. V. Butorin (1965a; 1965b) and others are devoted to the water masses of the Rybinsk reservoir, and, furthermore a study of the formation process of river water masses requires the setting up of special investigations in the catchment area of the reservoir.

VOLGA WATER MASS

The volume of the Volga water mass entering annually into the Gorky reservoir is determined by the magnitude of the annual run-off from the Rybinsk reservoir basin. It is modified as a result of regulation of the run-off by the three upper reservoirs of the Volga series. A. P. Braslavskii, R. F. Byurig and Z. A. Vikulina (1951) evaluated the effect on the annual flow of these reservoirs as a whole, and of the Rybinsk reservoir in particular,

The authors reached the conclusion that the influence of the Rybinsk reservoir on variation in the annual run-off is not large. On the basis of the water balance for 1941-1947 in the reservoir in question, and the regulations regarding the discharge control at the Rybinsk hydro-electric power station, they established that in dry years, it is possible with a supply of about 90% not only to replenish the evaporation losses and the feeding of the Moscow canal, which constitute about 12% of the normal annual flow of the Volga but also the average flow increase of 10% due to draw-off from the year-to-year prism storage of the Rybinsk reservoir control.

As is now possible to determine more accurately the degree of influence of the Rybinsk reservoir on the annual Volga flow, and to determine the variability of this value by using factual data on the discharge of the Rybinsk hydro-electric power plant for the seventeen year period (1947-1963) which elapsed after the usable capacity of the reservoir was filled. In Table 3 the values of inflow into the Rybinsk reservoir are compared. They were calculated by TN, Kurdina and published in part in the work dealing with the water balance of the reservoir (Rutkovskii and Kurdina, 1959) and discharges made by the Rybinsk hydro-electric generating station. The values quoted in Table 3 characterize the discharge during one hydrological year from April to March of the next year. /11

Between 1947 and 1963 the average annual inflow into the reservoir was equal to 35.1 km^3 and represents a flow rate of 1112 m^3/sec. The volume of discharge from it averaged 33.3 km^3 per annum with an average annual flow rate of 1057 m^3/sec. This last value varied from year to year within the limits of 687 to 1447 m^3/sec. Although the variations in the average annual flow rate of water of the Rybinsk hydroelectric plant in general repeat the pattern of inflow into the reservoir, the influence of this body of water on the annual Volga flow proved to be more significant than was assumed in the initial period of its existence. Variation in flow due to water accumulation in the reservoir and subsequent draw-off reached 20 percent of the inflow in some years (Table 3), with a flow increase being observed not only in dry years (1949, 1954, 1963) but also in years with a flow close to the normal (1959), and even in wet years (1957, 1961). The reduction of the Volga flow by the reservoir was noted not only during wet years, but in average years (1948, 1960). Such type of regulation promoted a certain increase in variations of the annual Volga flow, and not a decrease. The variability coefficient C_v of the annual rate of inflow into the Rybinsk reservoir for 1947-1963 is equal to 0.21, while C_v of its discharge for the same period is 0.23 .

The study of water masses in the Gorky reservoir was carried out in years with various amounts of rainfall. The annual volume of Volga water flowing into the body of water in 1961 represented roughly 20%; in the wet year 1962 - 10%, and in the dry year 1963 - less than 85%1). The annual inflow and discharge are determined from correspond- /12
ing long-period curves which R. F. Byuriga (1950) gives in his work.

The intra-annual regime of the inflow of Volga waters from the Rybinsk into the Gorky reservoir is characterized by considerable uniformity of the monthly flow, the volume

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1) Should be probably 8.5% (Translator).

of which on the average fluctuates between 6% and 10% of the yearly value (Table 4).

The minimum monthly discharges of water from the Rybinsk reservoir as a rule occur in the spring, at its filling-up period; at the same time the mean flow rate of water for April and May in dry years (including also 1963) is reduced to 400 - 500 m^3/sec. Usually the discharge is gradually increased in the summer and autumn months, and reaches its peak in winter, when it often exceeds 1500, and sometimes even 1800 m^3/sec. In individual years considerable deviations of the monthly flow values from the mean annual distribution took place, as a result of hydrometeorological peculiarities of the year as well as the operating conditions of the hydroelectric plant. Thus, in May of 1961, the hydroelectric plant discharged the maximum monthly volume of water, a fact that is typical of years with considerable spring high water. In 1962, which was characterized by a very high summer flow, the greatest average monthly water flow rate was observed in August.

The flow control by the Rybinsk reservoir is revealed not only in typical seasonal and annual re-distribution of the water volumes which it discharges into the tailwater but also by substantial balancing of their physical and chemical properties during the year. Investigations by N. V. Butorin (1965 c) proved that the water mass of the central part of the water body is found all year round, the range of annual variation of the characteristics being relatively small (Table 5).

The Volga water mass in the Gorky reservoir, formed chiefly from these waters, inherits their physical and chemical properties and peculiarities. Due to intensive mixing in the basins and tailwater of the Rybinsk hydroelectric plant, it enters the reservoir as a fully homogenous flow over the whole cross-section. In the vicinity of Rybinsk we determined several characteristics of this water mass. These are given in Table 6. From the data given in the Table 6 it follows that the electrical conductance of the Volga water mass had a comparatively small range of variation (133-237 µ mho/cm). Accordingly, fluctuations of bicarbonate content and hardness were not large. The water colour was 35-60; its intense colour in the winter of 1963 is uncommon for the Volga water mass. It seems that in 1963 this was connected with an exceptionally high autumn run-off in the previous year. Water transparency in the vicinity of Rybinsk fluctuated between 80 and 110 cm, and only during storms at the Rybinsk reservoir did it decrease to 40-60 cm. The low variability of the characteristics typical of the Volga water mass is confirmed by the chemical water analyses at Yaroslavl' (Table 7), cited by A. A. Zenin in his work (1964). Thus, /13 the general water mineralization values fluctuate within the range of 86.6 and 147.8 mg/liter.

Despite the lowered intra-annual variability of the physical and chemical characteristics, the Volga water mass is notable for a marked lag in extreme values of indices in comparison with normal conditions of flow. In spring the highest indices of its electrical conductance, alkalinity and hardness are observed, and the minima fall in the summer-autumn period (Tables 5 and 6). Years with very high floods are exceptions, when modified and low-mineralized spring waters of the Upper Volga may advance to the Rybinsk hydroelectric station (Ershova, 1965). Under such conditions, mineralization of water and the electrical conductance of the Volga water mass in the Gorky reservoir may sharply decrease in May in comparison with the values given in Table 6. /14

The water mass investigated differs noticeably from other initial masses in temperature, especially in spring, when it is considerably colder than waters of the lateral tributaries (Table 8).

Hence, the Volga water mass, averaging about 64% of the total annual inflow into the Gorky reservoir, is characterized by great uniformity of distribution of monthly and seasonal flows and by small changes in most of its physical and chemical indices. In the spring period these waters are relatively cold and highly mineralized; they constitute on the average about 30% of the total inflow into the reservoir. In the summer-autumn period, the water mass of Volga represents 70-80% of the total inflow into the reservoir; the mineralization and colour of the waters have the lowest values of the year. In winter, the relative importance of this water mass in the incoming part of the water balance of the reservoir reaches 88-90%, and its mineralisation and colour gradually increase at this time.

Water masses of tributaries.

/15

There are a great number of rivers which discharge into the Gorky reservoir. They are fed by the run-off from the watershed of about 79,000 km^2. This catchment area is a slightly hilly plain characterized by low elevations separated by river valleys (their peaks average 150 - 170 m absolute height) alternating with flat boggy lowlands and stretching from the south-west to north-east. The Unzha and Kostroma are the largest tributaries of the reservoir. Their basins occupy in sum more than half of the total watershed. Besides these rivers, the most important are the Kotorosl', Nemda and Mera. The tributaries of the reservoir are mostly snow-fed. Regardless of the fact that the ratio of the volumes of water of different origin changes within a fairly wide range, the share of the melt run-off in them exceeds the share of subsurface drainage and rainfall run-off. By the character of their water regime the tributaries of the reservoir belong to the East European type of river. They have high spring flood water and moderately low dry weather water level. At other seasons they are disturbed only by rain induced freshets in the summer-autumn period.

The total flow of rivers which feed the reservoir averages about 36% of the inflowing part of the annual reservoir balance. In the formation of the water mass of the reservoir the role of lateral inflow varies greatly from season to season. In spring, the rivers provide an average of 60-80% of total inflow to the reservoir, and during periods of maximum high water flow in them, up to 94% (Kavchuk and Yaroslavtsev, 1964). In the summer-autumn period, the participation of the river water in the exchange of the reservoir water decreases roughly by half, as compared with the spring period, but in winter 16 the part of the fluvial inflow shrinks to 10-16%. In Table 9, average values of annual and seasonal volumes of run-off of the largest reservoir tributaries are given for 1957-1963. Taking into consideration the particular features of the annual distribution of river flow into the reservoir basin (Fig. 2), April and May are included in the spring period, and during this period all these rivers have a high water level. The summer-autumn period, from June to November, is marked by fairly low runoff, on which are superimposed rain induced freshlets. Winter, from December to March, is characterized by a low and steady river flow. The volumes of tributary flow given in Table 9 are calculated for their entire drainage areas, using the method employed since 1961 by the Volga Hydrometeorological Observatory when calculating the water balance of the Gorky reservoir (Kavchuk and Yaroslavtsev, 1964).

As Table 9 shows, the Unzha and Kostroma have the largest volumes among the river water masses. Their flow constitutes on the average 13% and 8% of the total annual figure, and 25% and 17% of the spring inflow into the reservoir. The volumes of each of the remaining water masses are less than 5% of the total inflow into the reservoir at any time of the year. The relatively high stability of the ratio of volumes of individual initial water masses should be noted from year to year and by comparing seasons of various years. The specific proportion of each of them in the reservoir water exchange varies only by a few percent of the total inflow into the body of water depending only on hydrometeorological conditions in individual years. Consequently, the share of each of the initial water masses in forming the reservoir water mass is relatively stable in years with varying amounts of rain, and this may be explained by the common climatic and orographic conditions under which the drainage takes place in the catchment area of the reservoir. N. V. Butorin (1965 a) came to a similar conclusion. He established the stability of the ratio of water flowage down the Volga, Sheksna and Mologa towards the Rybinsk reservoir, independently of the rainfall of the year.

The spring high water begins in all reservoir tributaries at approximately the same time. The maximum spring flow rates in mouths of small rivers coincide with the beginning of a rapid-rise in level of the reservoir, and the subsidence of the floods takes place before the reservoir is filled to its normal storage level (Fig. 2). In 1961, the maximum flow rate of the Unzha and Kostroma occurred after the reservoir was already filled to the normal storage level, while in 1962 and 1963, the maximum flow in these rivers took place during the rise in level of the body of water, and only waters of the final stage of flooding entered into the already filled up reservoir. The correlation of the times at which the various tributaries' flood crests pass and of the stage of the reservoir at this particular time plays an important part in the distribution of water masses in the reservoir, in their dynamics and alteration.

The influx of river waters into the reservoir may be looked upon as a process of uninterrupted inflow through the upstream cross-sectional area of a water mass, the physical and chemical properties of which change within definite limits in the course of the year. The range of variation of these properties of the water mass of each of the tributaries and its specific peculiarities are determined by the physical and geographical conditions under which the run-off forms in the catchment area, as well as by the processes of water alteration in the river channel. In accordance with the periodically changing relationship of the basic genetic categories of water, such as surface-slope, soil-ground and ground water (Voronkov, 1963) the properties of the river water mass passing through the upstream cross-sectional area change with time: one water volume having a certain complex of characteristics is followed by the next one with different values of indices. Thus, the water mass of a river is composed of constantly /17 alternating water volumes of different quality which may be considered to be individual modifications of the river water mass; flood waters; summer-autumn low-level waters; rainfall-induced freshet waters, and winter low-level waters. The alternation of individual modifications of water masses in small rivers is especially well marked; their basins, as seen by V. V. Voronkov, are closest to "elementary catchments". In the water masses of the large tributaries of the reservoir, such as the Unzha and Kostroma, the boundaries between individual modifications are blurred.

The waters of the reservoir tributaries are but little mineralized and belong to the calcium group of the bicarbonate class of natural waters. The data collected by A. A. Zhenin (1965), shown /18 in Table 10, give a good idea of the range of fluctuations of total mineralization and relative chemical composition of waters in the main tributaries of the reservoir. A sufficiently close link was established between the flow rate of the water in the rivers of the reservoir basin and its total mineralization as well as the concentration of individual chemical ingredients (Galaktionova, 1964). The mineralization of water, the absolute value of which is very low, changes only slightly during high water, whereas during the low water period the relatively high ion concentration is extremely sensitive to even small changes in the water flow rate.

The waters of the reservoir tributaries under investigation can be divided into two sharply different groups on the basis of their physical and chemical properties. The difference is particularly marked during the summer-autumn period. The first group of rivers with relatively highly mineralized and weakly coloured waters, is represented by the Unzha, Kostroma, and Mera; the second with lightly mineralized and coloured waters - by the Nemda, Zhelvata and Mocha. In Table 11 are shown the values of the characteristics of the river water masses entering the reservoir at various phases of the hydrological cycle of its tributaries. As a rule, the river waters at the inflow were uniform through the whole cross-section of the stream, since the river flow was always observed at these points.

The minimum mineralization of the waters of the reservoir tributaries is observed in the spring during flooding. At this period, in the Unzha waters the electrical conductance decreases to

50-60 μ mho/cm and in the Memda to 30 μ mho/cm. At the same time the minimum pH values were also recorded as 6.4 in the Unzha, and 6.0 in the Nemda. The Elnat' water mass characteristics at high water were close to the values quoted. In the early spring, no observations were made in other rivers. It may be assumed on the basis of the reservoir survey data collected between May 3 and 4, 1963, that the Kostroma flood water mass had an electrical conductance of about 80 μ mho/cm, a pH not exceeding 6.6 and colour over 60. The spring river waters differ markedly in temperature both in the Volga and the reservoir water mass: they are 2 to 3° warmer than the latter.

At the time of the summer-autumn low water, in rivers belonging to the first group the conductance rises to 250-320 μ mho/cm, the bicarbonate content and total hardness to 2.0 - 3.0 mg equivalents per litre, and colour is reduced to 20-40. Low colour and low turbidity (2-5 mg/l) determine the relatively high transparency of these waters (120-155 cm). The rivers of the second group have a conductance of 120-180 μ mho/cm, total hardness and alkalinity are characterized by values not exceeding 1.5 mg. equ./l, and their colour reaches 80-100°. Accordingly, transparency in these waters is also only 60-80 cm. /23

During the periods of the rain-induced freshets, the basic ion content and conductance dip sharply in the river waters, while their colour increases. During the rain-induced freshets, in the rivers of the first group, the maximum colour values were about 120, in the rivers of the second group they reached 180-190. The freshet waters contain a very large amount of suspended matter. As a result of the high colour and turbidity, rain waters in rivers were grey-brown to hazel, brownish-yellow and even yellow, and their transparency dropped down to 30-40 cm.

In winter, conductance and mineralization reach their maximum values (Table 11). The differences in river waters with regard to colour are less noticeable, because the colouration of water is at this time minimal.

The differences between the rivers examined in respect of the chemical and physical properties of their waters, which are highly mineralized and "clear" or low-mineralized and coloured, are very striking, as already noted by A. F. Nikitin (1905). These two types of rivers differ also in their discharge; the mean annual discharge for the 1957-1966 period was 8.1 - 8.6 for the first group, and 7.3 - 7.5 l/sec per km^2 for the second group. Accordingly, these groups of rivers also differ in their spring discharge rates. The differences recorded between the reservoir tributaries as to their run-off, and particularly as to the physical and chemical characteristics of their waters, are explained by the physical and geographical peculiarities of the basins of these rivers. The centres of formation of the run-off of the rivers of the first group are hills in which the river network is deeply incised and drains several horizons of ground waters. The basins of the second group of rivers are noted for increased swampiness and forestation, as compared with the drainage system of the rivers that belong to the first group.

Correlative connection may be traced between the individual characteristics of the initial water masses. The closest relationship is observed between the electrical conductance, bicarbonate content and total hardness. (Fig. 3 and 4). The relationship between these characteristics may be expressed by a linear equation. The correlation coefficients, angular coefficients of regression and values of free members of these equations for several water masses are given in Table 12. The high correlation coefficient (0.90 and over) of these relations is quite regular since the $HCO_3^{'}$ and $Ca'' + Mg''$ ions are predominant in the natural waters of the region studied. The extremely high values of the coefficient of correlation between the concentrations of $HCO_3^{'}$, $Ca'' + Mg''$ and the electrical conductivity indicate relatively high stability of the calcium carbonate equilibrium in the initial water masses of the Gorky reservoir. The equations cited may be used both for controlling the individual hydro-chemical determinations and for tentative calculation of the balues of one characteristic by using the known value of another. It was not possible to determine the regular variation of regression equation parameters from river to river in connection with their specific physical and chemical properties.

Apparently, the differences of these parameters are immaterial. They may be caused by errors in hydrochemical determinations as well as by an insufficient number of members of the series being correlated. The monotypicity of these equations indicates the relatively homogenous chemical composition of the waters in the rivers investigated. That is why A. A. Zenin succeeded in discovering a common relationship between the electrical conductance and total mineralization of the waters of the Volga and its major tributaries.

The existence of the correlative link between transparency and electrical conductivity of water was recorded in the water masses of three rivers: the Unzha, Nemda and Mera (Fig. 5). This relationship, unlike that noted in previous investigations, is not a functional one having a chemical nature, but is due to peculiarities of river water mass formation, i.e., it is a stochastic link of a geographical order. Within the range of values observed this relationship may be expressed by a linear equation of regression.

$$P = \alpha K + b$$

where P is the transparency in cm,

– the electrical conductance in μ mho/cm.

The parameters of these equations are shown in Table 13.

The existence of a relationship between these characteristics is explained by the fact that with a change of water flow rate in the river, e.g., during the rise of the rain freshet, the mineralization and conductance decrease, with simultaneous increase of turbidity and colour of the water, leading to reduction of the water mass transparency. That the coloration of water influences this link is shown by the regular variation of the free member of the equation (with angular coefficient constant) from the Mera - the river with the lowest colour to the Nemda, with water strongly coloured by organic matter. Due to the small amount of observation data it is not possible to establish such a relationship for water masses in other rivers.

There are relationships between the chromaticity and electrical conductance of river waters resulting from particular features of the process of formation of water masses in the reservoir tributaries (Fig. 6). They are curvilinear and inverse, that is, with increase of one characteristic the magnitude of the other decreases. This /27 is explained by the fact that when the subterranean portion of feeding increases, the mineralization and electrical conductance of the river water mass also increases, but its colour decreases. On all graphs shown in Fig. 6, the dots characterizing the water mass at the time of high water rise form detached groups to the left of the dot field common to the other periods. This most probably results from the fact that in the initial period of snowmelt in spring, the ground and swamps of the river basins are still in a frozen state. As a result, the waters of the initial phase of high water have decreased colour as compared with the equally low-mineralized waters which are formed in basins of rivers in the late spring period or during rain freshets. The general slope of the curves of the relation between electrical conductance and colour and their curvature depend on the physical and geographical characteristics of the river. For ease of comparison of these interrelationships we calculated the regression equations for them, conditionally replacing curved lines by straight lines. It is obvious from a comparison of the parameters of these equations (Table 14) that as the swampiness and afforestation of the watershed increases and the depth of river network carving, the values of these parameters increase, that is the angle of slope increases. It is not possible to determine such relationships for water masses altered under conditions of retarded water exchange. Lack of relation between electrical conductance and colour is characteristic of the Volga water mass formed in the Rybinsk reservoir, or for the waters of the Kostroma and its tributaries, which form and alter in the Kostroma expansion (Fig. 6), etc. These facts indicate the mixing of waters of different origin and the change of the initial colour in the process of their alteration that occur in bodies of water having slow water exchange.

DISTRIBUTION AND BASIC PROPERTIES OF WATER MASSES IN THE RESERVOIR.

The original water masses entering the reservoir retain for some time their typical character and peculiar features; owing to this it is possible to determine their distribution within the boundaries of the reservoir, according to a number of the most representative characteristics. At the same time as a result of transformation processes of these masses and their mixing at definite periods, a new water mass originates in the reservoir, different from the initial water masses in the whole range of their properties. /29

Let us examine in the Gorky reservoir the most characteristic types of distribution of water masses, both from primary sources and the waters of the reservoir at different seasons of the year. Let us take as the beginning of the hydrological spring the time of inflow into the reservoir of the first portions of flood waters from its tributaries. The beginning of the summer-autumn season follows at the time when the waters of the spring flood on the whole have been displaced from the reservoir, or completely changed. The start of winter coincides with the time when the rivers commence to be fed exclusively by ground water and an ice-sheet has been formed on the reservoir. The length of the hydrological seasons varies somewhat due to peculiarities of the hydrometeorological conditions in each year.

SPRING PERIOD.

The observations of the fifteenth survey (Table 1) give an idea of the main aspects of the distribution of water masses at the beginning of the spring filling of the reservoir. So far as hydrological observations made from the ice-breaker are concerned, data relating to the temperature, electrical conductance, colour and pH characterize only waters on the two basic navigable routes of the reservoir - from the locks of the Gorky hydro-electric generating station to Rybinsk and from Yur'evets to Kobylin in Unzha Bay. On the basis of observations made through the ice away from these routes it is possible to draw up, diagrams - admittedly far from complete - of the distribution of the enumerated data on water masses within the lake part of the reservoir (Fig. 7).

At the start of the survey the part of the reservoir in the vicinity of the dam to the south of Sokolskoe was occupied by uniform winter waters of Volga origin. At the eastern shore of the basin, northward from Sokolskoe a small patch of altered winter Unzha waters was discovered. In the lower half of the five meter deep vertical the temperature was 0.2^{o} and electrical conductance 252 μmho/cm. Approaching the lower edge of the ice the electrical conductance dropped to 217 μmho/cm and the temperature to 0.0^{o} owing to melt waters seeping under the ice. The horizontal gradient of electrical conductance in the frontal zone between the Unzha winter waters and the waters of the reservoir was approximately 85µ mho/cm/km. Winter Volga waters, much changed because of mixing with flood waters of small tributaries of the river part of the reservoir, occupied the above-bed stretch of the body of water northward from Sokol'skoe. The floodplain section of the Yur'evets expansion was filled with flood waters of the Unzha and Nemda Rivers, the indices of which are given in Table 11. From here they spread southwards, wedging in tongue-like in the central area of the reach of the reservoir, situated to the north of Sokol'skoe. In this region the spring altered waters of the Unzha showed an electrical conductance of 126-128µ mho/cm and colour index of 50-52. The eastern wing of the frontal waters of the Unzha flood was their border with winter river waters, and the western wing separated the spring Unzha waters and much altered Volga water mass. Nemda flood waters, still less mineralized than those of the Unzha, occupied the northern part of the Yur'evets expansion. From here they flowed in a narrow stream to the south along the submerged edge of the Volga channel, separating the Volga and Unzha water masses. On the border of the Volga waters and Nemda waters at Yur'evets, the greatest horizontal gradient of electrical conductance - 160µ mho/cm/km was observed in the Gorky reservoir.

/30 By the end of the survey, the location of water masses had changed, but the values of their main characteristics remained similar to those already quoted. The part of the reservoir near the dam, southward from Puchezh, was filled by altered Volga waters replacing winter waters of the reservoir which had been there previously. At that time, flood waters of the Kostroma, altered on their way by the Volga water mass, and those of the Kotorosl' and other tributaries started to enter the lake part of the reservoir from the river part.

/31 In these waters the electrical conductance was 105-121 μmho/cm, temperature from 4° to 6°C, colour index 45-50 , and pH value 6.7-6.9. This water mass filled the whole river part of the reservoir below the Kostroma expansion and penetrated the lake part along the old Volga channel where these waters cooled to 0.5°-2.0°C due to heat lost in thawing of ice. At Sokol'skoe they intermixed with flood waters of the Unzha and Nemda which enter here by the left shore floodplain part of the body of water. Between Sokol'skoe and Puchezh were waters of mixed origin. The reservoir area between the Kotorosl' mouth and Kostroma expansion was filled by flood waters of the Kotorosl' mixed with the Volga water mass. Their electrical conductance was 168-181 μmho/cm and temperature 7°-10°C. The area of the Yaroslavl'-Rybinsk hydro-electric station was filled by the Volga mass, the waters of which at this time of the year were relatively cold and highly mineralized (Table 6).

The character of the distribution of water masses in the reservoir in the mid-spring period may be illustrated by the results of the sixteenth survey made in May, 1963. Inflowing from the Rybinsk reservoir the Volga water mass at this time had the highest mineralization with an electrical conductance of 235-247 μ mho/cm, and a temperature of 10°-12°C. It occupied the uppermost section of the reservoir - up to Yaroslavl'. Lower, down to the Kostroma expansion extended mixed waters of this mass and of the Kotorosl', a fact that is confirmed by the increased values of the electrical conductance and the higher temperature. At this time the Kostroma expansion was filled with flood waters of the rivers feeding it. In the southern and central sections of the expansion, waters had an electrical conductance 110-120 μ mho/cm and a colour index of 65, while its northern part was filled by waters with an electrical conductance of 130-150 μ mho/cm and a colour index of 80. The lower stretch of the river part of the reservoir was occupied by the Kostroma water mass which had the same indices as in the first days of May. Penetration of slightly altered Kostroma water mass into the river part of the reservoir, observed by us in 1963, is a comparatively rare occurrence, and possible only during periods of high water with low run-off when discharges of the

Rybinsk hydro-electric station are sharply reduced at the time of filling of the reservoir. In years with a high spring run-off or with one close to the average of many years, the volume of water being used by the Rybinsk hydro-electric station is commensurable with or exceeds the spring run-off of Kostroma. In such years, apparently, the river part of the reservoir is sometimes filled up with Volga water which in greater or lesser degree is diluted by Kostroma waters.

In the lake part of the reservoir the Kostroma water mass front moved from Yur'evets westward along the left edge of the old Volga channel towards the chain of islands, situated between the villages of Vospitsa and Stolpino. The presence of this front is well seen by the crowding of isolines on the charts of distribution of the electrical conductance, bicarbonates and hardness (Fig. 8), temperature oxygen and pH. The lake part below this frontal zone right to the dam of the Gorky hydro-electric station was filled by the only water mass formed mainly from the flood waters of the Unzha and Nemda. We assume the origin of these waters because of the low values of the electrical conductance (50-90 μmho/cm), alkalinity (0.30-0.80 mg-eqv./l) and total hardness (0.50-0.90 mg-eqv./l). The alteration of the initial masses indicated by the values of the other indices of temperature, oxygen, pH, colour, etc., is so significant that in this case it is possible to speak about the origin in the lake part of the reservoir of a new water - the spring water mass of the reservoir proper.

Typical in this case is the stratification of temperature, oxygen, pH and low colour (35-45), which /32 decreased to half in comparison with that of the initial masses. In the surface layer of this mass intense growth of the phytoplankton was observed. The enumerated features of the spring water mass in the reservoir originated as a result of the rapid warm-up of its waters under the conditions of extremely slow water exchange. The degree of water alteration in various sectors of this mass was not the same and depended mainly on the duration of stay in this or that part of the water body. This was the reason why in the north-east of the Yur'evets expansion the characteristics of the water were somewhat different: colour up to 80°, pH of surface water layers about 7.0, etc. The bays of the Unzha and Nemda were, at that time, filled by vertically uniform river waters formed in channels of these rivers at the stage of high water drop (Table 11). In the least flowing areas near the shore in the vicinity of the dam of the reservoir there remained waters of the Volga mass that were greatly altered at the time of the spring fill-up of the reservoir (Fig. 8).

The results of the first, fifth and nineteenth hydrological surveys give an idea of the distribution of water masses of the reservoir at the late spring period (Table 1). At this stage only in individual sections of the reservoir lake part, there still remain relatively small patches of water masses of the reservoir formed as a result of the spring high water. In 1961, at the time of the first survey, the whole river part of the reservoir was filled by the summer Volga water mass, the electrical conductance of which was 175 μmho/cm near Rybinsk, but towards the lake part the value of this characteristic increased to 200 μmho/cm. The colour index of these waters was 50-70 , and the transparency averaged 100 cm. In the lake part of the reservoir the summer Volga waters, homogeneous through all their mass, filled the north-western part of the Yur'evets expansion, and the lower reaches of the bay along the Nemda (Fig. 9). In the Sorochkov area there was a sharply marked front between these waters and those blocked by them, the highly /33 coloured and low mineralized altered flood waters of the Nemda. In the east and south-east the Volga waters came into contact with the flood waters of the Unzha. Their main body, the least changed by the mixing process, was located at the south-eastern edge of the Yur'evets expansion. The front between the Volga and Unzha waters passed from the group of Isakovski Islands towards Yur'evets, and turned southward along the lip of the Volga bed and the western chain of the Yur'evets Islands. The least width of this frontal zone was on the lip across from Yur'evets, where the horizontal gradient of electrical conductance reached 25 μmho/cm /km. In the expanded reach, northward from Sokolskoe, was the mixing zone of Volga and Unzha waters and of the formation of the water mass of the southern half of the lake part of the reservoir, homogeneous in its properties. The front of the water mass, so distinctly marked at Yur'evets, was becoming blurred in the zone of mixing.

The distribution of water masses at the same period in 1962, and their basic characteristics were similar to those described. The earlier published article (Edel'shtein, 1965 a) contains more information on the data obtained in the course of these two surveys.

In 1963, the distribution of water masses typical for the late-spring stage reappeared (Fig. 10). But due to the increase in the river flow in June of the same year, as compared with 1961 and 1962, at the time under discussion the waters of the Nemda and Unzha advanced southwards more /34
swiftly than usual and occupied the central part of the Yur'evets expansion. The bay along the Nemda, northwards from Lubyany was filled by the waters of the rainfall induced freshet of the river, indices of which are given in Table 11.

The eastern part of the Yur'evets expansion and the lower reaches of Unzha bay were filled by the spring waters of the Unzha. In the Nezhitin area these waters were separated by the clearly marked frontal zone from the higher bay waters of the rain-induced freshet of the river. The southern half of the lake part of the reservoir was filled by the water mass of the reservoir proper. In contrast to previous years, at the time under consideration, its electrical conductance (130-150 μmho/cm) was lower than normal, and in the area adjacent to the dam, the values of this characteristic were even approximately 100 μmho/cm. As for the other indices, this water mass was the same as in 1961 and 1962. Reduced mineralization of the reservoir water mass as well as greater than usual movement of the river waters into the open part of the reservoir are explained by the peculiarities of the water balance of the reservoir in the spring of 1963, when the inflow into it of the Volga water mass was lower than in previous years, and the discharge of rivers in June was higher. This caused a reduced water exchange in the spring period and a lower speed of displacement of the spring water mass from the reservoir.

V. I. Rutkovski (1963) also observed on 22.VI.1960 a distribution of the electrical conductance values along the axis of the Gorky reservoir typical of the late-spring period, when the values of this characteristic were decreasing from 185-190 at Kineshma to 90-100μmho/cm at the Gorky hydro-electric plant.

SUMMER-AUTUMN PERIOD

/35

Judging by the data of the three-year long observations, the beginning of the summer-fall season, with its typical water mass distribution, usually occurs in the Gorky reservoir in the middle of July. Towards this time all waters that by their origin are connected with the spring river flood are either forced out of the reservoir or completely intermixed with the summer water masses. The peculiarities of the summer-fall distribution of water masses in the reservoir will be examined in the light of four hydrological surveys - the third, seventh, ninth and eleventh (Table 1). The first two give an idea about the distribution of water masses in the reservoir and their basic properties during the summer low-water period in tributaries; the last two were conducted during the heavy run-off of the freshet waters in the very wet summer-fall season of 1962.

At the time of the July survey in 1961, all the river part of the reservoir was filled with Volga water having an electrical conductance of 160-180μmho/cm, a transparency of 90-100 cm and a colour of 50-60°. The water mass of the reservoir in its lake part did not differ from the Volga mass as regards electrical conductance and colour, which proves, so to speak, its Volga origin. With the exception of the area adjacent to the dam, southward of the mouth of the Yachmen', the electrical conductance of the waters gradually dropped and was 142 μ mho/cm at the locks of the Gorky hydro-electric plant. However, despite the same values of the two basic characteristics of both water masses the reservoir water differed from the initial Volga waters in a number of other features: an increased transparency in the deep-water areas (from 130 to 190 cm) and the presence of temperature stratification, with the thermocline at the depth of 10 m. At all channel stations in this water mass the metalimnion was well marked (Fig. 11). The above mentioned indications of transformation of the initial mass into the water mass of the lake type appeared between the mouth of the Elnat' and Yur'evets, where, consequently, the conditional boundary line lay between the Volga and the summer waters of the reservoir proper.

In the Vtarushenski Island area, to the south of Kobylin, the front of the summer water with the Unzha waters, of an electrical conductance in excess of 200 μ mho/cm, was clearly expressed (Fig. 12).

In July, 1962, the water mass distribution in the reservoir resembled that described above. The river part was fully taken over by Volga water; its electrical conductance was lower than in the corresponding period of 1961 by only 10 μmho/cm. In the southern part of the Kostroma expansion a very blurred zone of blending of this mass with the low level waters of the Kostroma was observed, which were found in the "purest" state in the northern part of the expansion. Their characteristics are given in Table 11. In the lake part of the reservoir the Volga water mass occupied the above-bed right shore area of the Yur'evets expansion and the western half of the expanded reach northward from Sokol'skoe (Fig. 13). The remaining part of the lake region of the reservoir was filled by the summer water mass of Volga origin, here greatly altered due to intermixing with the remainders of the flood water of tributaries and warming up under conditions of slow water exchange. /36

And only in the north-eastern part of the Yur'evets expansion were found the low level waters of the Unzha with increased mineralization and electrical conductance. In the upper reaches of Unzha Bay - at Nikolo-Makarov - there appeared at this time freshet waters sharply differing from the low-level waters of the river in all indices (Table 11).

A very high summer flow in the Unzha of little mineralized and highly coloured waters, mostly due to rain towards the beginning of September, 1962, determined the character of distribution of water masses in the lake part of the reservoir which closely resembled that inherent in the late spring period. The Volga waters were filling up the western part of the Yur'evets expansion and the channel area of the reservoir between its right bank and the Yur'evets Islands (Fig. 14). The altered Unzha freshet waters, differing from its flood waters by greater turbidity and increased colour, were found in the Unzha bay, in the eastern part of the Yur'evets expansion and in the floodplain stretch of the reservoir between the Yur'evets Islands and the left bank. The center of the altered waters of the flood stage, just as at the end of spring, was located in the left-bank station area of the Yur'evets cross-section. The northern part of the Yur'evets expansion and the lower reaches of Nemda bay were taken over by the Nemda waters, modified by mixing with Volga waters. In the broadened reach above Sokol'skoe and southward down to Puchezh, there was a zone of vigorous intermixing of the Volga and Unzha waters. That part of the reservoir adjacent to the dam, just as in August, was filled by the uniform summer water mass of the reservoir proper. /40

The distribution of water masses in the reservoir at the late fall period may be judged by the data obtained during the October, 1962, survey. At this time the river part of the reservoir was filled, as before, by Volga water. Its electrical conductance was 150-170 μmho/cm and gradually increased on approaching the lake part of the reservoir. The temperature of water was 5.0°-6.5°C. The bays near the mouths of the tributaries were filled by river waters which differed from the Volga waters not only as regards increased mineralization but also by lowered temperature. So, in the Kostroma expansion, the maximum temperature measured by us during this survey was 4.8°C, and in shallow-water areas it did not exceed 2.5°C. In the bays of the Mera, Zhelvata, Elnat' and others, the water temperature was 2° - 4° lower than in the Volga water mass. In the lake region of the reservoir the latter occupied the central, northern and western parts of the Yur'evets expansion. In the north, in the area of Lubyany, it adjoined the waters of the Nemda which had indices typical of a freshet stage of this river (Table 11). The temperature of the Nemda waters was lower than 2.0°C. The Unzha water mass, less mineralized and much more coloured than that of the Volga, filled the eastern part of the Yur'evets expansion and a large part of the left bank floodplain of the expanded reach at Sokolskoe (Fig. 15). In Unzha bay, more to the north of Nizhitin, the mineralization and electrical conductance of the water increased, while the colour decreased slightly. Just as in Nemda bay, the temperature of water here was lower than 2.0°C. All of the remaining part of the lake area of the reservoir was filled with lake water formed mainly of waters of the river freshet stage, and uniform as regards its characteristics. This is proved by the colour of the reservoir water mass, higher by 15 - 20°

as compared with the purely Volga waters. As for its other characteristics, their values are close to those of the Volga water mass.

WINTER PERIOD.

Since the reservoir is difficult of access in winter, only limited data are available. These comprise the characteristics of distribution and basic features of water masses collected during only two hydrological surveys (Table 1) carried out within an abbreviated program as compared to surveys made in navigational periods. However the limited extent of observations in winter, would not seem to be the reason for the less detailed characteristics of the water masses in the reservoir investigated, since its high winter flowage, considerable preponderance of the Volga water mass over the river water mass, and isolation of water masses by the ice cover from the direct effect of meteorological factors cause great uniformity of the water which fills the reservoir in the winter season.

According to the data of the first winter survey, the reservoir was almost wholly filled by Volga water, very uniform as regards its properties (Fig. 16). The temperature of Volga waters from the surface to the bottom showed values of 0.0° - 0.2°C. Surface layers were occupied by water with identical characteristics down to the depth of 4 - 5 m in the lower area of the bay along the Mera, but here their temperature was higher, increasing up to 0.8°C with depth. In the lower reaches of the bay, but above Dolmatovo, the water layers close to the bottom and through the entire vertical represented the winter water mass of the Mera, the indices of which are given in Table 11. Towards the head of the bay, the temperature of water near the bottom decreased, and at Dolmatovo it was 0.3°C. An analogous picture of the vertical /41 water stratification was also observed near the mouth of the Elnat' at the vehicular bridge. In the surface layer, four meters deep, there were Volga waters with a conductance of 189 μ mho/cm and pH of 7.0, and a near-bottom layer two meters deep - winter waters of the river - having an electrical conductance of 242 μ mho/cm, a pH of 6.8, and colour of 40. Vertically, the temperature of the water gradually increased with the depth and reached at the bottom 0.7°.

In the northern part of the Yur'evets expansion waters of the Nemda were found having a conductance of 140 - 160 μ mho/cm, high colour (up to 100), and pH of 6.4. The values of these characteristics show that these were river waters formed in the late fall period. Their prolonged stay in the same place is indicated by high values of the near-bottom temperatures: in the flooded floodplain 1.2°, in the old Nemda channel opposite Zavrazh'e 1.5°C. The clearly defined front between this water mass and the Volga waters advanced from Zavrazh'e towards the southern tip of the group of Isakovski Islands and further north-eastward toward the Nemda-Unzha watershed. Further up Nemda bay, the conductance of the water increased to 190 µ mho/cm, pH to 6.8, and colour decreased to 30, which indicates the penetration of Nemda winter waters into the bay.

Unzha bay was at that time completely filled up by Unzha winter waters. In the open part of the reservoir the waters of this river were found close to the bottom on the vertical at Isakovski island in the old Unzha channel. At this station, the upper layer, five meters thick, was composed of waters of the Volga mass, having a conductance of 187-190 µ mho/cm, colour of 75 and pH 7.0. At a depth of 7 m and deeper there were waters the conductance of which was about 225 µ mho/cm, colour 85 and pH 6.6. On the vertical, the temperature of the water increased gradually towards the bottom, where it reached 2.1°, the maximum was measured by us in the Gorky reservoir at the period of total ice cover. Apart from the described backwater region with the waters of the Unzha on the bottom, the presence of the autumnal Unzha freshet waters was established on the left bank of the Yur'evets cross-section, with a conductance of 172 µ mho/cm, water colour 95° and pH 6.7, which, possibly, occupied also the eastern part of the left-bank floodplain of the expanded reach northward from Sokol'skoe. With the exception of the areas enumerated, all the remaining volume of the reservoir in February, 1963 was filled by the Volga winter water. /42

During a very early spring survey the picture of the distribution of water masses in the body of water hardly changed. As before, the Volga water mass occupied all the river and the greater part of the lake portion of the reservoir. Around this time its electrical conductance increased to 200 - 216 µ mho/cm, water colour was 70° and pH 6.9 - 7.0. The temperature through the entire depth was close to 0°. The front between the Volga water mass and Nemda waters maintained its position at the same place, but the characteristics of the river waters had changed as a result of intermixing of the fall waters and winter waters which approached Zavrazh'e. In the Zavrazh'e area the electrical conductance of Nemda water increased to 194 - 197 µ mho/cm, water colour decreased to 40° and pH became 6.5. The temperature near the bottom had hardly changed and was 1.1 - 1.3°C. Nemda winter waters occupied the head of the bay with values of the characteristics typical for this period (Table 11). Just as in the previous survey, the near-bottom layers of the eastern part of the Yur'evets expansion were occupied by Unzha waters, but their thickness increased from 3.5 to 7.0 m. The Volga water mass occupied 1.5 - 2.0 m on the surface. In Unzha waters the electrical conductance increased to 286 µ mho/cm, but water colour decreased to 70°. The near-bottom temperature dropped to 1.6°C. In the Yur'evets section waters of Unzha origin were found, where they occupied all the space between the eastern chain of the Yur'evets islands and the left bank of the reservoir.

In the area near the dam of the reservoir southward from Puchezh a noticeable heterogeneity of waters along the transverse section of the reservoir occurred. The right bank part above the bed was taken over by waters having a conductance of 216 μ mho/cm, water colour of 70° and pH 6.9. The left bank above the floodplain part was filled with waters with a conductance of 177 μ mho/cm, water colour 80° and pH 6.6, with the temperature in the near-bottom layers of 0.4°C, while in the channel the temperature throughout the whole depth was 0°C. This heterogeneity of the water mass in the stretch adjacent to the dam may be explained, it seems, by the considerably greater flow of the part above the bed as compared with that above the floodplain, which is especially well marked during the lowering of the reservoir level at the end of the winter period. This is why at the time of the survey the former was taken over by "fresh" Volga waters, while the Volga waters which had come to the dam considerably earlier were delayed above the floodplain. Proof of this is the continuity of the values of the characteristics of the waters in the left-bank part of the stretch adjacent to the dam in the period between the first and second winter surveys, that is during more than one-and-a-half months.

Summing up the character of the distribution and properties of the water masses in the Gorky reservoir within the hydrological year, we give in Table 15 the most typical, according to our observations, limits of fluctuations of the values of some characteristics of the main water masses, and of their modifications found within the reservoir.

THE MOVEMENT AND ALTERATION OF THE WATER MASSES IN THE RESERVOIR

The distribution of the water masses in the reservoir and some of their qualitative properties are the result and the manifestation of dynamic processes occurring within a body of water. The character of the movement of the water and its alteration change considerably both from season to season and in various regions of the reservoir. The intensity of these correlated processes is determined by many factors: (1) the inflowing regime of the initial water masses into the body of water and their properties, which undergo changes during the year; (2) the character of the reservoir water discharge by the Gorky hydroelectric station, which, combined with the inflow, determines the water stage regime and flowage both in separate regions of the reservoir and in the entire body of water as a whole; (3) meteorological conditions of the basin, the most important elements of which are wind, radiation balance and the temperature of the air; (4) morphometric peculiarities of the reservoir, its configuration, depths, as well as the nature of the ground and shoreline; (5) the vital processes of the water organisms; (6) ice phenomena; (7) ground waters and atmospheric precipitation entering the body of water, etc. In this work, the first four factors that are of the utmost importance are discussed in more detail and others are only mentioned. Analysis and comparison of the evidence obtained in the course of repeated hydrological surveys in the body of water served as the basic method for investigating the movement and alteration of the water masses in the reservoir. The rate of transport of this or that water mass we judged by the speed of movement of either its core, that is the volume of water with a stable set of characteristics in their "purest" form, or by the movement of the frontal boundary of the water masses which is characterized by the maximum values of the representative characteristic gradient. The changes in values of the individual characteristics of the water mass between the subsequent surveys make it possible to form an opinion as to the direction and rate of water alteration, and to determine the leading factors in this process.

MOST IMPORTANT FACTORS IN THE ALTERATION AND DYNAMICS OF WATER MASSES.

<u>Flowage of the reservoir</u>. In the displacement and alteration of water masses found in the Gorky reservoir the principal role undoubtedly belongs to its general flowage. /44

The flowage of the reservoir during the year on the whole changes greatly; periods of intensive exchange of waters alternate with periods of delayed water exchange. Considerable variability in the reservoir flowage is connected with the peculiarities of the agricultural control of the Volga flow at the sites of the Rybinsk and Gorky hydro-electric schemes, as well as with the water conditions in numerous tributaries of the body of water under examination.

The degree of water exchange in the reservoir directly determines the rate of transport of water masses and the duration of stay of any given water mass in the reservoir. As a rule, the alteration of water properties decreases with the increase of the rate of water transport, as the time of the influence upon them of transforming factors is reduced. In conditions of delayed water exchange, they develop features peculiar to water masses of the lake type, in which the hydrometeorological and biological factors play the basic transforming part. The intensity of the process of intermixing, which leads also to alteration, modification of original properties of waters, depends on the relative movement rate of the adjacent water masses. The degree of change in optical properties of water masses, process of deposition and suspension of debris, the development of plankton and coagulation of humic matter that determine the colour, is closely connected with the flowage of separate areas of the body of water.

As has already been shown, the flowage of the Gorky reservoir is determined by the interaction of two hydroelectric schemes and the discharge of rivers falling into it. The characteristic variations of annual and monthly volumes of water entering the reservoir at the time of our research were given above when we described the original water masses. But the intramensual irregularity of water flowing through the Rybinsk hydroelectric scheme shows the strongest influence on the hydrodynamic conditions of the water masses, particularly of the river part of the reservoir.

In contrast to the relatively even character of the flow alteration of the river waters, the Volga water mass discharges into the Gorky reservoir by separate short-term releases which cause irregular conditions of water movement in the river part of the reservoir.

On the average about 98% of the annual volume of discharge of the Rybinsk reservoir passes through the hydroelectric station plants (Belykh, 1959) and enters the Gorky reservoir by the Sheksninski channel. For most of the year the station operates on a half-peak regime with prolonged night stops of 6-8 hrs and double reduction of the load down to full standstill of turbines from 12 to 2 p.m. and from 4 to 7 p.m. (Balagurov, 1957). In the transition of the units from idle run to full load, the flow being discharged to the tailwater in a short interval of time increases by tens of times. The duration of the night interruption in the discharges, the time of the beginning and end of the peak period, change from season to season in accordance with the duration of daylight. Maximum diurnal discharges are usually observed twice in 24 hrs., at 9 a.m. and 9 p.m. The flow rate of water at these moments is different at various periods of the year and depends on the water supply of the hydroelectric scheme, power load and pressure.

Daily alternation of day maxima and night minima of discharge is disrupted on inoperative days, when, owing to the decrease in the power load, only one or two turbines run idle and the remainder do not run at all. On such days the quantity of water passing into the tailwater is determined by the small load-free discharges of the hydroelectric station and filtration, and in addition, during the navigation period, by water consumption by locking. The water for the latter enters the Gorky reservoir by the Volga channel and usually during 24 hrs. average 2% of the total discharge into the tailwater of the hydroelectric station. In individual months the fluctuation amplitude of diurnal average of water usage by Rybinsk GES may reach 2000-2500 Departures from the usual peak load of the hydroelectric scheme occur only at periods of high flood, when the capacity of the Rybinsk reservoir is close to full (for instance, May, 1961).

The second factor which determines the flowage of the reservoir on the whole is the draw-off regime of the Gorky. On the operation of the latter depend the annual changes in level and volume of its headwater, and, consequently, gradients and rates of flow along the whole reservoir. The special features of discharge regulation by this hydroelectric plant are connected, in the first place, with the relatively small usable volume of the reservoir (2.75 km^3), which allows the realization of only seasonal control of discharge; in the second place with its position as a closing reservoir of the upper Volga series. The maximum water discharge from the reservoir in the spring takes the form of an annual clearly expressed peak. During the navigational season discharges are made in such a way that, on the one hand, they keep the level close to the normal storage level and, on the other, secure an inflow into the tailwater of enough water to maintain navigable depths. While this discharge is flowing into the reservoir the draw-off continues at the peak level.

In winter, the amplitude of fluctuations in diurnal discharges increases owing to the decrease in the volume of guaranteed discharges, increase of transit flow from the Rybinsk reservoir and pre-spring usage of the usable volume of the reservoir. The discharges in the summer of 1962, caused by high summer inflow into the reservoir, were considerably larger than usual.

A highly useful index of flowage of the entire reservoir as a whole is the coefficient of its water exchange (Table 16).

As is shown in the Table given, the largest flowage of the reservoir is observed in the spring - in April and May - when the monthly draw-off from the reservoir on the average is commensurable with its volume. During the summer-fall season the flowage of the reservoir is at its minimum; during winter the flowage gradually increases. As compared with the normal summer of 1962 the increased water exchange in the reservoir should be noted: it was the result of high steam flow and intense discharges hydroelectric generating station at this period. Both the annual and the monthly water exchange coefficients are subject to considerable variation and depend on the precipitation of of the year. The magnitude of the annual coefficient of water exchange in the reservoir varied from 8.63 in 1957 to 4.78 in the dry year 1960 with an average annual value of this index for 1957-1963 of 6.72. In order to compare the intensity of flowage in the Gor-ky reservoir with other analogous water bodies Table 17 is provided. As may be seen from this table, only five large reservoirs of the European territory of the Soviet Union are characterized by smaller /46 values of the water exchange coefficient than the Gorky reservoir. More complete data concerning water exchange in reservoirs of the USSR were published in the work of O. P. Antipova (1961), however the coefficients of water exchange cited by her do not in all cases coincide with the data of other authors.

Principal features of the meteorological regime of the reservoir. The meteorological regime of the reservoir plays a very important role in the process of transformation of its water masses. Strength and direction of wind, components of the radiation balance and air temperature are particularly important. Above all, these elements of the meteorological regime primarily determine the thermal condition of water masses - the character and speed of their warming and cooling. The effect of wind on waters of the reservoir causes mixing, waves and tidal effects which accelerate transformation of the water mass, and in individual cases (under conditions of the lake part of the Gorky reservoir) have a marked influence on their movement. During the period of ice cover, the influence of meteorological factors on the water mass of the reservoir is minimal, and depends only on the thickness of the ice and snow cover of the reservoir, and heat exchange with the atmosphere depends on weather conditions.

The climate of the reservoir basin is temperate continental; there is a short and comparatively warm summer and a prolonged cold and snowy winter. According to the long-term data of many years of observations, the mean diurnal air temperature rises above 0°C in the first ten days of April, after which a high snow melt begins with a gradual increase of the temperature of the water under the ice. The break-up of the ice cover and disappearance of ice from the reservoir is normally observed at the end of April and in the first ten days of May. As the peak of solar radiation occurs in May, June and July, the spring warm-up of water masses in the reservoir is quite intense. Gentle breezes (2-5 m/sec.) prevalent in May from the western and southern quarters stimulate vertical mixing of the reservoir waters, which warm up towards mid-May to 8°-11°C with almost complete homothermy. Later on, when the flowage in the reservoir decreases, as a result of warming of the surface layers at a time of absence of great wind-induced mixing, a thermocline develops. The daily (24 hr.) variations of the air temperature sometimes reach 15°-20°C and intense heat exchange between water and atmosphere causes considerable daily periodic temperature changes in the surface layers of the reservoir, the maximum amplitude of which may occasionally be 5°-6°C. The spring water mass of the lake part of the reservoir undergoes stratification, during which alteration processes of waters in the epilimnion proceed more intensely than in the hypolimnion, due mainly, to the active life of /47 plankton organisms. The density stratification in the lake waters determines also the character of the inflow of the initial water masses into the open part of the reservoir.

In summer, under the influence of wind-wave mixing and further warming, the thermocline either sinks or completely disintegrates, which leads to the formation of a vertically highly uniform summer water mass in the reservoir proper. Of particular importance in the formation of the latter are water shiftings caused by tide-induced variations in the level, reaching 30-40 cm at times (Yaroslavtsev, 1965), and currents in the near-shore zone. During strong winds the speed of these currents accelerates to 30-80 cm/sec. (Yaroslavtsev, 1961); this contributes to concentration of suspended matter in open parts of the reservoir. Since the reservoir was established, winds over its water area have became noticeably stronger. At Yur'evets, according to data of the Volga hydrometeorological observatory, the frequency of winds with velocity of 6-10 m/sec. increased from 32% to 48%, winds with a speed of 11-15 m/sec. - from 4.0% to 5.4%, and of over 15 m/sec. - from 2.0% to 4.3%.

In connection with the lowering of the air temperature and decrease of solar radiation heat transfer in the reservoir water masses starts to predominate from mid-August. Autumn water cooling, which, as a rule, takes place at a time of moderate and strong winds, occurs relatively uniformly through the whole depth of the reservoir water mass; its temperature in the first half of November decreases to 0°-1°C. Normally, in mid-November comes the period of stable ice cover.

The main features of the changes in the most important elements of the meteorological regime of the reservoir during the years of our investigations are shown in Fig. 17, where the ten day values of maximum and minimum mean air temperatures are represented, sunshine duration expressed in percent of the possible duration, total precipitation, and wind velocity in average and maximum monthly values, according to data of Yur'evets and the Volga hydro-meteorological stations. These points represent quite well meteorological conditions above the water area of the lake part of the reservoir, where the alteration of water masses due to meteorological factors is most clearly expressed.

Distinctive morphometric features of the reservoir.

The character of displacement of water masses and their alteration in the reservoir are closely connected with the morphometry of its bed. The configuration of the reservoir and the distribution of depths substantially influence the speed and prevailing directions of water mass movement. Different depths and roughness of the channel and flood plain areas cause great speeds of water transport over the flooded beds of rivers. Numerous shallows and islands within the old flood-plain areas slow down, and sometimes even prevent, the movement of the water masses; therefore, the boundaries of separate water masses often pass through these /48 shallows and islands. In the constricted parts of the reservoir the role of the main dynamic factor falls to run-off gravitational currents; in the enlarged stretches wind action becomes more important, leading to mixing and the creation of drift currents. The depths of individual areas are very important during the water-mass alteration - during the warming and cooling, intermixing, rolling and precipitation of suspended matter, etc.

The configuration and morphometry of the Gorky reservoir are determined by the particular features of the structure of the Volga valley and its lower tributary stretches. From the Rybinsk hydro-electric development to Kostroma, the reservoir waters do not flow outside the limits of the old Volga channel, and that is why the reservoir preserves here the outer appearance of a river. The width of the river part of the reservoir varies from a few hundred metres up to 1.5-2 km; narrowing at Tutaev and Ples where the Volga intersects moraine highlands, and widening in the Kostroma lowland and below Kineshma. The greatest depths in this part of the body of water, with a /49 general tendency toward an increase from 3-6 m at Rybinsk to 12-17 m below Kineshma (at normal storage level), vary greatly along the waterway due to large preserved features of the channel relief. The upper stretches of the reservoir, there are also marked by variations in depths at the time of the sharp fluctuations of the water level, caused by the releases of the Rybinsk generating station.

The lake part of the reservoir, about 100 km long, is made up of a series of widenings and narrowings, its width varies here from 4 to 16 km. Depths over the submerged floodplains gradually increase north to south, from 3-4 m to 9-12 m; in the channel sections they reach 15-22 m. Of great importance in the process of the mixing of water masses in the lake part of the reservoir is the fact that the Volga channel in the Sokol'skoe region comes close to the left bank of the reservoir, while in the remaining stretches it is found mainly along the right bank and more seldom in the middle of the reservoir.

There are two groups of islands in the lake part of the reservoir - the Isakovskie, which are a continuation of the Nemda - Unzha watershed, and the Yur'evetskie, which consist of the non-flooded upper parts of the floodplain ridges. These groups of islands and the shallows around them are the obstacles to the mixing of the water masses by which they are surrounded.

There are a great number of bays in the reservoir, /50 formed as a result of flooding of the lower areas of its tributary valleys. Amongst them, the largest are the bays along the Kostroma (Kostroma expansion), Unzha, Nemda, Meza, Zhelvata, Yelnat' and a few others. As a rule, these bays are largest and deepest in their lower reaches, but they become narrower towards the headwater and gradually merge with the channel of the corresponding tributary. The only exception is the Kostroma expansion which has three wide and shallow reaches which are joined to the main Volga channel by a narrow strait.

Since the fluctuations of the level in the lower part of the reservoir are not large for most of the year, its configuration and depths remain practically unchanged during the whole navigational season. In the winter time the level is lowered (according to the scheme by 2 m) and the reservoir's area and volume change - by 23% and 32% respectively. (Butorin, 1963). This is mainly due to the drying of shallows located principally near the bays at the mouth and partly in the northern area of the lake section of the reservoir. During the period of ice cover the lowering of the level and decrease of depths contribute to the increase of the relative roughness of the floodplain areas of the reservoir as compared to the channel areas, and bring about considerable non-uniformity of water exchange in these areas.

Dynamics and alteration of water masses in the river part of the reservoir. The dynamic condition of the waters filling the river part of the reservoir is determined chiefly by the rate of the Rybinsk hydroelectric station discharges. The run-off of tributaries and the character of regulation of the level of the headwater of the Gorky reservoir play a lesser role in the process of displacement of the Volga water mass. Because of the small width and considerable sinuosity of this part of the reservoir, the effect of the wind on it is immaterial.

The Volga water mass entering from the Rybinsk reservoir fills almost the whole water area of its river part. The water masses of the Kotorosl' and the Kostroma, the largest tributaries of this reservoir region, for most of the year occupy small areas (the pre-estuarine zones of their channels in the backwater) and only sometimes, at a high water period, can they extend into the former Volga channel. The influence of the waters of the remaining tributaries of the river part on the main water mass of the reservoir is negligible and is perceived only in the headwaters of their bays near the mouth.

During its movement through the river section of the reservoir the Volga water-mass alters as a result of mixing with water of the tributaries as well as under the influence of meteorological factors. In the spring, the most significant changes in the Volga water characteristics are observed during their mixing with large volumes of low mineralized and relatively warm waters of the large tributaries. Fig. 18a shows changes in electrical conductivity and water temperature at the surface along the Volga waterway typical of various dates in the spring season.

In the first ten days after the melting of the ice cover (the survey of 3-4 May, 1963) highly mineralized waters with electrical conductance of over 200 μ mho/cm enter the Gorky reservoir from the Rybinsk one. Below the mouth of the Kotorosl' and particularly below the new mouth of the Kostroma (more precisely, the strait connecting the Kostroma expansion with the Volga channel), the electrical conductance decreases sharply.

During late spring, when the high water declines in the large tributaries (surveys of 16-18 and 28-30 May, 1963) the water electrical conductance increases below the mouth of the Kotorosl' but decreases below the /52 Kostroma expansion. In 1963, during almost a whole month, water electrical conductance remained stable - at about 110 μmho/cm at the lower limit of the river area of the reservoir. (Fig. 18). The invariability of this characteristic apparently indicates the slowing down of the movement of waters and their accumulation here in this period. Considerable vertical stratification of the water-mass, observed in the Kineshma area in mid-May (Fig. 19), coupled with the seepage of warmer and less mineralized waters into those which had earlier entered here, also indicates the rise of the level, due to the accumulation of spring waters.

Alteration of the Volga water mass in the spring is very noticeable by changes not only in conductance, but also in temperature (Table 18). First, cold waters entering from the Rybinsk reservoir get heated rapidly in the upper section owing to the intensive heat-exchange with the atmosphere which is facilitated by good mixing of water during water discharges by the hydroelectric station. Secondly, the increase of temperature occurs as a result of mixing of the Volga waters with those of rivers which at this time have become much warmer (Table 8).

In other seasons changes of the physical and chemical properties of water in the river part of the reservoir are less significant. In the summer-autumn season the conductance fluctuates within 135-160 μmho/cm, just as the water temperature usually increases gradually from Rybinsk toward Kineshma. Judging by the data of two cruises in 1963, the water mass all the way along the river part of the Gorky reservoir is almost completely uniform in winter (Table 19).

Under conditions of the highly complex and irregular dynamic cycle of waters in the river part of the reservoir, the usual methods of field work with regard to currents do do not describe fully the character of water movement in this section of the body of water. That is why we attempted to determine the main features of the hydrodynamic regime of this water indirectly, by analysing the pattern of water inflow into the reservoir and fluctuations of the level and gradients of water surfaces jointly with distribution peculiarities of some water mass characteristics.

During hydrological surveys, small but regular fluctuations of water conductivity in space and time were repeatedly recorded within the Volga water mass. As a result of investigating all the cases of non-uniformity of this water mass which were observed during navigation from 1961 to 1963, the following conception of the qualitative aspect of water movements in the river part of the Gorky reservoir was formed. /53

In the course of the greater part of the year the entry of the main part of the inflow into the reservoir takes place through the Rybinsk hydroelectric station, as periodical releases subject to a definite diurnal rhythm. With each new diurnal water discharge by the hydroelectric station, a release wave originates in its tailwater which speedily spreads downwards along the Volga channel. At the same time, in the upper reach of the reservoir, almost simultaneously, begins the discharge current. The velocity of thrust propagation related to the start of release and inducing a discharge current is very great under conditions of a pent-up backwater, when it exceeds 60 km/hr. (Edelshtein, 1956). The speed of the discharge current at the moment of release gradually decreases as the distance from the hydroelectric station increases, and its value in the individual sections of the reservoir may apparently be determined with sufficient accuracy from the maximum measured speeds: from 130-140 at Rybinsk to 10-20 cm/sec. at the mouth of the Yelnat'.

At night after the day-time release has stopped, the discharge flow in the upper reach slackens. By analogy with the pent-up tailwater of the Uglich hydroelectric station (Butorin and Litvinov, 1962) at night, in the immediate vicinity of the plant, there may even be expected a reverse movement towards the hydroelectric station, following the sharp dip in the water level.

Such a pulsating regime of water mass movement resulting from its inherent inertia is gradually balanced in the middle section of the river part of the Gorky reservoir, below which variations of current velocity in the course of a day induced by discharges of the Rybinsk hydroelectric station are imperceptible.

The usual diurnal rhythm is disturbed every week by the absence of daily water releases on inoperative days. On such days discharge currents stop almost completely throughout all of the river part of the reservoir, and in individual parts movement in the reverse direction may sometimes occur. The possibility of this phenomenon is indicated by frequently observed reverse gradients of the water surface (Edelshtein, 1965b). The pulsating movement of the water mass, which is typical of the river area of the Gorky reservoir, becomes distorted and distrubed by temporary changes in the work timetable for the Rybinsk hydroelectric station, by floods and freshets in large tributaries, ice phenomena, morphological peculiarities of the individual sections of the reservoir, etc.

As a result of analysis of the micro-heterogeneity of the Volga water mass in respect to water conductance, it was established (Edelshtein, 1965b) that waters flowing into the tailwater of the Rybinsk hydroelectric plant then flow through the river part of the Gorky reservoir as separate volumes or "portions". Such "portions" of 10 mln.m^3 and over, differing slightly from the enclosing waters in conductance, do not blend with the neighbouring water for several days despite the considerable velocity of flow and intensive blending in the tailwater of the hydroelectric plant. Movement of these "portions" of the water mass may be sometimes observed at a distance of 80 km or more from the Rybinsk plant. They may serve as an indicator of the true speed of water advance in the upper area of the reservoir, as an index of its flowage and water exchange. /54

THE INFLOW OF THE RIVER MASSES INTO THE RESERVOIR.

The water flow regime of the tributaries is the leading factor determining the process of inflow of the river-water masses into the reservoir. However, the character of the inflow and the mixing of the river waters and the water masses of the reservoir are so different in its upper section and in other areas that it is possible to talk about the existence of two types of inflow process within the limits of the Gorky reservoir. One of them is peculiar to the tributaries of the upper part of the reservoir, where its hydrodynamic regime is determined by the water releases by the Rybinsk hydroelectric station. The second type of inflow is characteristic of the tributaries of the lake part of the reservoir, where processes of mixing and alteration of river masses take place on the whole within the limits of the estuarine bays of the reservoir and depend on the water stage regime of the headwater of the Gorky hydroelectric station. In comparison with other factors, the role of the wind factor in the dynamic processes in the estuarine bays, as well as in the river part of the reservoir, is minor. The mixing process of the Kotorosl' waters with the Volga water mass may be considered a characteristic example of the first type of river-water mass inflow into the reservoir. A pronounced diurnal rhythm during the greater part of the year, with the exception of the spring period, is characteristic of the conditions of the estuarine part of the Kotorosl'. In the night hours, when discharge from the Rybinsk hydrostation is small, the flow of Kotorosl' waters into the Volga channel is observed, where mixing of both water masses takes place. In the morning hours, 3 - 5 hrs. after the start of heavy discharge by the hydrostation, the level of the Volga at Yaroslavl' rises so much that a reverse current appears in the channel.

The Volga waters advance into the mouth of the tributary, and the zone of mixing of water masses moves up-river. Thus, in the winter of 1963, with hydro-electric station discharges of more than 1,500 cm/sec. at a point 3 km upstream from the mouth of Kotorosl', considerable vertical heterogeneity of water was revealed in its channel. Judging by electrical conductance and a number of other indices, the cold waters of the Kotorosl' were found on the bottom, and in the upper half of the vertical they were diluted 50% with Volga waters.

During the observations, water started running out of the holes onto the ice. With maximum discharges from the Rybinsk hydroelectric station every 24 hrs. the Kotorosl' waters accumulate at the mouth area of the river, hardly entering the Volga's channel at all. The largest volumes of tributary water evidently flow into the reservoir when the level diminishes after a sharp reduction of the discharges from hydroelectric station.

Data concerning the distribution of the electrical conductance of the water along the Volga waterway, shown in Fig. 18, serve as an indirect confirmation that the inflow of waters from the Kotorosl' into the reservoir varies depending on the discharge regime of the Rybinsk hydroelectric station. When discharges by the Rybinsk hydroelectric station are intensive and the flow of the Kotorosl' is small there is no increase on electrical conductance below its mouth (surveys 16 VI, 18 VII, 3 VIII, 1962 and others). With slight discharges by the hydroelectric station there was either a pronounced general increase of electrical conductance, or separate peaks, below the mouth of the Kotorosl', indicating transversal heterogeneity of the current with respect to electrical conductance owing to the inflow of Kotorosl' waters (surveys 1/VI, 24 VII, 31 VII 1961, 21 VIII 1962 and others).

When a discharge flow into the reservoir occurs, waters flowing out of the Kotorosl' mix with the Volga water mass, and these altered waters press themselves against the right-hand shore of the body of water. The width of the mixing zone depends upon the relationship between the tributary rate of flow and the discharge of the hydroelectric station (Edelshtein, 1956 (b)). This factor also determines the extent of the mixing zone. At favourable moments it can extend along the right shore of the reservoir as a narrow strip of a fairly considerable length, up to 70 km. The boundary between purely Volga waters and those altered owing to mixing with the water mass of the Kotorosl' is usually located in the vertical plane (Fig. 20).

Similar conditions also characterize the rest of the areas located near the mouths of the reservoir's tributaries which flow in above the Kostroma expansion, but they are revealed less clearly because of the small discharge of the other rivers.

The peculiar features of the process of inflow into the reservoir and of the alteration of the water masses of the tributaries of the lake part of the reservoir are most pronounced in the bay at the mouth of the Mera. This bay is not wide (0.5 - 1.5 km) and is very winding with high forested banks. Its length is 16 km. The depth in the pre-estuarine stretch of the river at Pavlikha is 3-4 m; below which it increases to 9-11 m at the old mouth of the Mera. In the upper reaches of the bay the depth above the submerged floodplain on the average does not exceed 1 m; this part of the bay is heavily overgrown in the summer with higher aquatic plants. Further down the bay, the depth above the floodplain increases to 3-4 m. Morphological peculiarities of the inlet prevent any substantial wind effect on its waters.

High water of the Mera occurs at a reservoir level of 1.0 - 2.0 m below normal storage level, and in the early spring period the bay is washed out intensively by river flood-waters. Later on, as a result of the fast rise of level during the period of the filling of the reservoir, waters from its open parts penetrate the bay, and, being colder and more dense, flow under the water of the Mera. So, according to data of a survey (18 V 1963), waters from the Volga channel with an electrical conductance of 112-126 μ mho/cm and temperature of 10-15° occupied the near-bottom layer in the lower nine-km stretch of the bay. /57

The surface layer of the lower reach and the whole of the upper reach were occupied by warm (21°C) subsiding flood-waters with an electrical conductance of 160-200 μ mho/cm (Fig. 21 a).

The front of these water masses at the surface lay approximately 3 km from the former mouth, and up the bay it gradually plunged, coinciding with the thermocline. The blocked waters of the Mera high water, located in the middle part of the bay for over two weeks in May, 1963, had been greatly altered. Inside this mass temperature stratification appeared, its turbidity decreased, transparency increased to 1 m, and the pH of the surface layer became 7.9.

The vertical heterogeneity of the bay water usually remains until the beginning of the autumn cooling. The layer near the bottom is sometimes occupied by the Volga water mass; in the surface layer, located above the level of the river channel edges, spring waters are replaced by the river waters which have summer values of indices. In Fig. 21 (b) is shown the distribution of electrical conductance and the temperature of waters along the longitudinal section of the bay for a time when the water mass of the Mera had index values corresponding to the summer low water level; and in Fig. 21 (c) to the waters of a rain-induced freshet. The pycnocline prevents the mixing of water masses and divides the mobile river-waters from the slowly moving Volga mass.

With straight temperature stratification in the bay, relatively warm river-water always accumulates on the colder and denser Volga waters in the spring and in the first half of summer, independently of the ratio of the mineralization values of both masses (Fig. 21). This is explained by the fact that at high temperatures the vertical gradient of water density, conditioned by temperature, enormously exceeds the gradient caused by differences in water masses by reason of mineralization (Table 20).

Horizontal gradients of electrical conductance in the frontal zone between the water masses of the Mera and the Volga had much lower values - 20-50 μ mho/cm in 1 km - which corresponds to a density gradient of approximately 20-50 x 10^{-11}g/cm^4.

From the beginning of the autumn cooling, or with a sharp drop in temperature, which was the case in 1962, the temperature differences between the two water masses even up and conditions arise for the vertical intermixing of waters in the bay. Thus, mixing of the two water masses and their subsequent displacement from the bay into the Volga channel takes place; as a result of this the front of the water mass of the Mera approaches right to the mouth of the bay (Fig. 21 d).

The Mera waters flowing out of the bay show an insignificant influence on the alteration of the Volga water mass. According to our observations in August, 1962, a belt 150 m wide of very slightly altered waters with a conductance only 9 μ mho/cm greater than that of the Volga mass was extending along the left bank of the reservoir for no more than 5 - 6 km while being gradually eroded. /58

The basic peculiarities of the process of inflow and alteration of the estuaries of the tributaries of the lake part of the reservoir, such as the Unzha, Nemda, Zhelvata and Nadoga, Yelnat', Mocha, and others, were similar to those observed for the bay on the Mera.

In view of the smaller sinuosity of the valleys of other tributaries and greater wind-action on the waters of the bays, intensive intrusion of river-waters on water of the open parts of the reservoir was lacking, as in the Mera. The frontal zones dividing water masses are set either in a vertical or in a slightly inclined plane. The rate of advance of waters in the bays and the intensity of their alteration process were diverse, due mainly to the river water run-off regime and the morphological peculiarities of bays near the mouth.

By comparing the distribution of sufficiently conservative characteristics of the water masses (e.g. conductance or water colour) along the longitudinal axis of bays near the mouth of the reservoir with hydrographs of the corresponding tributaries, it was possible to determine tentatively the average speeds of movement of river water in these bays. As an example of such a calculation we shall examine the transport of freshet waters in the bay of the Nemda during the last ten-day period of July, 1962 (Fig. 22). The lower reach of the bay on 20/7 was filled with the summer water mass of the reservoir with a conductance of 150-155 μ mho/cm. The upper reaches of the bay were filled with waters of the rain freshet of the Nemda, the electrical conductance of which was 96-98 μ mho/cm. Between Sorochkovo and Khorobrovo there was the frontal zone of these water masses, extending for approximately 8 km. The maximum horizontal gradient of conductance here was 9.0 μ mho/cm in 1 km. It may be assumed as highly probable that the decrease of the conductance in the frontal zone was caused by the mixing of the water mass of the reservoir with the first portions of freshet waters. Judging by the hydrograph of the Nemda run-off (Fig. 2), waters of the initial phase of the freshet of that river traversed the final range at Selishche on July 10. Thus, from the 10th until the 20th of July these waters travelled 58 km along the Nemda channel between Selishche and Sorochkovo at an average speed of 6-7 cm/sec. According to data of a subsequent survey of the bay, carried out 11 days later (1.8.1962), the core of the freshet moved 10 km further on and approached Sorochkovo, while the frontal zone shifted 6 km down the bay, coming near to Zavrazh'e. Consequently, the speed of movement of the first portions of freshet waters in the following 11-day period was reduced on the average to 0.7 cm/sec., and the speed of movement of the core of the freshet to 1.0 cm/sec. With this, the extent of the mixing zone of the water masses decreased from 8 to 4.5 km, and the maximum horizontal gradient of conductance increased to 17.4 μ mho/cm in 1 km. /59

As a result of a similar analysis of the displacement of waters of the rain freshet of the Nemda in the same bay over the period between the 1st and the 9th of July 1963, it was established that, as the exit from the bay was approached the length of the frontal zone of the water masses decreased, and the maximum of the horizontal gradient of conductance increased from 10 to 38 μ mho/cm in 1 km. At the same time, the rate of transport of the core of the freshet was very considerable, being on the average 15 cm/sec. Similar calculations were made also for Unzha bay. Average rates of transport of freshet waters in the upper reaches of this bay fluctuated within the range of 10-20, falling in the lower reaches of the bay to 3-5 cm/sec.

Tentative computations of the transport of waters in bays near the mouth allow one to formulate an idea of some general traits of the dynamics of water masses for all similar parts of the reservoir.

1. The rate of transport of the initial river-water masses in the bays gradually diminishes on approaching the open part of the reservoir. This deceleration of the movement of the waters is a consequence of the gradual enlargement of the area of the stream-flow section of the bays from their upper to their lower reaches, and the increase of the hydrodynamic pressure head. Indeed, in a comparison

of the rate of transport of the declining waters of the Unzha freshet in the bay near its mouth in 1961 and 1962 it was found that, with equal rates of flow of the river at the terminal range, the speed of the water movement in the second case was approximately 1.5 times greater than in the first case. This was due to fact that in 1962 the water level in the open part of the reservoir at Yur'yevyets was, at the time of calculation, 20 cm lower than in 1961.

2. The rate of transport of the river waters in the bays depends on the discharges of the tributary. Thus, the speed of movement of waters in Unzha bay was higher, and consequently the water exchange was more intense than in the bay of the Nemda near its mouth, which is explained by the greater volume of water of the first river as compared to the second. Besides this, in the same bay, with increase of the river run-off, the speed of the movement of the river-water increases, so that cores of freshets move quicker than the waters of their primary phases. Due to the unequal speeds of movement of the different phases of freshets and back-water, the extent of the mixing zones of the water masses, when approaching the lower reaches of bays, decreases, and the horizontal gradients of the physical and chemical characteristics increase sharply, which results in a sharper demarcation of the hydrological front in the lower reaches near the mouths of the bays of the reservoir.

It is highly interesting to compare the rate of water exchange of the reservoir's largest bays with its water exchange as a whole. Thus, in June, 1961 and 1962, the coefficient of water exchange for the whole reservoir was 0.42 (Table 16), which means a replacement time of 71 days. According to the data of our calculation the replacement time in Unzha bay in June 1961 was 27 days, in Nemda bay 30 days, and in June 1962, in Unzha bay, 17 days. Thus, the real water exchange of the bays during those periods was 2.5-4 times greater on the average than for the whole water volume of the reservoir.

TRANSPORT AND ALTERATION OF WATER MASSES IN THE LAKE PART

Transport and alteration of the water masses in the lake part of the reservoir are at a maximum during the spring fill-up. The records of the 1963 observations give a sufficiently adequate idea of the features of this process. The first portions of the spring flood /60 waters began entering the lake part of the water body from the estuaries of the Unzha and Nemda on April 18-19. In consequence, the beginning of the rise of water level was registered at all hydrometric stations of the river part of the reservoir, despite the fact that the Gorky hydroelectric development discharges had considerably increased (Fig. 23). The greatest rise of level (16 cm in 24 hours) was observed between April 21 and 22, when the Gorky hydroelectric plant for some reason reduced its outflow. Its maximum discharges were observed between April 27 and 29; they averaged approximately five thousand m^3/sec. per 24 hours. At this time the southern half of the lake part of the reservoir was filled up by winter Volga water, and relatively highly mineralized winter waters were discharged into the tailwater of the Gorky hydroelectric plant. The front of the river flood waters, inflowing from Nemda and Unzha Bays over the left shore floodplain of the northern half of the lake part of the body of water, approached Sokol'skoe on April 25, and had moved towards the Puchezh region by April 28. As the mixing zone of flood water and winter waters moved southward, and particularly as the spring waters penetrated into the

Volga channel at Sokol'skoe, it became more and more eroded. The width of this zone continuously expanded due to the winter water mass dilution by flood waters, and by approximately May 2 it covered the entire southern half of the lake part of the reservoir. Since a slight inverse thermal stratification (0.3° at the surface and 0.5° at the bottom) was observed in the area of water near the dam, flow of the low-mineralized spring waters over the winter waters was very insignificant, and was found only at Puchezh. In other areas of the reservoir, waters were practically fully homogeneous through the vertical.

Thus, the lake part of the reservoir was filled by the flood waters pushing the winter water mass from the northern to southern part of the water body, that adjacent to the dam. As a result of this, the level at all points of the lake area of the reservoir rose almost simultaneously (Fig. 23). Because of the heavy discharges of winter waters and the resultant formation of a comparatively low gradient along the longitudinal axis of the lake part (14 cm per 95 km), the penetration speed of the flood water into the part adjacent to the dam was considerable. The first portions of flood water, which entered between April 18 and 19 into the Yur'evets expansion, had reached the dam by May 1-2, that is, the mean speed of their movement was 6 to 7 km per day, or 7-8 cm/sec. During this movement they mixed evenly through the entire vertical with the winter waters receding towards the dam. Not so much mixing of water masses as the displacement of winter waters by those of spring is obviously typical of the process by which a great number of reservoirs are filled in spring, and this has been pointed out by many researchers (Kriventsov, 1959; Ershova, 1962; Zenin and Fesenko, 1962).

When the spring fill-up of the reservoir is completed, the lake part proves to be almost entirely occupied by the river flood waters intermixed with remnants of the winter waters. Around that time the level of the water body becomes stabilized and flowage sharply decreases. At the end of May in 1963, due to decrease of flowage and to intensive heating under conditions of hot and mostly calm weather, the water filling the lake part of the reservoir commenced to acquire the features of a lacustrine-type water mass, with characteristic thermal stratification in the vertical, and considerable heterogeneity of the water temperature throughout the water body (Fig. 24). At individual cross-sections the temperature of the surface water layer above deep-water areas was 7-8° lower than above shallow water. The same sharp contrasts in temperature were observed in the near-bottom layers of the northern, shallower part of the lake section. More intense heating of waters in the left shore area as compared with the right shore was aided by the lesser flowage in the floodplain areas as compared with the channel, where the speed of water movement, and consequently vertical mixing of the water mass, were much larger. This is proved /61 by the distribution of electrical conductance (Fig. 24 c), indicating that the advance of water from the northern to southern half of the lake part of the body of water is primarily in its above-channel area.

The thermal stratification of the spring water mass of the reservoir is well seen in Fig. 25. In the near-bottom layers in the old Volga channel, the water temperature gradually decreased from 10° at Yur'evets to 4.3° C at the dam. The thermocline at Yur'evets was at a depth of 6-8 m; towards the dam the thickness of the epilimnion gradually decreased, and in its vicinity the thermocline was at a depth of only 0-2 m. Inside this layer, the thermal gradient reached very high values (5-8°). The density stratification of the reservoir water mass, hindering its vertical mixing, created conditions for oxygen stratification: near the bottom the oxygen content ranged from 7 to 9 mg/l. For the same reason the pH value of the water mass was heterogeneous (approximately 7.0 at the bottom and 7.5 to 8.2 at the surface). /62

The distinctive character of water penetration from the river into the lake part of the reservoir was determined by the temperature stratification of the reservoir water mass. Particularly active water movement occurred directly below the thermocline, as can be seen from the curve of kappas* on longitudinal sections of the lake part of the

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* Literal translation for a word meaning lines of equal conductance - Transl. note.

reservoir, illustrated in Fig. 25. Flow of waters with increased electrical conductance from the river part into the Yur'evets expansion underneath the thermocline was observed by us also at the diurnal station made 4 km north-westward from Yur'evets (Fig. 26). While at the 2 m level the current was typically unsteady both in direction /63 and in speed, at the depth of 5 m the prevailing current was from west to east.

In the summer-autumn period, the mass of the reservoir proper, which fills the lake part of the body of water, has features similar to water masses of the shallow flowing lakes situated in the surrounding territory. The thermocline, which forms during the spring-summer heating period, gradually sinks to the bottom and disappears, and the water mass becomes relatively uniform vertically as far as temperature is concerned, as well as in oxygen content, pH and water chemistry. Its transparency increases to 2.0 m. In the surface layers these characteristics undergo diurnal and periodic changes on hot and calm days. During periods of storms the water mass becomes mixed to the bottom, its transparency decreases to 1.0-1.5 m due to turbidity in shallow waters and penetration of suspended matter from them into the open parts of the /64 water body.

In the lake area of the reservoir intense development of phytoplankton takes place. The green-blue algae are here the dominant group, particularly in autumn. In the river part of the reservoir, the concentration of phytoplankton is lower than in the lake part; it is composed mostly of diatoms (Pyrina, 1959). According to the evidence of A. D. Priimachenko (1960), the areas near the mouths of the Nemda and Unzha are relatively poor in phytoplankton in comparison with other areas of the reservoir. Thus, the information found in the literature regarding the distribution of phytoplankton in the Gorky reservoir provides a basis for assuming that the main water masses of the reservoir may have varying levels of primary development. In order to check this assumption, we carried out a hydrological survey of the Yur'evets expansion on 9 May 1963 with simultaneous determination of the primary development by the radio-carbon method (Sorokin, 1956). At this time in the area surveyed, there was the Volga water mass, freshet waters of the Unzha, and the summer water mass of the reservoir proper. The magnitude of the primary development in the first was 0.110 - 1.60, in river waters 0.215, and in the reservoir water mass 0.350 - 0.470 mg C/l per day. In the reservoir proper, within the surface layer of the water mass, considerable fluctuations of the above values were connected with the redistribution of algae by a weak drift current as well as by their being concentrated principally by the left windward shore of the reservoir.

The enumerated properties of the water mass which in summer and autumn is present in the wide part of the reservoir near the dam indicate that due to alteration of the initial water masses entering here, a water mass of the lake type evolves, with inherent processes of energy and matter accumulation. In this water mass the biological factors are of great importance in processes of alteration and water accumulation, since the intensity of production of organic matter is much larger here than in the initial water masses located in other areas of the body of water. In periods when there are no considerable rain-induced freshets in the Nemda and Unzha, the waters in the lake part of the reservoir are fairly uniform in their chemical properties. When freshets occur, river waters invade the open areas of the body of water and then in the Yur'evets expansion the mixing zones of these waters with the water mass of the reservoir proper are well defined.

Thus, during the last third of July, 1962, the front between the water mass of the reservoir proper and the low level waters of the Unzha lay in the region of Isakovsky Island. This can be seen in Fig. 27 from the sharp increase in the electrical conductance of water in the section Yur'evets-Kobylino. By repeated measurement of electrical conductance in that section, it was possible to determine tentatively the advancement speed of the Unzha water front towards the center of the Yur'evets expansion. On July 22, this front, having a maximum conductance gradient of 5 - 6 μ mho/cm in 1 km, advanced 6 km over 10 hrs, /65 with a mean speed of approximately 17 cm/sec. (Fig. 27). Evidently, two factors explain such relatively high speeds for this body of water. One of the factors which caused the westward water movement was a drift current related to a north-easterly wind blowing during these hours with a velocity of 4 - 5 m/sec. However, between July 22 and 23, observations carried out at the diurnal station in the centre of the Yur'evets expansion indicated that in this area such a wind can cause a drift current with a speed not exceeding 10 - 12 cm/sec. The second possible reason for the relatively high rate of advance of the front could have been an increase in the speed of the discharge current in Unzha bay, which must have happened in connection with the appearance of the rain-induced freshet waters in the headwaters of this bay.

The practically invariable magnitude of the horizontal electrical conductance gradient during the relocation of the front indicates that the Unzha waters advanced by forcing out and replacing the reservoir water mass, and not as a result of displacement or overflow of one water mass by another. This was related to the fact

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* There "mixing" is probably meant. Transl.

that the densities of both water masses had approximately equal values. On July 31, the advanced waters of the Unzha freshet reached Kobylino, moving 45 km along Unzha bay in the course of 10 days with average speed of 5.2 cm/sec. During the next 20 days the front of the freshet waters of the Unzha was stationary at Vtarushensky Island, because the volume of freshet was stored entirely by the bay and its flowage sharply decreased owing to the low discharge of the Unzha in Aubust 1962.

The evidence of the cruise of July 1963 may serve as the second example characterizing the dynamics of the water masses in the Yur'evets expansion. On July 8, the core of the Unzha freshet reached Vtarushensky Island, but the front of this water mass was deflected to Isakovsky Island (Fig. 28). The mean rate of transport of the Unzha water was 2.7 km/day per week. The front of the Nemda freshet advanced from Zavrazh'e southwards but its transport rate was much lower than that of the Unzha waters. During the following 24 hrs., waters of both rivers filled up the entire central part of the Yur'evets expansion floodplain. The maximum rate of their advance, judging by the isolines of conductance (Fig. 28), was observed above the old Volga channel, where it was 2.3 km/day. In the course of the following 24 hours, the transport rate of the Unzha water mass remained approximately the same. As a result of heavy inflowing of the river waters, the horizontal gradient of electrical conductance continually increased, reaching 20 μ mho/cm in 1 km on the morning of July 10 at the lip of the flooded Volga channel. The increase of horizontal gradients in the frontal zone and its vertical uniformity of waters, just as in the previous example, indicate that we witnessed the process of displacement of the water mass previously existing in this area of the reservoir by freshet water.

So, the investigated examples of the movement of the water masses in the bays and open parts of the Gorky reservoir bear witness to the fact that the process of replacing some water masses by others occurs by displacement under conditions of vertical temperature uniformity. When temperature stratification is present the new water mass flows under or over the old one. It seems that in waters of low overall mineralization, such as all spring and summer-autumn water masses in the reservoir the differences in density between the separate masses due to mineralization are not so great that, under homothermal conditions, the less mineralized water mass overflows the more mineralized mass. With greater mineralization of waters and low termperatures, the differences in density of the water masses due to their chemistry increase relatively. This leads to some waters overflowing others, as takes place in winter in the Gorky reservoir. /66

The stability of the frontal zone, its speed of movement and the intensity of the mixing process of waters of various origin within its limits may be assessed by the magnitude of the maximum gradient of any representative characteristic. The greatest speed of movement and considerable intensity of the mixing process characterize, so to speak, the "vanguard" sections of the front, which delimit the frontal portions of the moving water mass. These sections of the front are most often greatly diluted, their horizontal gradients of characteristics are low (e.g. for electrical conductance from 4-5 to 18-20 μ mho/cm/km). More stable and steady are "lateral" front sections of a water mass which have penetrated another mass. In such rather stagnant sections of the frontal zone the mixing of water masses is slight and horizontal gradients of electrical conductance have high values, sometimes reaching 160 μ mho/cm in 1 km in the lake part of the reservoir; in the river part where the flow speeds are higher, 60 μ mho/cm per 100 m, that is 600 μ mho/cm if calculated per 1 km (Fig. 20). The contact zones of superimposed water masses have still more stability and resistance to mixing. In these areas of the frontal zone the vertical gradients of electrical conductance reach at times 20 - 30 μ mho/cm/meter, that is values 50 - 100 times greater than those of the horizontal gradients. For comparison we shall cite a few values of maximum gradients for separate characteristics in the frontal zone of large lakes. Thus, from the evidence of the hydrological surveys in Lake Huron /67

(Ayers et al., 1956) it may be deduced that from among those observed in the lake the greatest horizontal gradient of conductivity was 14 μ mho/cm/km (in the mouth of Saginaw Bay, on June 29, 1953). In Baikal, between the lake and the Selenga river waters, considerably higher horizontal gradients were registered, that is 0.24 - 0.30 mg-equ./l per 100 m (Votintsev et al., 1963), which is approximately equivalent to 200-300 μ mho/cm in 1 km.

CONCLUSION

As the result of 3 years of limnological research on the Gorky reservoir, the existence was established of isolated water masses in the reservoir characterized by comparatively intense water exchange. Just as in the slower flowing Rybinsk reservoir, the waters of the Gorky reservoir, formed under fixed physical and geographical conditions, have a stable complex of physical and chemical characteristics and every year they fill the same comparatively easily delineated areas of the body of water. Without giving further space to the regional peculiarities of the water masses of the Gorky reservoir, their dynamics and alteration, which are examined in detail in this work, we shall make an attempt to single out some basic patterns which, in our opinion, are common to the majority ot flatland reservoirs of the middle zone of the European territory of the Soviet Union.

1. In the reservoirs, two types of water masses are to be distinguished - river and lake. The first are formed in the drainage system of the reservoir tributaries, and on flowing into it they preserve for some time their distinctive properties, which on the whole depend on the physical and geographical features of the basins. Between the various characteristics of the river water masses correlative relations can be established, conditioned by the character of the processes oftheir formation in the drainage systems. In the first place, the distinctive features of these masses are the vertical homogeneity of most of their characteristics due to the relatively intense constant mixing of these waters caused by drainage currents. In the second place, the river water masses are characterized by a considerable variability of the values of their indices, determined by the changes in the predominant type of feeding occurring during the year. Thus, the river water mass is made up of continuously alternating water volumes of diverse quality which may be considered various modifications of it. The latter show most contrast in small rivers, as the boundaries between modifications of water masses in large rivers are often blurred.

The river water masses are of a primary nature; from them are formed secondary water masses of the lake type during the process of alteration in the body of water.

The most important feature of the latter must be considered the process of accumulation of matter and energy, which is peculiar to them and characteristic of bodies of water with a slowed-down water exchange (Rossolimo, 1964). One of the most essential factors and at the same time indications of such accumulation is the more or less long-lasting thermal and density stratification of the lake masses, and also, in comparison with the river waters, increased production of organic matter. The duration of existence of the lake type mass water in the reservoir depends on the intensity of its water exchange. In a slowly flowing reservoir with annual or long-term regulation (e.g. the Rybinsk reservoir) its own water mass remains during the whole year, gradually being renewed owing to incoming initial water masses. In reservoirs with a faster flowage, having a seasonal flow control of the Gorky type, the lake water mass lasts only for a part of the year, in the period of the least water exchange. It emerges annually in spring after the flood has passed through the hydro development, and is replaced by new waters of primary masses at periods of increased water exchange.

2. In the reservoir the nature of the process of replacement of one water by another depends on the correlation and vertical distribution of water mass density. With a homogeneous distribution of this characteristic, displacement of the old water

mass by the newly arrived one is observed. In cases where waters are heterogeneous as regards density, one water mass flows over of under the other. With the comparatively high temperature of water in the summer, overflow by waters of low and average mineralization is possible only in the presence of temperature stratification, regardless of the concentration of salts in the adjoining water masses. With the temperature of the water close to 4°C this process can result even at an almost uniform temperature, due to different mineralization of adjacent masses. According to the observations, values of the maximum gradients of hydrological properties in their frontal zone may serve as indicators of the rate of movement of water masses and their mixing.

3. In the reservoirs of the plain, which in most cases are comparatively shallow, vigorous processes of alteration of water masses occur, as reflected in a substantial change in their primary physical, chemical, and biological peculiarities. The basic factors in the alteration of the water masses are flowage, the morphometric peculiarities of the basin, the meteorological conditions of the reservoirs, and also biochemical and biological processes. Evidently, there exist two basic types of alteration of the water masses of reservoirs: frontal and internal.

The first takes place within the limits of the frontal zones of adjoining water masses, where the main process is the mixing of these masses and their mutual dilution. The discharge and wind currents are the most important factors in the frontal alterations.

By internal alteration is understood the process of the change of properties inside one and the same water mass, mainly under the influence of hydrometeorological and biological factors. Both alterations may be partial, if only some of the water mass indices undergo change or if all of them undergo comparatively little change. Moreover, complete alteration of waters in reservoirs is also observed when their peculiarities change so much that it is possible to speak about the creation of a qualitatively new water mass. The process of formation of the lake water mass of the reservoir proper from one or several initial masses serves as an example of such alteration.

4. The distribution of the basic water masses within the reservoir is determined mainly by the relation between the volumes of incoming initial masses.

Since the catchments of the tributaries of the investigated reservoirs have, as a rule, approximately the same climatic and orographic conditions of run-off formation, the volume correlation of the initial water masses of the flatland reservoirs is relatively constant and seldom depends on the wetness of the year. Therefore, the peculiarities of the distribution of the separate water masses in the reservoir during different phases of the hydrological regime are repeated from year to year. This circumstance may serve as a prerequisite for the use of water masses as a basis for geographic-hydrological zoning of the reservoir, because they reflect not only the qualitative specifics of waters of different origin, but also the dynamic, morphometric, meteorological and biological properties of separate parts of the water body. Such zoning will facilitate the development of principles for forecasting water quality in reservoirs. The balance methods for forecasting water quality in reservoirs which prevail at the present time do not entirely satisfy the requirements of the economy, because in order to solve problems of water supply, discharges, and purification of waste waters, etc., the physical, chemical and biological water properties must be preducted not so much for the entire reservoir as a whole, as for its separate areas. The success of further water mass investigations in reservoirs will, in our opinion, be promoted firstly by modernization of hydrological survey techniques, secondly by the inclusion of biological indicators among the characteristics of water masses. An improvement of observational methods is possible by equipping expedition vessels with multipurpose automatic recorders, recording along the path of the vessel a number of the most important water mass characteristics (temperature, electrical conductance, optical properties, oxygen content and some others). This will make possible reduction of the duration of the survey, and more precise determination of the boundaries, and consequently the volumes of the water masses. The inclusion of biological indicators among the water mass characteristics will provide a more comprehensive description of the water properties and will help us to determine the distribution pattern of water organisms in reservoirs.

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Character and extent of the field work. <ins>Table 1</ins>

Number of surveys	Cruise	Date	River part of reservoir			Lake part of the reservoir		Bays near the river mouths	
			Number of stations	Number of cross-sections	Number of sections along the ship's course	Number of stations	Number of cross-sections	Number of stations	Number of longitudinal sections
		1961							
1	1-a	18 VI - 5 VII	12	-	-	35	9	28	6
2	1-b	8 - 11 VII	14	-	-	11	-	-	-
3	II-a	23 - 28 VII	30	7	-	41	9	-	-
4	II-b	29 VII - 1 VIII	19	-	-	9	-	-	-
		1962							
5	I-a	15 - 23 VI	8	1	1	37	8	18	6
6	I-b	28 - 30 VI	5	1	-	32	7	1	-
7	II-a	17 - 27 VII	6	1	1	26	5	23	8
8	II-b	31 VII-1 VIII	3	1	1	36	8	5	1
9	III-a	28 VIII-7 IX	6	23	1	35	8	29	9
10	III-b	10-14 IX	6	18	1	36	8	2	-
11	IV-a	17-26 X	8	4	1	36	8	25	9
12	IV-b	28-30 X	4	-	-	36	8	2	-
		1963							
13	I winter	2-15 II	4	-	-	15	3	19	-
14	II winter	27 III - 4 IV	6	-	-	17	4	19	-
15	Spring	24 IV - 3 V	-	-	1	22	5	-	-
16	I-a	15 - 22 V	4	12	1	37	10	22	8
17	I-b	23 - 24 V	-	-	-	36	8	-	-
18	I-c	26-30 V	6	10	1	12	3	2	-
19	II-a	27 VI - 5 VII	4	24	1	40	9	26	10
20	II-b	7 - 8 VII	-	-	-	39	9	2	-
21	II-c	9 - 12 VII	6	20	1	15	5	5	-
		TOTAL	151	122	11	603	134	228	57

<ins>Note.</ins> Symbols: a - the direction of expedition movement from Rybinsk towards Gorodets; b - expedition movement in opposite direction; c - supplementary survey of water masses in the Yur'evets expansion.

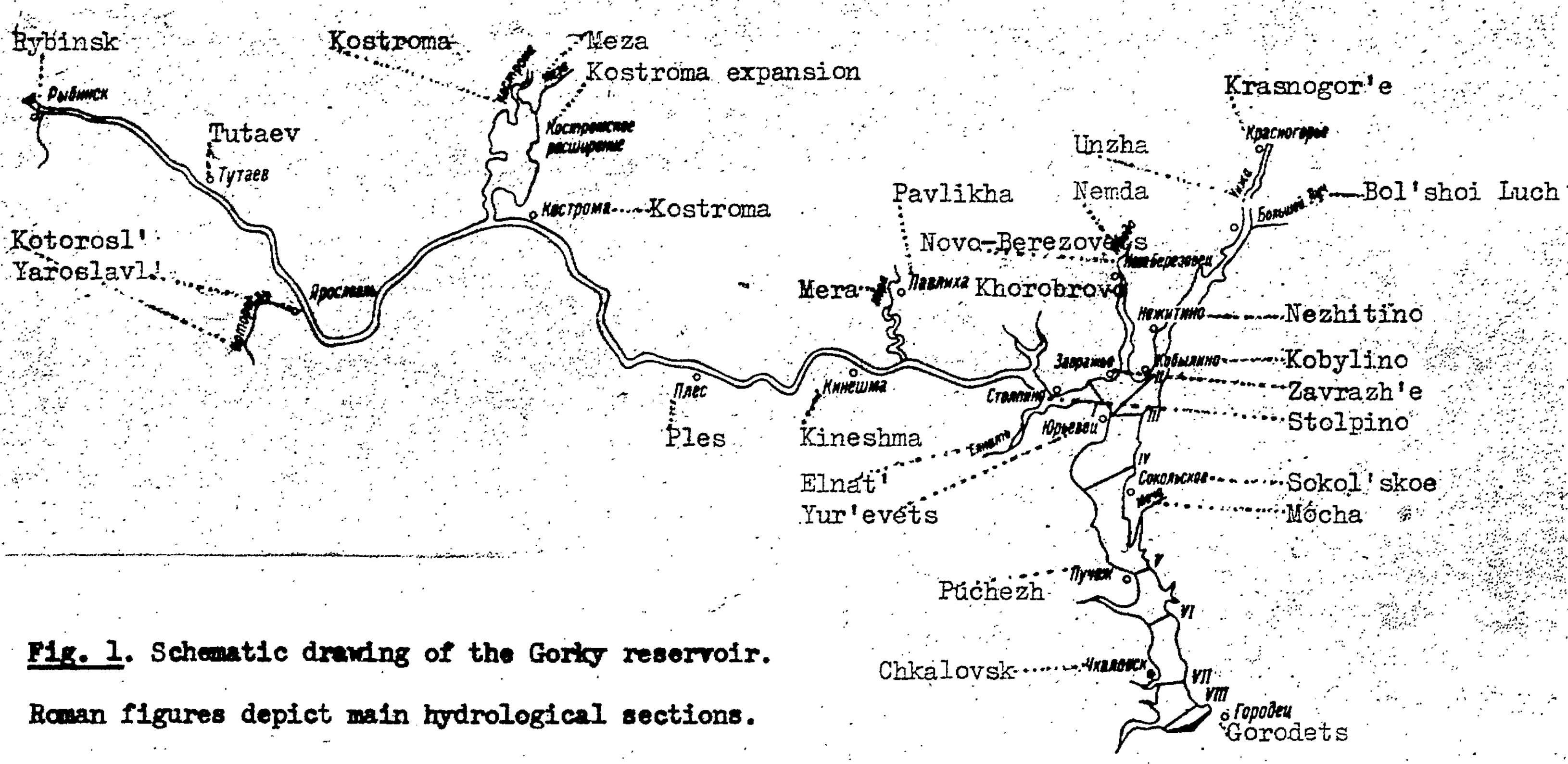

Fig. 1. Schematic drawing of the Gorky reservoir.

Roman figures depict main hydrological sections.

Table 2

A comparison of the representativeness of water mass characteristics in the Gorky reservoir

Characteristics	Maximum range of variations R_{max}	Average error of determination, ε	Parameter of representativity $K = \frac{R_{max}}{\varepsilon}$
Temperature, oC	6.9	0.1	69
Electrical conductance, μ mho/cm	212	5	42
Total hardness, mg-equivalent/l.	2.38	0.07	34
Bicarbonate content, mg-equivalent/l.	2.99	0.10	30
Water colour, degrees	140	5	28
Transparency, cm	160	10	16
pH	1.0	0.1	10
Total strong acids, mg-equivalent/l.	0.71	0.09	8

Table 3

Changes in annual run-off of Volga due to the Rybinsk reservoir between 1947-1963

Years	Average annual water discharge m^3/sec.		Changes in flow		Inflow frequency, %
	inflow	discharge	m^3/sec.	% of inflow	
1947	1124	951	-173	-15.3	35
1948	942	753	-189	-20.0	54
1949	879	910	+ 31	+ 3.5	65
1950	1042	995	- 47	- 4.5	37
51	916	1015	+ 99	+10.8	58
1952	1176	941	-235	-20.0	23
1953	1470	1410	- 60	- 4.1	3
1954	881	962	+ 81	+ 9.2	65
1955	1497	1435	- 62	- 4.1	3
1956	1211	971	-240	-19.8	19
1957	1378	1447	+ 69	+ 5.0	8
1958	1297	1192	-105	- 8.1	13
1959	988	1033	+ 45	+ 4.6	48
1960	943	744	-199	-21.1	54
1961	1120	1212	+ 92	+ 8.2	27
1962	1369	1306	- 63	- 4.6	9
1963	664	687	+ 23	+ 3.5	86
rage	1112	1057	- 55	- 4.9	

Note: Minus (-) means decrease, and plus (+) - increase of the Volga run-off as a result of its regulation by the reservoir.

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Table 4

Intra-annual distribution of flow in the range of the Rybinsk hydro station (in % of yearly discharge)

Years	Months											
	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III
Average in 1947-1964	5.9	8.3	8.6	7.8	7.7	7.8	8.5	8.5	9.8	9.7	9.6	7.8
1961-1962	5.3	14.4	7.7	6.4	7.5	7.9	8.2	7.1	8.9	7.4	8.9	10.0
1962-1963	7.9	7.5	8.6	9.8	10.2	6.9	7.8	7.9	10.1	10.9	6.2	6.1
1963-1964	7.1	5.1	9.2	8.1	11.3	10.6	7.6	8.5	11.1	9.0	6.0	7.4

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Table 5

Some characteristics of water mass in central part of Rybinsk reservoir (according to N.V. Butorin, 1965 c)

Characteristics	Spring	Summer	Autumn	Winter
Electrical conductance, mho/cm	211-272	163-172	159-161	164-243
Bicarbonate content, equivalent of mg per litre	1.80-2.42	1.41-1.49	1.30-1.42	1.34-1.94
Hardness, equ. of mg/l	2.06-2.73	1.96-2.49	1.88-2.19	1.82-2.90
Water colour, degrees	20-40	15-25	30-35	25-40
Transparency, cm	150-180	170-190	110	—

Table 6.

Characteristics of the Volga water mass near Rybinsk.

Date	Temperature, °C	Transparency, cm	Electrical conductance, µ mho/cm	Bicarbonate content, mg-equival./liter	Hardness, mg-equiv./l	Colour, degrees	pH
1961							
11 VII	18.0	80	162	—	—	55	—
23 VII	20.0	110	158	—	—	50	—
31 VII	21.0	95	157	—	—	35	—
29 VIII	15.9	—	157	—	—	—	—
1962							
15 VI	14.1	—	194	1.54	1.80	65	7.8
18 VII	18.5	110	147	1.25	1.62	45	7.8
10 VIII	16.6	—	145	—	—	—	—
28 VIII	14.7	100	139	1.13	1.51	55	7.6
14 IX	11.4	90	133	0.83	1.46	—	—
17 X	5.1	40	149	1.15	1.58	58	7.4
1963							
2 II	0.0	—	196	—	—	80	7.0
27 III	0.0	—	205	—	—	85	6.9
3 V	6.4	—	204	—	—	55	7.0
16 V	10.0	110	237	2.16	2.51	40	—
30 V	15.6	80	202	—	—	35	7.6
12 VII	17.0	60	147	—	—	45	7.4
24 VII	19.4	—	194	—	—	60	7.6
21 VIII	17.9	90	154	—	—	—	—
4 IX	19.5	—	166	—	—	55	—

Table 7. / 14

Ranges of ionic composition variation in water near Yaroslavl'

(1956 - 1958)

Ions	Equivalent percent
$Ca^{\cdot\cdot}$	29.7—35.5
$Mg^{\cdot\cdot}$	12.2—16.4
$Na^{\cdot}+K^{\cdot}$	2.1—8.1
HCO_3'	37.7—41.3
SO_4''	6.7—19.1
Cl'	2.4—3.4

Table 8. / 14

Mean monthly water temperature (°C) of the Volga water mass near Rybinsk and in some tributaries of the river part of the Gorky reservoir

in spring-time.

Water monitoring station	1961		1962		1963
	IV	V	IV	V	V
Gorky reservoir - Rybinsk	1.2	5.4	1.6	8.3	9.8
Cheremukha River - Dmitrievka*	-	11.5	3.9	12.8	15.6
Urdoma River - Belyatino*	-	10.9	-	13.0	15.4
It' River - Nesterovo*	1.2	11.5	3.4	13.3	16.1
Kotorosl' River - town of Gavrilov-Yam	-	12.0	4.5	13.6	17.1

*** All three are villages (Transl.)**

Table 9

Relationship between water masse, volumes feeding the Gorky Reservoir between 1957 - 1963.

Water masses	Spring inflow			Summer - autumn inflow			Winter inflow			Total annual		
	Average per period		Fluctuation ranges in individual years, in % of total inflow	Average per period		Fluctuation ranges in individual yars, in % of total inflow	Average per period		Fluctuation ranges in individual years, in % of total inflow	Average per period		Fluctuation ranges in individual years in % of total inflow
	km^3	%		km^3	%		km^3	%		km^3	%	
Volga	5.51	31	23-39	16.44	75	68 - 82	13.13	88	84 - 90	35.08	64	61 - 66
Unzha	4.57	25	22-28	2.17	10	7 - 13	0.61	4	4 - 5	7.35	13	12 - 15
Kostroma	2.97	17	15-18	1.22	6	4 - 8	0.35	2	2 - 3	4.54	8	8 - 9
Kotorosl	0.73	4	3-6	0.40	2	1 - 3	0.17	1	1 - 2	1.30	3	2 - 3
Nemda	0.72	4	3-5	0.32	1	1 - 2	0.12	1	0.5- 1	1.16	2	1 - 2
Mera	0.60	3	3-4	0.21	1	0.5- 1	0.08	1	0.5- 1	0.89	2	1 - 2
Other rivers ..	2.84	16	-	1.11	5	-	0.47	3	-	4.40	8	-
Total inflow into the reservoir....	17.92	100	-	21.87	100	-	14.93	100	-	54.72	100	-

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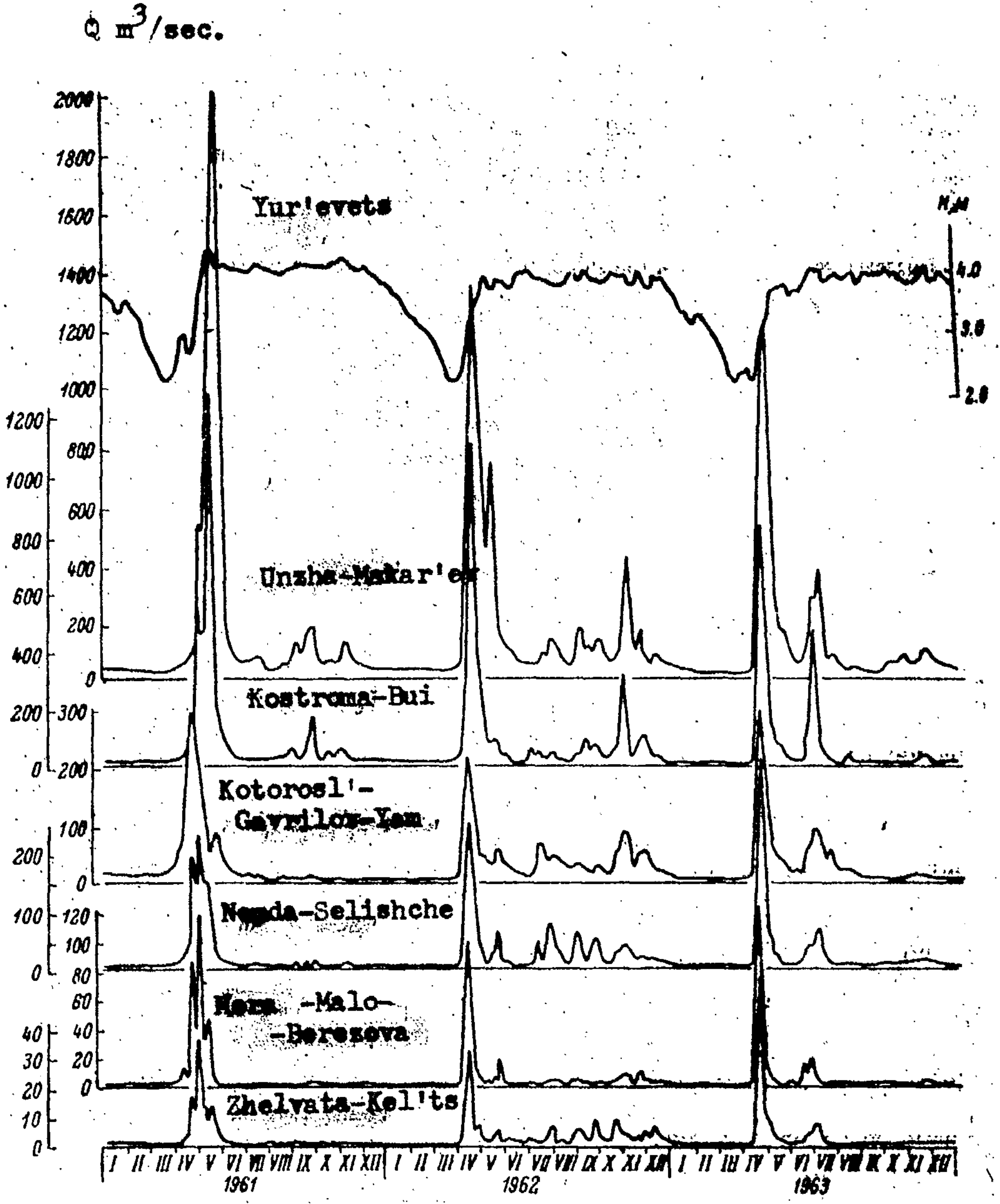

Fig. 2. Hydrographs of main tributaries of the Gorky reservoir and fluctuation of its level near Yur'evets.

Table 10 / 18

Ranges of total mineralization and ion content in water of main tributaries of the Gorky reservoir.

	Unzha	**Kostroma**	Kotorosl'	Nemda
Total mineralization, mg/liter	43.8 - 184.8	74.8 - 308.8	138.9 - 385.1	40.6 - 156.2
Ions, equivalent % :				
Ca$^{\cdot\cdot}$	27.1 - 37.8	23.7 - 33.0	20.8 - 32.2	28.3 - 33.0
Mg$^{\cdot\cdot}$	9.6 - 16.3	14.1 - 18.5	11.7 - 21.9	13.0 - 15.0
Na$^{\cdot}$ - **K**$^{\cdot}$	1.5 - 6.8	0.3 - 11.6	2.4 - 10.4	3.1 - 7.2
HCO$_3'$	31.3 - 41.0	36.4 - 43.5	38.0 - 44.2	33.7 - 47.3
SO$_4$	5.6 - 13.4	4.3 - 7.5	4.3 - 8.7	1.8 - 15.0
Cl	2.1 6.5	2.1 - 4.5	0.4 - 5.0	2.7 - 5.1

Table 11.

Characteristics of river water masses.

Site of sampling	Date	Temperature °C	Transparency cm	Electrical conductance µ mho/cm	Bicarbonate content, mg-equivalent per litre	Hardness, mg-equ. per litre	Colour	pH	Phase of river's hydrologic cycle
Kotorosl At Yaroslavl road bridge	18 VII 1962	20.6	40	207	2.06	2.35	65	7.3	Freshet
	29.VIII 1962	14.0	90	292	2.94	3.32	35	7.9	Freshet recedes
	18 X 1962	4.0	120	374	3.84	3.96	32	-	Summer-autumn low water level
	3 II 1963	0.0	-	521	-	-	18	7.0	Winter low water
	27 III 1963	0.0	-	546	-	-	25	7.0	" " "
	16 V 1963	17.5	80	278	2.30	2.62	30	7.9	Flood ebb
	27 VI 1963	16.9	70	202	-	-	60	7.4	Freshet
Kostroma At the Meza mouth	2 VIII 1962	17.8	100	216	1.75	2.38	70	8.0	Freshet recedes
	29 VIII 1962	15.4	110	303	2.92	3.56	55	7.9	Summer-autumn low water
	19 X 1962	4.6	80	287	2.78	3.07	82	7.8	Rise of freshet
	17 V 1963	16.8	80	150	1.32	1.73	80	7.4	Recession of flood
	28 VI 1963	17.2	70	179	-	-	120	7.3	Freshet
Mera Near Pavlikha	29 VI 1961	20.5	135	318	-	-	35	-	Summer-fall low water
	18 VI 1962	16.6	145	326	3.37	3.17	22	7.6	-"-
	19 VII 1962	21.6	40	133	2.03	2.14	60	7.2	Freshet
	31 VIII 1962	13.7	30	178	1.70	2.13	60	7.8	-"-
	20 X 1962	1.8	110	280	3.09	3.07	38	7.9	Rise of freshet

Table 11 (Continuati[illegible])

Site of sampling	Date	Temperature °C	Transparency cm	Electrical conductance µ mho/cm	Bicarbonate content, mg-equ./l	Hardness, mg-equ. per litre	Colour	pH	Phase of river's hydrologic cycle
At Dolmatovo	9 II 1963	0.0	-	320	-	-	10	6.9	Winter low water
	1 IV 1963	0.0	-	323	-	-	15	6.9	" " "
At Pavlikha	18 V 1963	17.3	90	201	1.92	2.33	45	7.2	Recession of flood
	30 VI 1963	19.2	30	122	-	-	100	6.9	Freshet
Zhelvata									
At the Kondoma mouth	30 VI 1961	21.9	60	124	-	-	105	-	Freshet recedes
At Nadoga mouth	18 VI 1962	17.1	80	118	0.90	1.07	108	7.2	" "
	20 VII 1962	20.6	110	144	1.18	1.44	65	7.3	Summer-fall low water
	1 IX 1962	12.8	50	53	0.24	0.65	170	6.8	Freshet
	21 X 1962	1.1	40	68	0.29	0.72	120	7.2	"
At Dymnitsa	4 II 1963	0.0	-	129	-	-	30	6.8	Winter low water
	28 III 1963	0.0	-	155	-	-	30	7.0	" " "
At Nadoga mouth	19 V 1963	16.9	90	66	0.45	0.91	65	6.6	Recession of flood
	1 VII 1963	20.0	100	100	-	-	75	7.2	Freshet
Elnat'									
At Kostyaev	1 IX 1962	13.9	30	137	1.09	1.50	40	7.4	"
Near the road bridge	10 II 1963	0.1	-	242	-	-	40	6.8	Winter low water
	2 IV 1963	0.4	-	258	-	-	30	6.8	" " "
	26 IV 1963	-	-	58	-	-	65	6.6	Flood
	1 VII 1964	20.3	-	174	-	-	60	-	Summer-fall low water

Site of sampling	Date	Temperature, °C	Transparency cm	Electrical conductance µ mho/cm	Bicarbonate content, mg-equiv. per liter	Hardness, mg-equiv. per liter	Colour	pH	Phase of river's hydrologic cycle
Nemda									
At Novo-Berezovets	19 VI 1962	16.9	80	162	1.45	1.47	73	7.2	Summer-fall low water level
	20 VII 1962	20.2	60	98	0.80	1.06	150	6.9	Freshet
	2 IX 1962	13.3	30	71	0.50	0.84	150	7.0	"
	21 X 1962	1.2	70	110	0.56	1.22	144	6.9	"
	6 II 1963	0.0	-	190	-	-	30	6.8	Winter low level
	1 IV 1963	0.0	-	204	-	-	20	6.6	" " "
At Zavrazh'e	27 IV 1963	0.2	-	30	-	-	80	6.0	Flood
At Novo-Berezovets	19 V 1963	18.7	70	80	0.69	0.90	100	6.7	Flood recedes
	1 VII 1963	18.8	50	83	-	-	120	6.8	Freshet
Unzha									
Near Nikolo-Makarov	2 VII 1961	20.0	155	250	-	-	40	-	Summer-fall low water
	26 VI 1962	17.5	110	227	1.75	2.02	47	7.2	Final recession of flood
	22 VII 1962	20.9	70	202	1.79	2.17	80	7.4	Rise of freshet
	3 IX 1962	13.3	70	150	1.14	1.68	110	7.7	Freshet
	22 X 1962	1.1	80	187	1.13	2.4	100	7.7	Freshet recedes
Near Krasnogor'e	6 II 1963	0.0	-	319	-	-	20	7.1	Winter low water
	29 III 1963	0.0	-	350	-	-	25	6.4	" " "

Table 11 (Cont.)

Site of sampling	Date	Temperature, °C	Transparency, cm	Electrical conductance µmho/cm	Bicarbonate content, mg-equiv. per liter	Hardness, mg-equ. per liter	Colour	pH	Phase of river hydrologic cycle
Near Kobylino	27 Iv 1963	0.4	-	58	-	-	80	6.4	Flood
	29 IV 1963	2.0	-	52	-	-	95	6.4	"
Near Nikolo-Makarov	20 V 1963	17.3	80	104	0.76	1.19	85	7.0	Flood recedes
	2 VII 1963	18.9	60	104	-	-	110	7.0	Freshet
Mocha	3 VII 1961	19.0	60	138	-	-	75	-	Summer-autumn low water
Near Belyaikha	24 VII 1962	20.8	50	88	0.56	0.74	85	7.1	Freshet
	2 X 1962	1.1	60	86	0.42	0.69	124	6.8	"
	21 V 1963	21.9	80	48	-	-	-	6.8	Flood recedes
	4 VII 1963	17.5	60	76	-	-	45	7.0	Freshet
Yachmen'	4 VII 1961	18.5	70	158	-	-	-	-	Summer-fall low water
Near Il'ya-Vysokii	23 VI 1962	16.4	40	169	1.38	1.47	42	7.2	-"-
	24 VII 1962	19.9	25	106	0.74	0.97	55	7.1	Freshet
	6 IX 1962	12.3	50	97	0.77	0.97	60	7.4	"
	25 X 1962	1.6	40	137	1.11	1.34	45	7.1	Summer-fall low water
	13 II 1963	0.1	-	127	-	-	8	6.6	Winter low water
	3 IV 1963	0.0	-	120	-	-	8	6.9	" " "

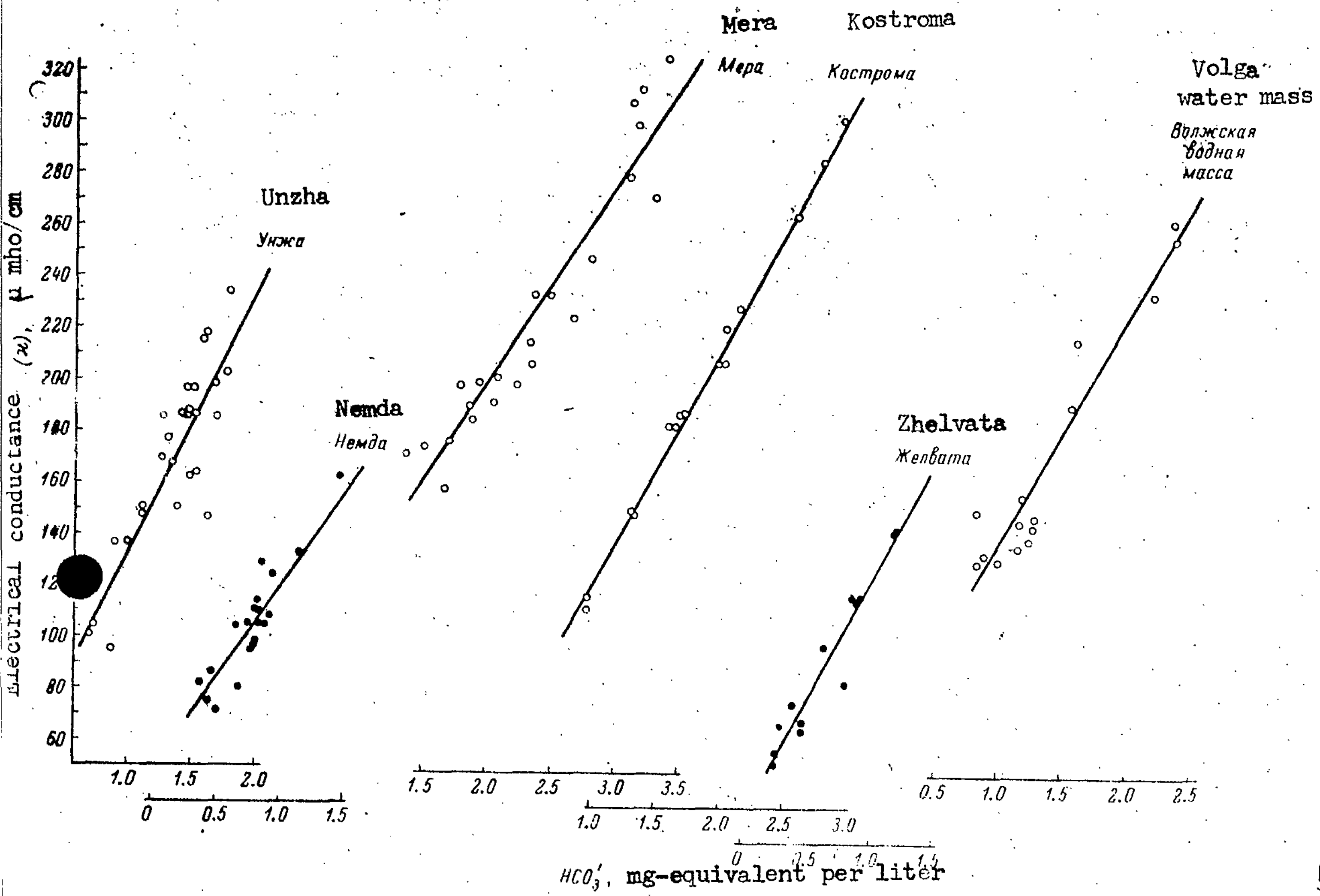

Fig. 3. Water electrical conductance as a function of bicarbonate content in separate water masses.

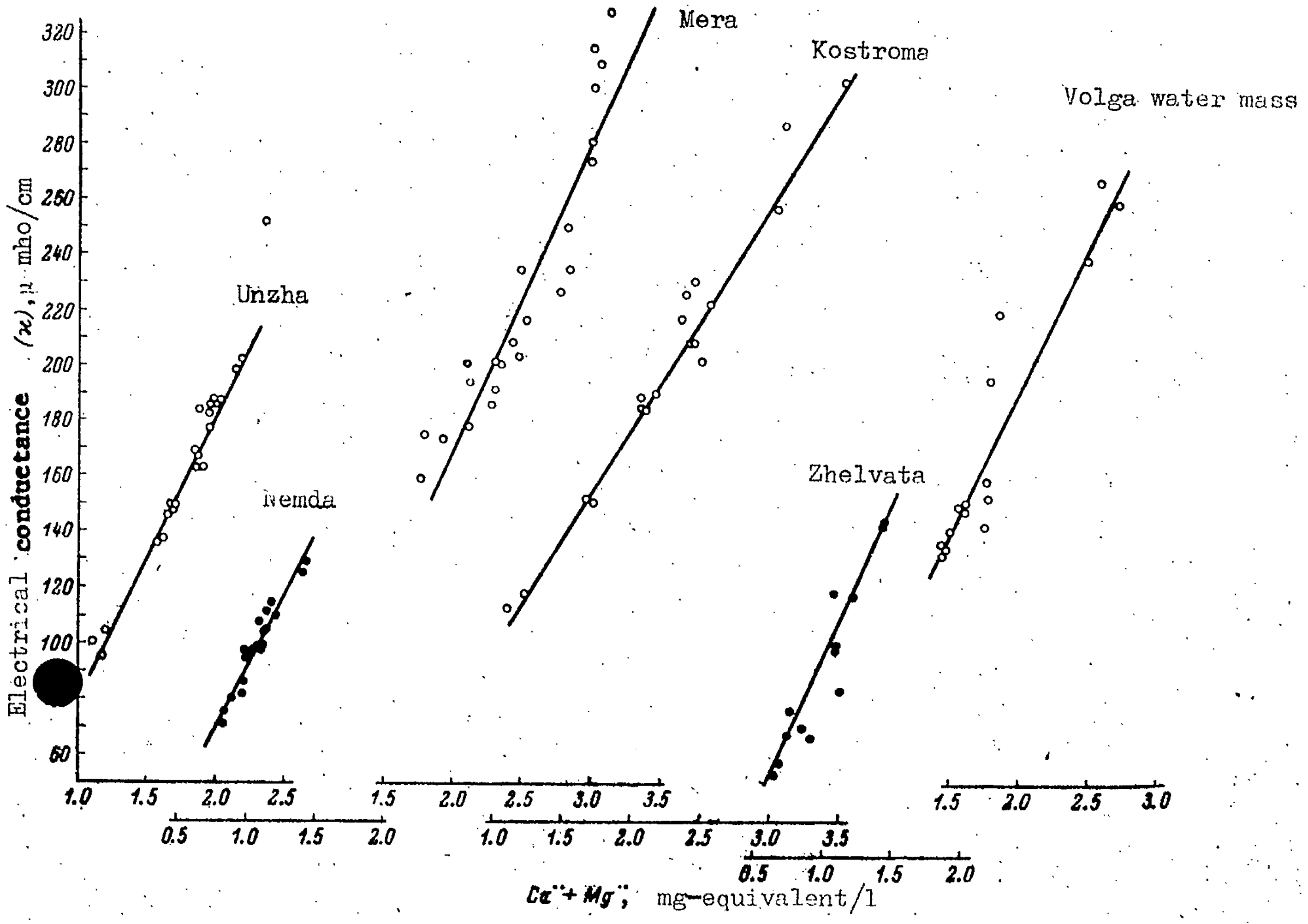

Fig. 4. Electrical conductance as a function of total hardness of separate water masses.

Table 12 /26

Relationship between electrical conductance of water and its content of HCO'_3 and Ca'' + Mg''

Water mass	x=f (HCO'_3)				x=f(Ca''+ Mg'')			
	Number of members in series	Correlation coefficient	Parameters of regression equation		Number of members in series	Correlation coefficient	Parameters of regression equation	
			Slope	Free member			Slope	Free member
Unzha	27	0.88 ± 0.03	100	30	22	0.99±0.01	101	- 19
Nemda	20	0.90 ± 0.03	72	48	20	0.97±0.01	96	- 5
Mera	23	0.95± 0.01	75	52	23	0.94±0.02	108	- 17
elvata	13	0.97 ± 0.01	93	33	13	0.93±0.02	111	- 47
Kostroma	15	0.97 ± 0.01	93	28	18	0.98±0.01	81	15
Volga, Rybinsk-Yaroslavl' area	15	0.96 ± 0.01	89	52	15	0.95±0.02	105	- 20

/ 26

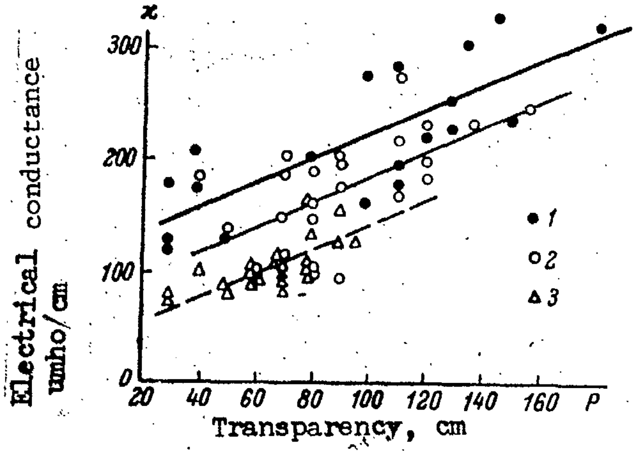

Fig. 5. Relation between transparency and electrical conductance of (1) Mera, (2) Unzha, and (3) Nemda waters.

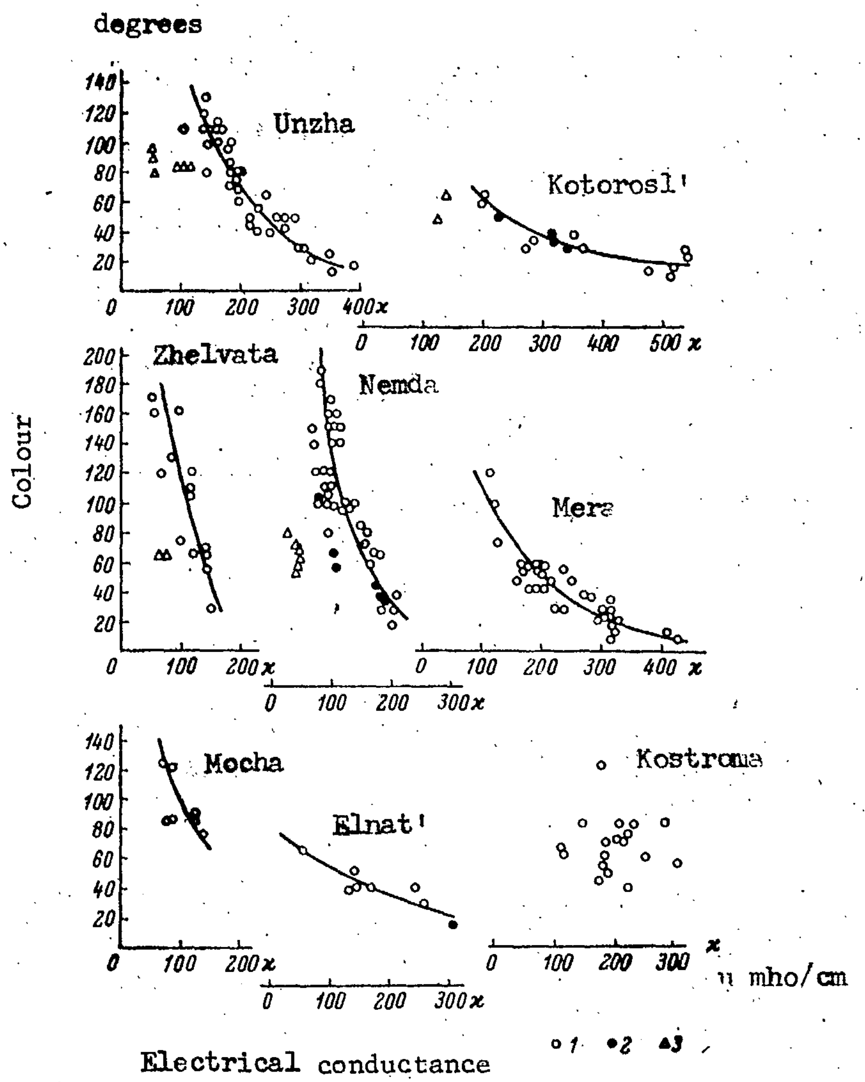

Fig. 6. **Relation between** colour and electrical conductance of individual water bodies.

(1) - observations during summer-autumn and winter periods
(2) - observations made by stations of the Hydrometeorological Service;
(3) - observations made during high-water.

Table 13. / 28

Relation between transparency and electrical conductance of river water masses.

	Number of members in series	Correlation coefficient	Parameters of regression equation	
			Slope, a	Free Member, b
Water mass of				
Mera	20	0.79±0.06	0.9	- 100
Unzha	25	0.62±0.08	0.9	- 67
Nemda	25	0.85±0.04	0.9	- 28

Table 14 / 28

Relation between colour and electrical conductance of river water masses.

	Number of members in series	Correlation coefficient	Parameters of regression equation	
			Slope a	Free member b
Water mass of				
Kotorosl'	..15	- 0.84 ± 0.05	- 0.14	85
Mera	..36	- 0.87 ± 0.03	- 0.36	132
Unzha	..39	-00.91 ± 0.02	- 0.53	174
Zhelvata	..14	- 0.86 ± 0.04	-0.91	198
Nemda	..22	- 0.98 ± 0.01	-1.25	273

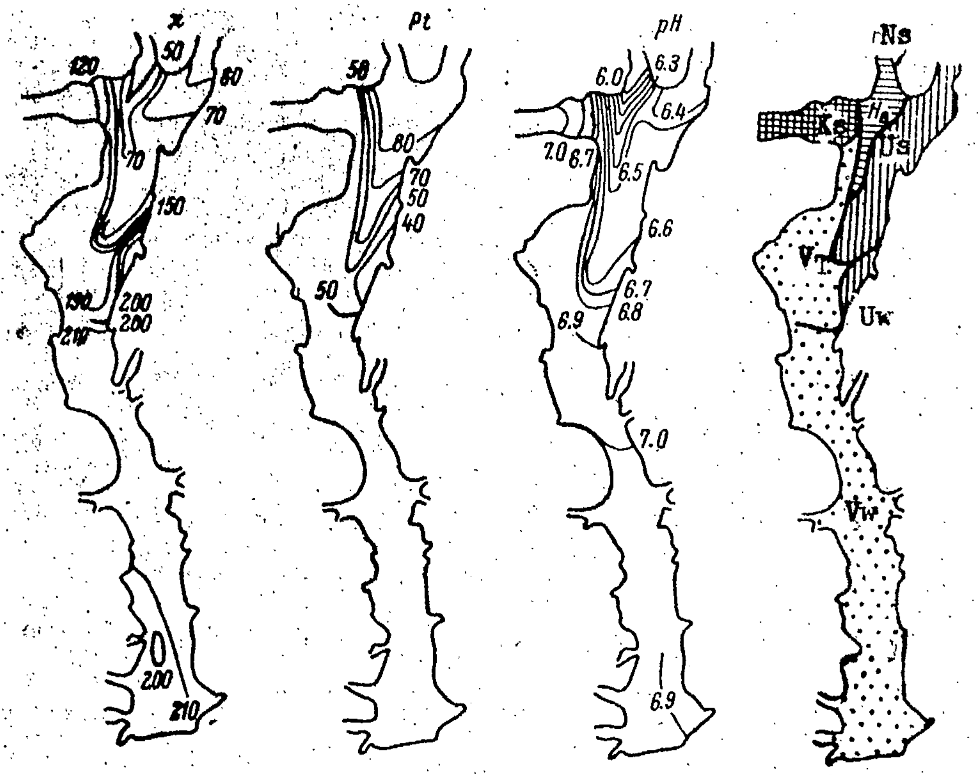

Fig. 7. Distribution of indices in the surface water layer of the lake part of the reservoir and location of water masses between the 24 and 27 April, 1963.

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Symbols in Figs. 7 - 10 and 12 - 16.

Water mass	Modifications of water mass	Legend	Index
Unzha	Spring	▥	Us
	Summer low level		Ul
	Freshet		Uf
	Winter		Uw
Nemda	Spring	▤	Ns
	Summer low level		Nl
	Freshet		Nf
	Winter		Nw
Kostroma	Spring	▦	Ks
Volga	Summer-autumn	░	Va
	Winter		Vw
Lake (reservoir proper)	Spring	☰	Ls
	Summer-autumn		La

T - greatly transformed water masses; - Distribution of electrical conductance, u mho/cm; HCO_3 - distribution of bicarbonates, in mg-equivalent per liter;
Ca Mg - distribution of total hardness, in mg - equivalent per liter;
Pt - colour distribution, units; P - distribution of transparency, cm.

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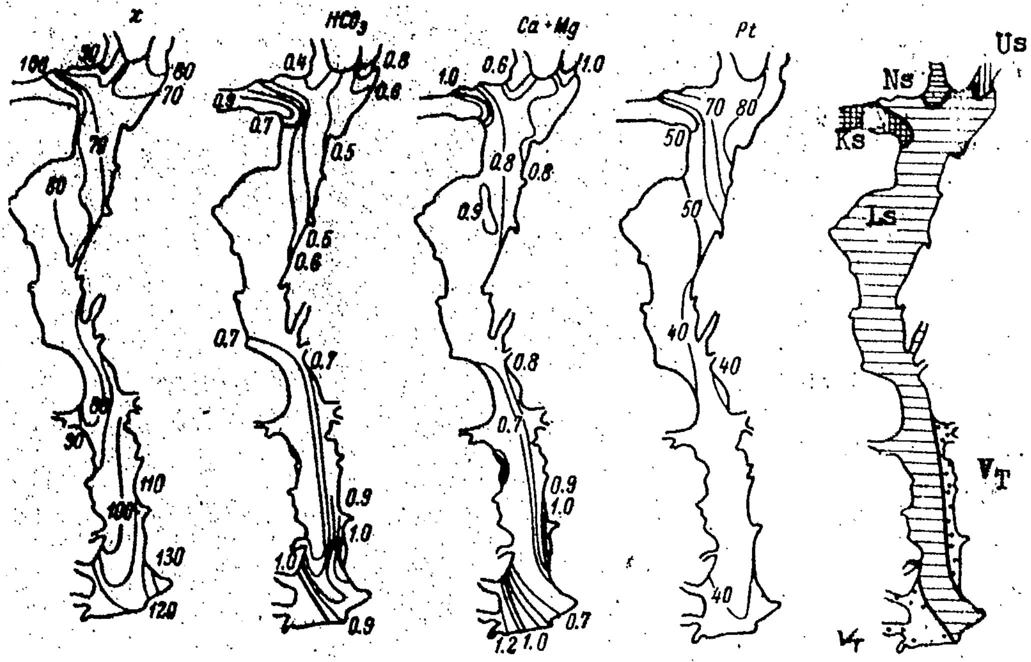

Fig. 8. Distribution of electrical conductance, bicarbonates, hardness and colour in the surface water layer, and position of water masses, May 19 - 22, 1963.

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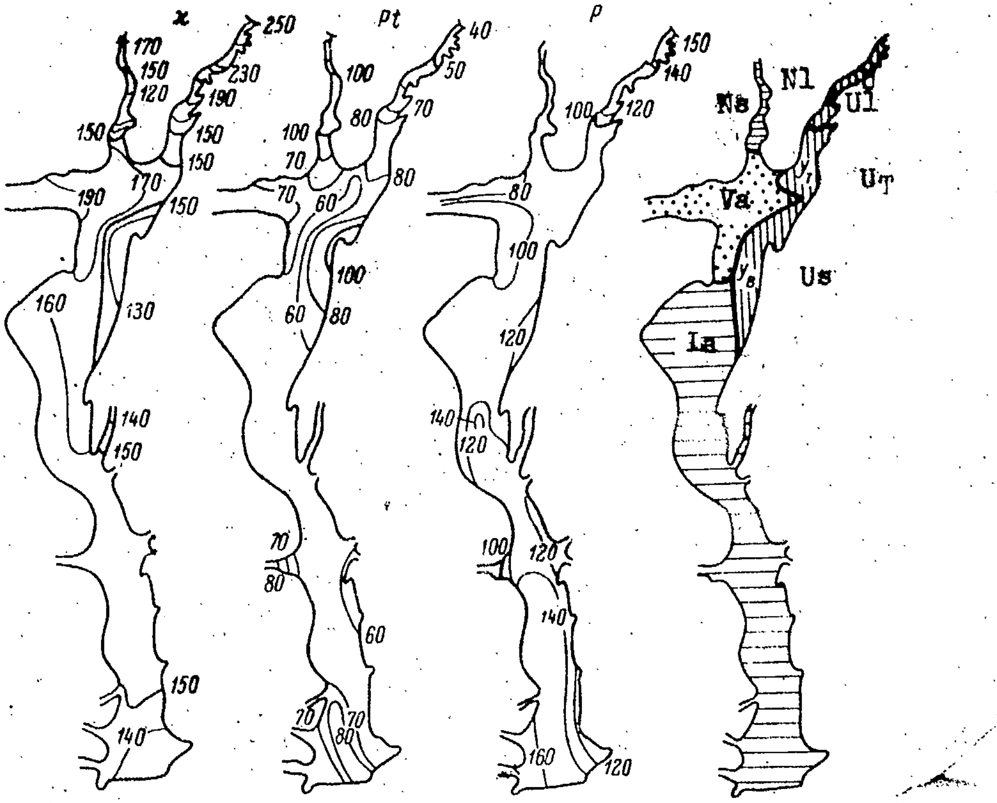

Fig. 9. Distribution of electrical conductance, water colour, transparency in the surface layer, and position of water masses, July 1-5, 1961.

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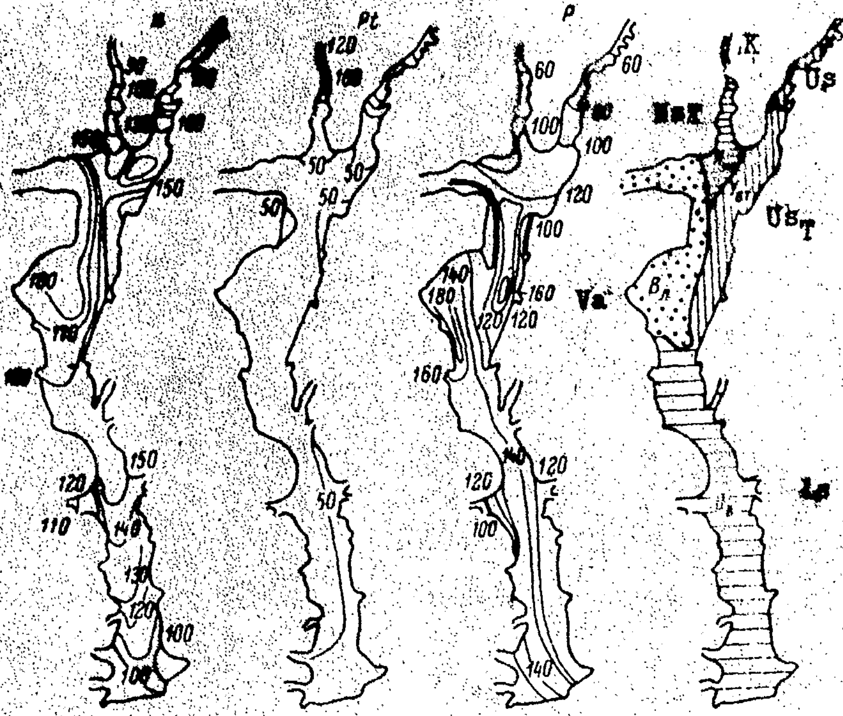

Fig. 10. Distribution of electrical conductance, colour and transparency in the surface water layer, and position of water masses July 1-5, 1963.

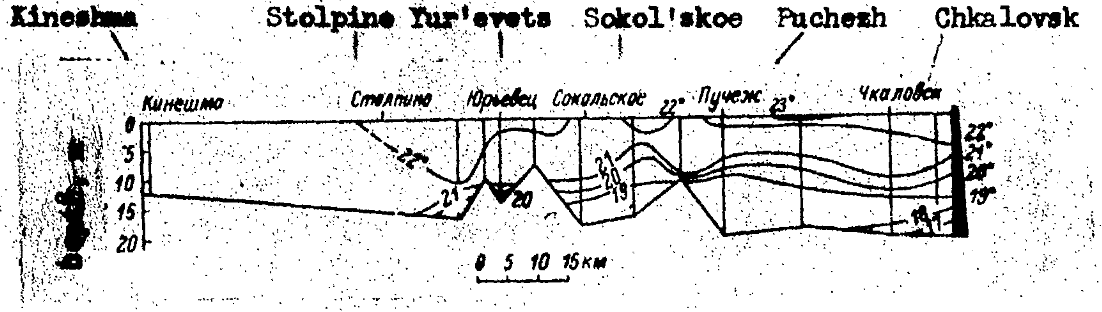

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Fig. 11. Thermal cross-section of the lake part of the reservoir (along the channel stations), July 25 - 28, 1961.

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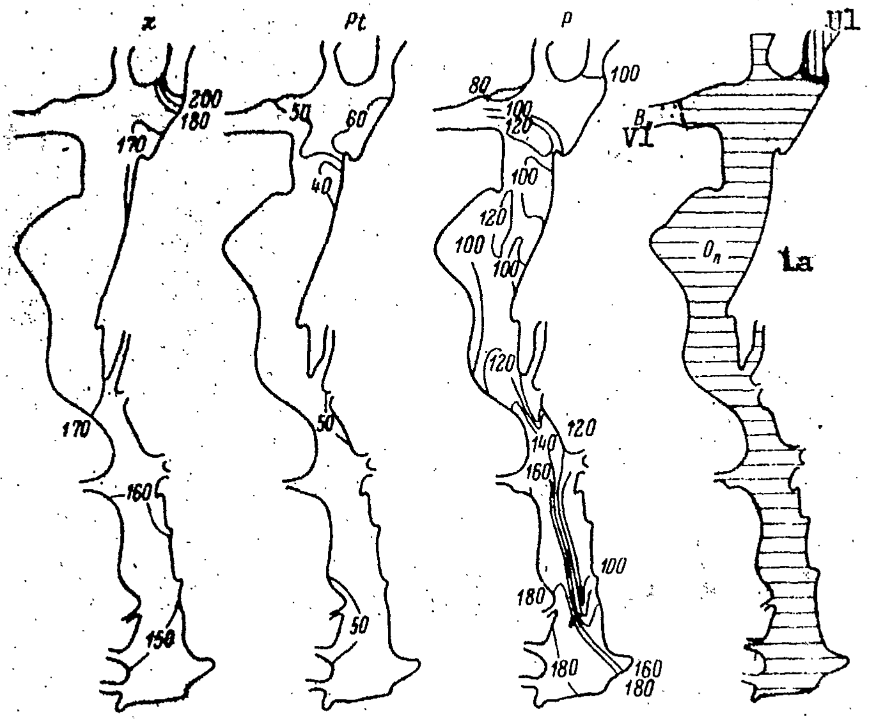


Fig. 12. Distribution of electrical conductance, colour and transparency in surface water layer and position of water masses.

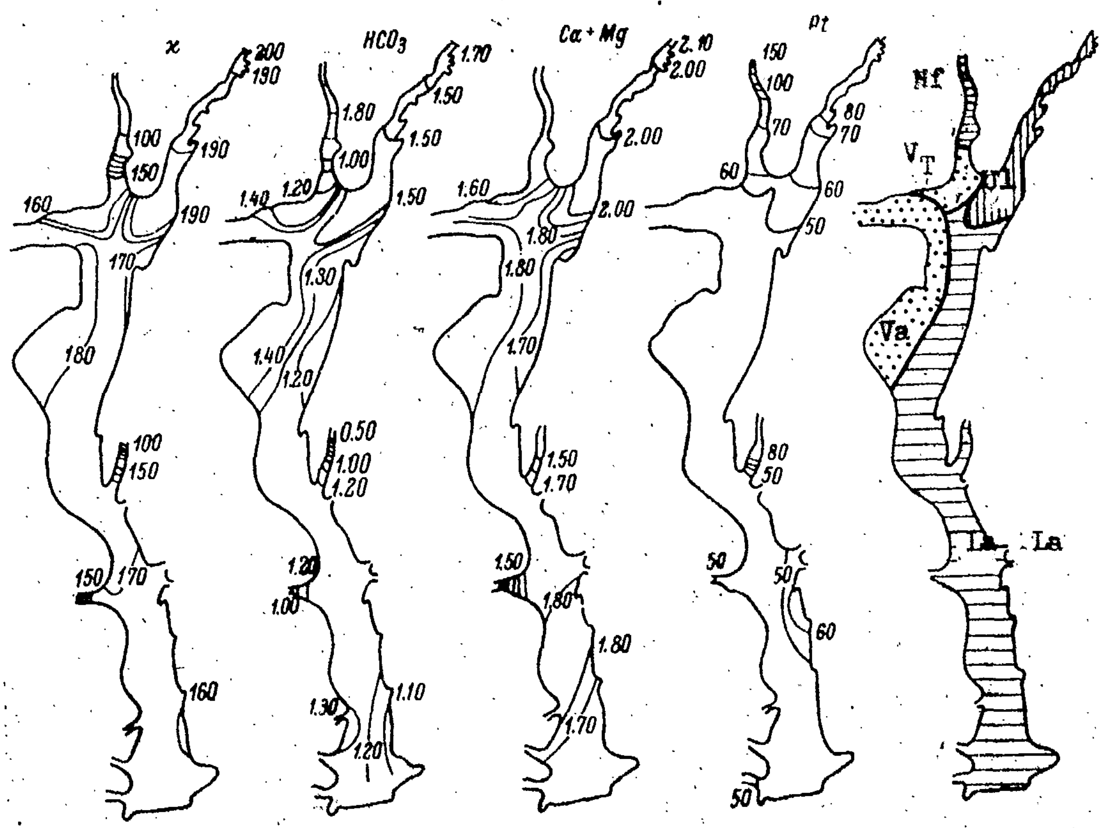
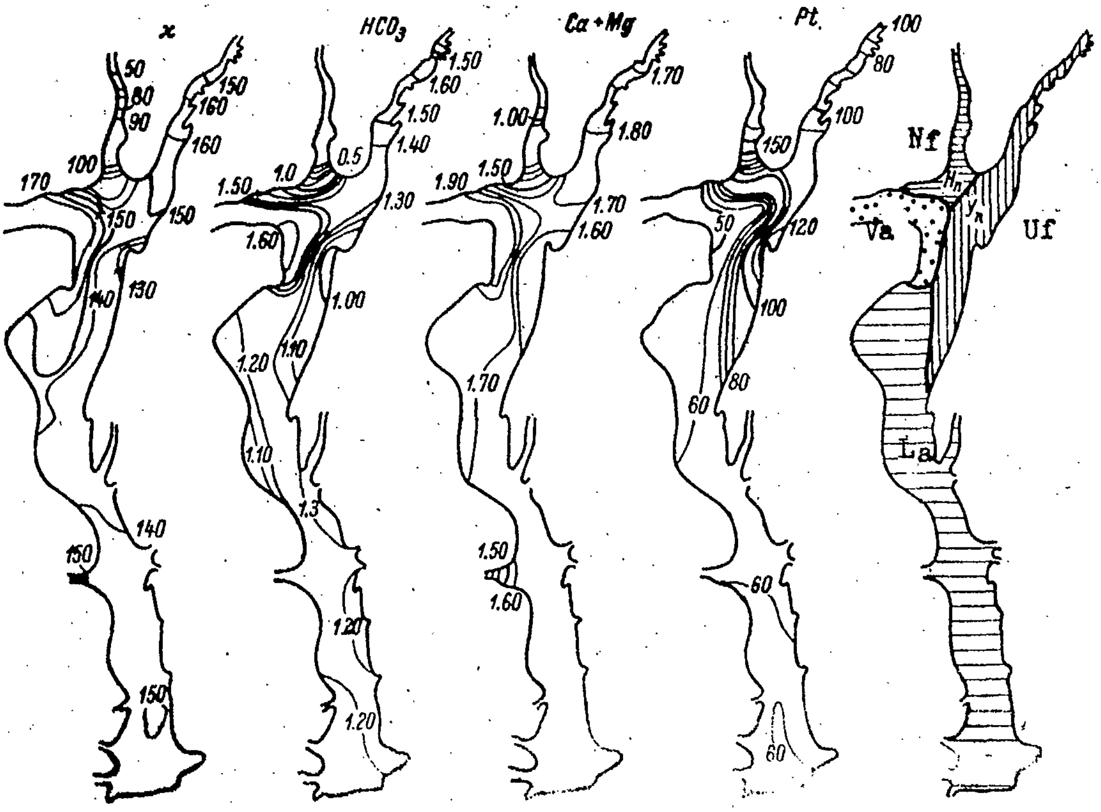


Fig. 13. Distribution of electrical conductance, bicarbonates, hardness and colour, in surface water layer and location of water masses, July 20 - 26, 1962.



<u>Fig. 14.</u> Distribution of electric conductance bicarbonates, hardness and colour in surface water layer, and location of water masses, for September 2 - 7, 1962.

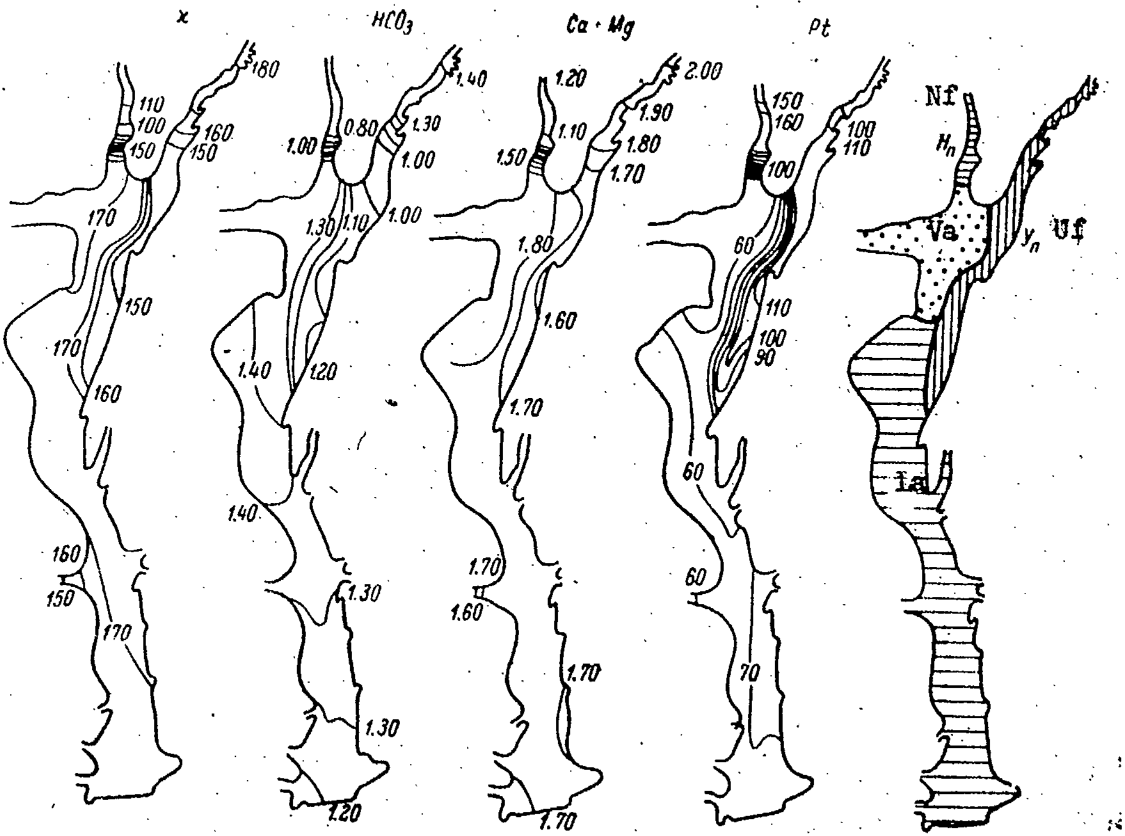


Fig. 15 Distribution of electrical conductance, bicarbonates, hardness and colour in the surface layer, and location of water masses, October 21 - 26, 1962.

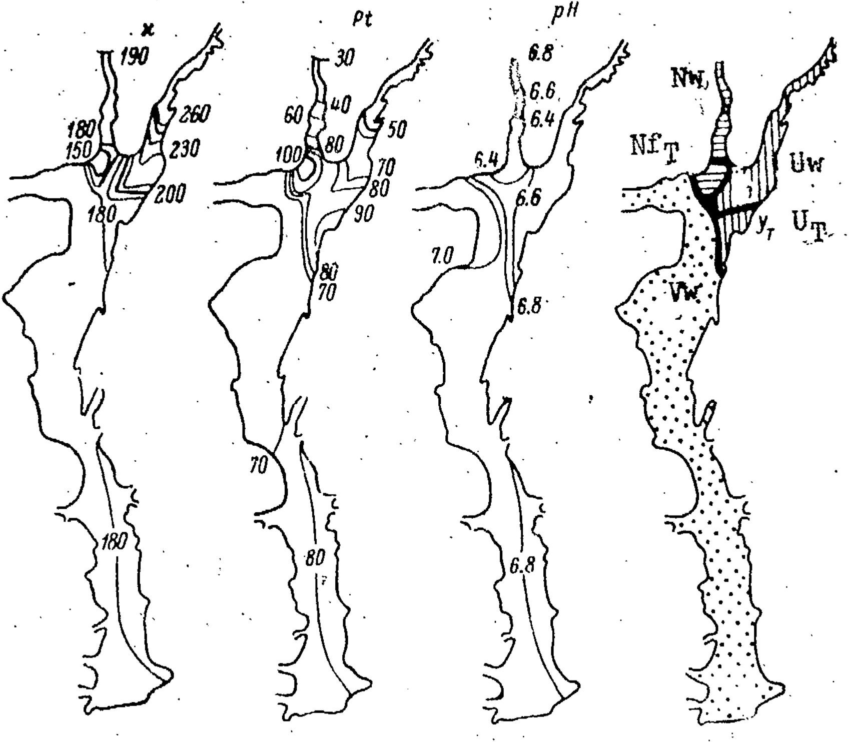


Fig. 16. Distribution of electrical conductance, colour and pH in the near-the-bottom layer and distribution of water masses, February 6-14, 1963.

Table 15

Typical values of some characteristics of basic water masses in the Gorky reservoir.

	Modification of water mass	Characteristics		
		electrical conductance, μ mho/cm	Colour, Pt units	transparency, cm
Water mass				
Volga	summer	130-190	35-60	40-110
	winter	200-240	50-80	-
Unzha	spring	50-100	80-110	60-80
	summer low water	220-250	40-50	120-155
	freshet	140-180	90-120	40-60
	winter	320-350	20-30	-
Nemda	spring	30-80	80-100	60-70
	summer low water	150-180	60-80	70-80
	freshet	70-110	120-150	30-50
	winter	190-120	20-30	-
Reservoir proper	spring	80-120	35-50	80-100
	summer fall	140-180	40-60	100-200

Table 16

Coefficients of water exchange in the Gorky reservoir

Years	Months											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1957	0.89	0.75	0.59	1.55	1.29	0.48	0.70	0.36	0.40	0.55	0.53	0.54
1958	0.66	0.81	0.99	1.50	1.43	0.59	0.45	0.40	0.34	0.40	0.35	0.44
1959	0.56	0.62	0.65	1.17	0.64	0.40	0.45	0.34	0.32	0.36	0.30	0.39
1960	0.43	0.64	0.77	0.77	0.28	0.27	0.28	0.26	0.26	0.28	0.27	0.27
1961	0.35	0.48	0.67	0.86	1.28	0.42	0.34	0.36	0.42	0.40	0.36	0.49
1962	0.46	0.53	0.73	1.25	0.61	0.42	0.66	0.57	0.51	0.49	0.59	0.59
1963	0.70	0.45	0.53	0.91	0.36	0.30	0.44	0.34	0.29	0.28	0.28	0.35
Average	0.58	0.61	0.70	1.14	0.84	0.41	0.47	0.38	0.36	0.39	0.38	0.44

Table 17 /46

Average annual coefficients of water exchange in some reservoirs in European territory of the USSR

Reservoir	Period	Coefficient of water exchange	Reference
Cherepovets	1964-1965	0.9	Ershova, 1967
Tsimlyansk	-	1.05	Lapitskii, 1961
Rybinsk	1948-1961	1.82	Butorin and Kurdina, 1965
Kakhov	-	2.5-3.5	Tseeb, 1962
Kuibyshev	1957-1963	5.4	Shirokov, 1961
Gorky	1957-1963	6.72	Our data
Volgograd	-	7.5	Eliseev, 1965
Kama	1957-1958	about 10	Dubrovin and al., 1959
Uglich	1950-1956	12.4	Kurdina, 1959
Ivan'kovo	1951-1956	13.6	Ziminova, 1959
Dnepr	-	17.0	Tikhii, 1959
Saratov	According to plan	17.0	Yakovleva, 1961
Dneprodzerzhinsk	" " "	21.0	Makeev, 1961
Kegumskoe	-	138.0	Tikhii, 1959

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Volga Hydro-Meteorological Observatory

Gorodets

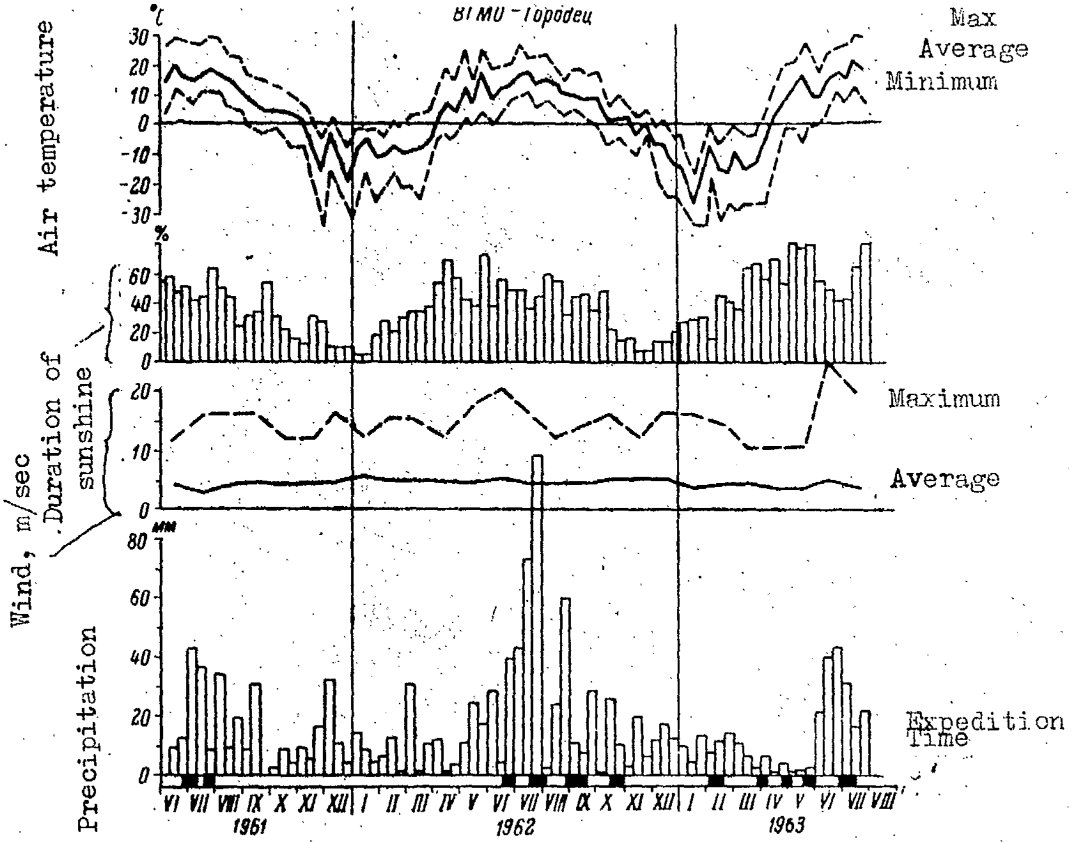

Fig. 17. Fluctuations of ten-day values of air temperature, duration of sunshine, wind velocity and amount of precipitation during the study of water masses in the Gorky reservoir.

Yur'evets

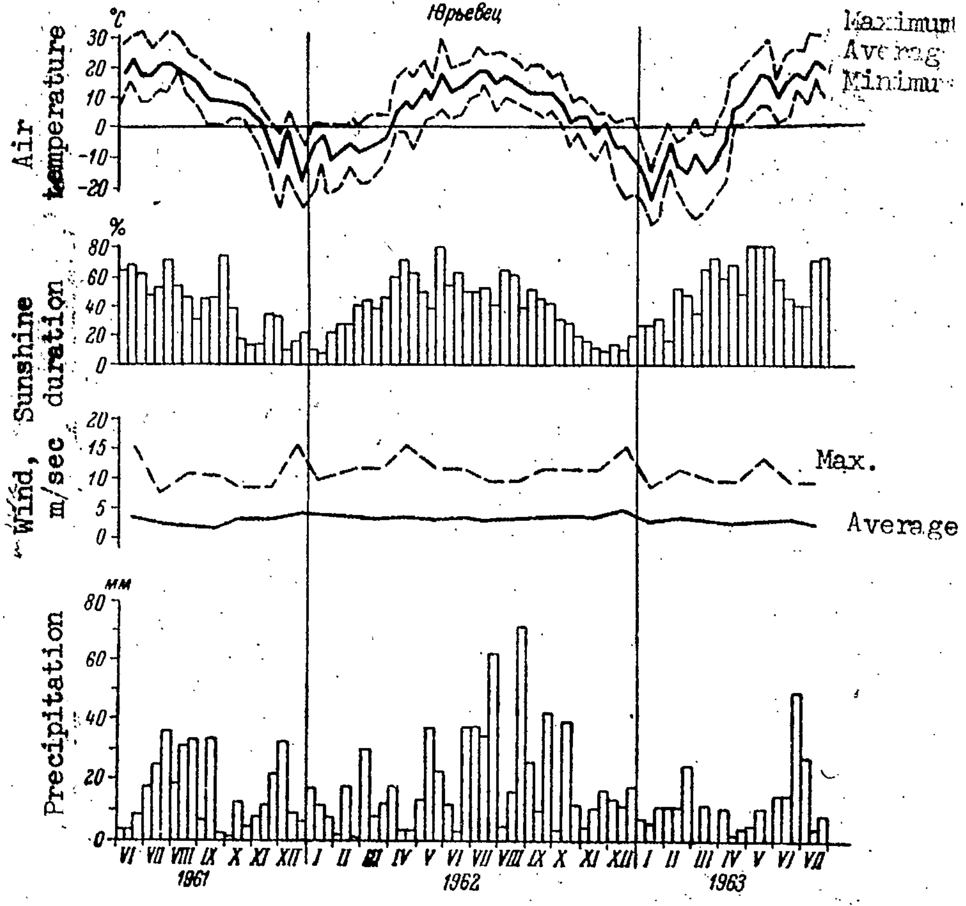

Fig. 17. (Continuation)

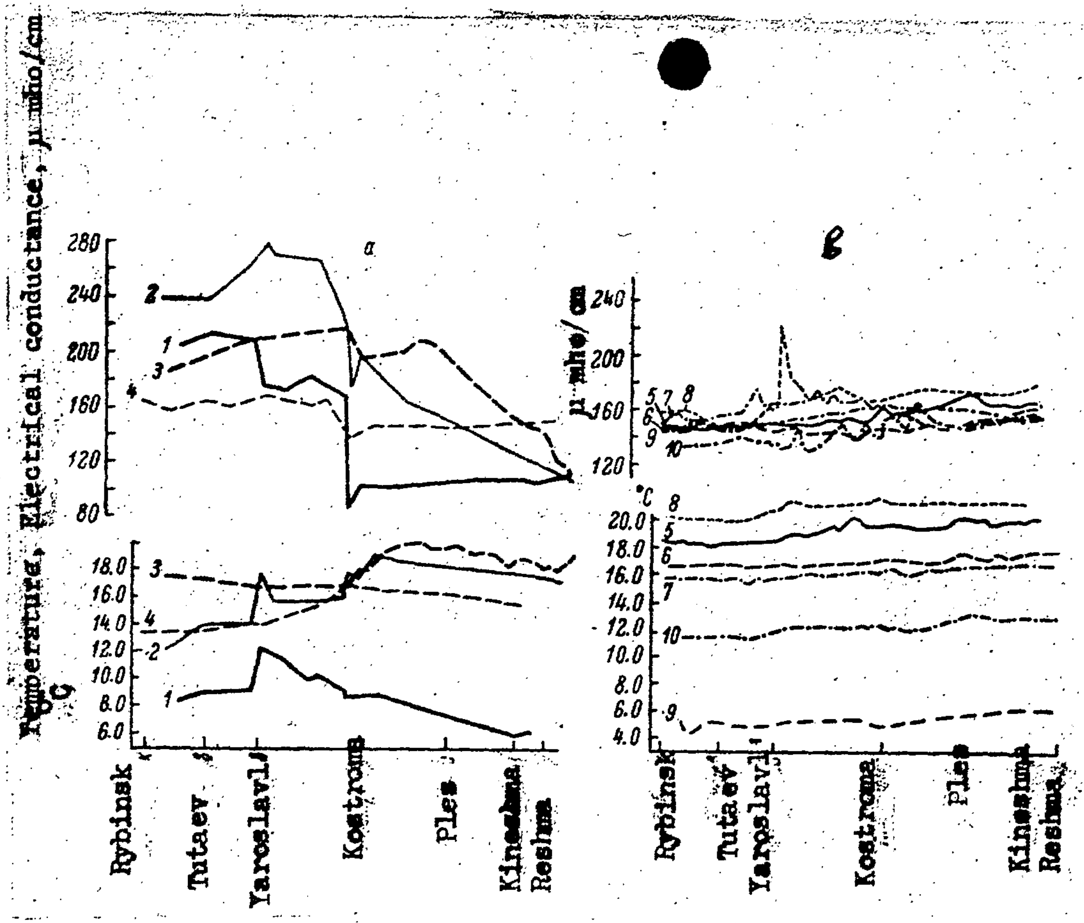

Fig. 18. Changes in electrical conductance and temperature in surface waters along the river part of the reservoir at
(a) - spring period
(b) - summer-autumn period.

1 — 3—4 V 1963; 2 — 18 V 1963; 3 — 28—30 V 1963; 4 — 1—3 VI 1961; 5 — 17—19 VII 1962; 6 — 1—3 VIII 1962; 7 — 20—21 VIII 1962; 8 — 23—25 VII 1961; 9 — 17—20 X 1962; 10 — 12—14 IX 1962.

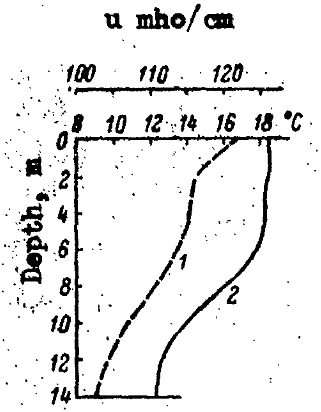

Fig. 19. (1) - Vertical temperature distribution and (2) - electrical conductance of water near Kineshma, May 18, 1963.

Table 18.

Average ten-day temperature of water in the upper area of the reservoir (Average for 1957 - 1963)

Water gauging station	April			May		
	I	II	III	I	II	III
Rybinsk	0.4	1.1	2.4	4.4	7.6	11.1
Tutaev	0.3	1.5	3.4	5.9	8.2	11.1
Yaroslavl'	0.2	1.5	3.8	6.6	8.4	11.2

Table 19

Some water characteristics in the river part of reservoir in winter 1963.

Observation point	Ist cruise				IInd cruise			
	date	electrical conductance, μ mho/cm	Colour, Pt units	pH	date	electrical conductance μ mho/cm	Colour, Pt units	pH
Rybinsk	2 II	196	80	7.0	27 III	206	70	7.0
Yaroslavl'	3 II	183	80	7.1	28 III	214	70	7.0
Kostroma	4 II	207	70	7.0	28 III	208	70	7.0
Kineshma	10 II	197	67	7.0	1 IV	224	70	7.0

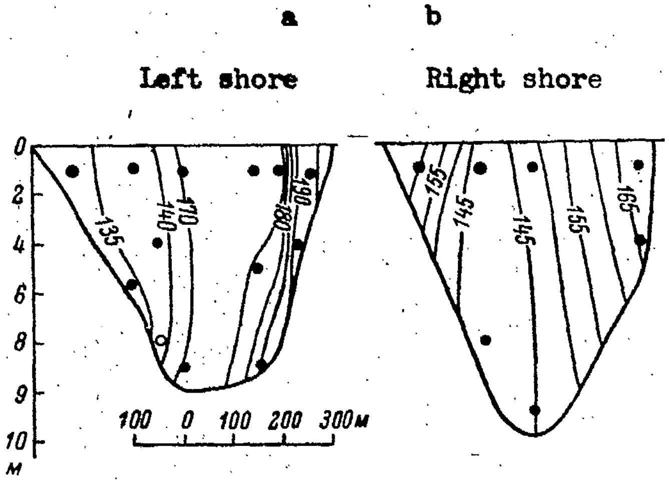

Fig. 20. Distribution of electrical conductance (in µ mho/cm) by cross-sections of the reservoir:

a - at 10 km and b - 15 km below the Kotorosl' River for 20 X 1962.

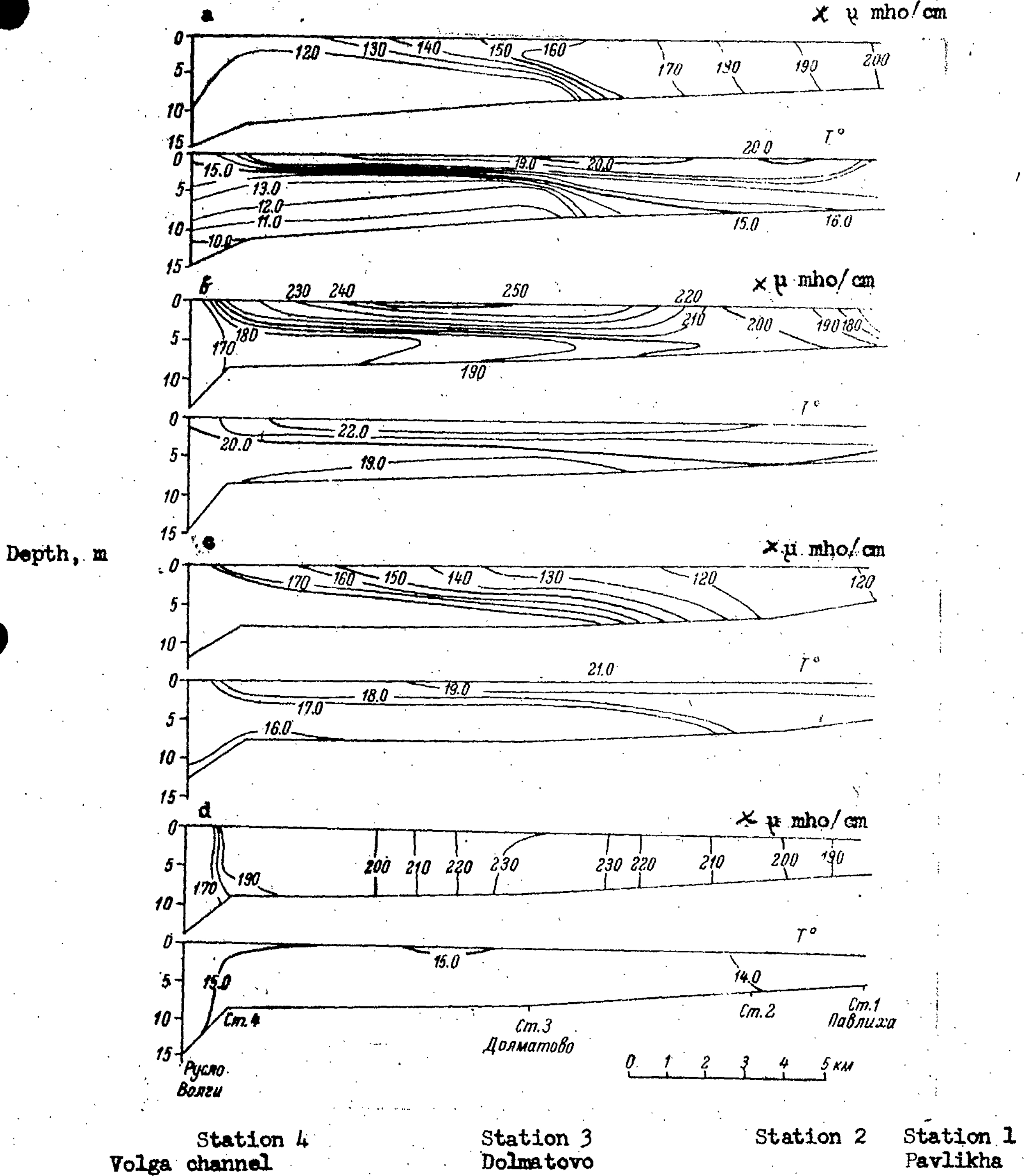

Fig. 21. Longitudinal sections of bay near-mouth of Mera showing electrical conductance and water temperature.
a – 18 V 1963; b – 19 VII 1963; c – 30 VI 1963; d – 31 VIII 1962

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Table 20

Vertical gradients of some characteristics of metalimnion waters in the Mera bay. Water density was calculated according to Berger (1955).

Date	Horizon, m	Temperature gradient, °C/m	Gradient of density due to temperature 10^{-8} g/ cm^4	Electrical conductance gradient, µ mho/cm in 1 m	Density gradient due to minerali zation, 10^{-8}g/cm^4	Total gradient of density 10^{-8} g/cm^4
19 VII 1962	3 - 4	1.1	220	23	20	200
18 V 1963	2 - 3	3.5	600	23	20	580
30 VI 1963	5 - 6	0.5	85	21	18	103

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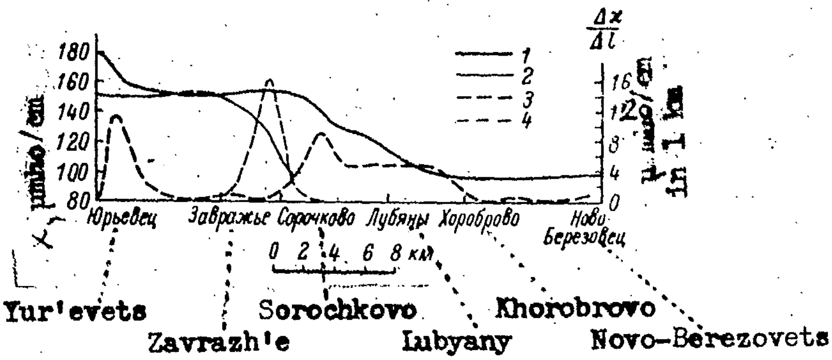

__Fig. 22.__ Variation in electrical conductance for (1) - July 20; (2) - August 1, 1962, and (3) and (4) - its horizontal gradient in surface water layer in longitudinal section of Nemda bay near the mouth.

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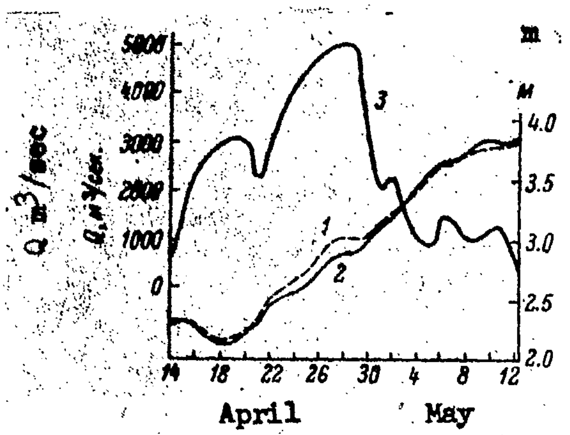

__Fig. 23__ Water level change at water gauging stations : (1) - Stolpino and (2) - Chkalovsk, and (3) - mean daily discharges of the Gorky Hydroelectric Power Plant for spring, 1963.

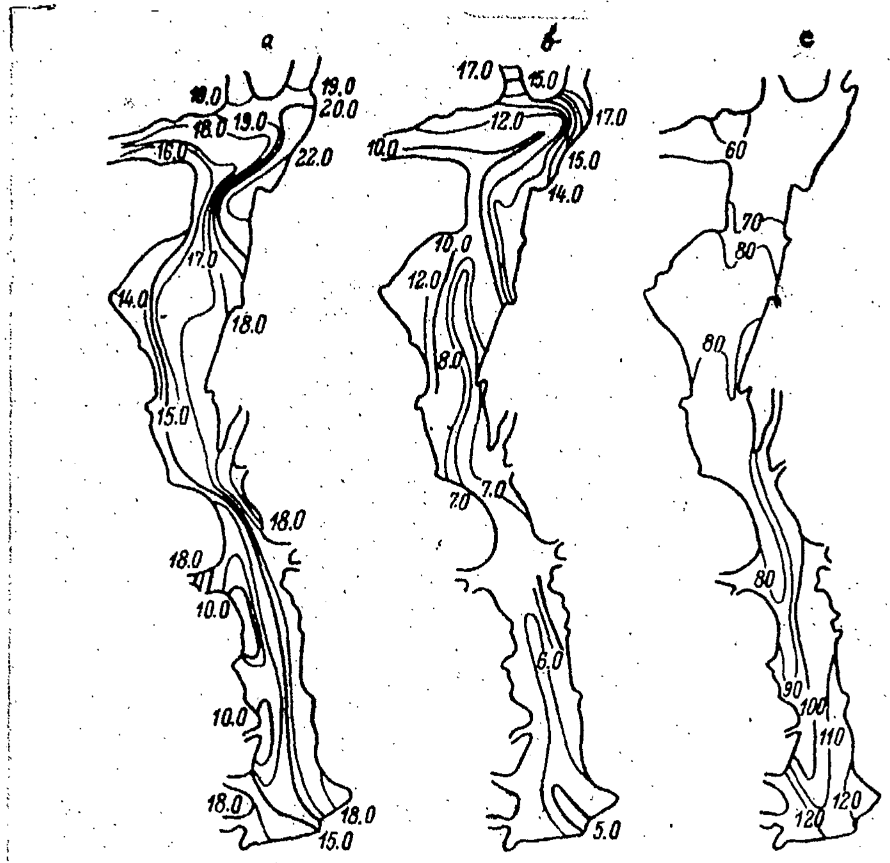

Fig. 24. Temperature distribution in: (a) - surface and (b) - near-bottom water layers between 19 and 22 May, and (c) - electrical conductance in surface layer between 23 and 24 May, 1963.

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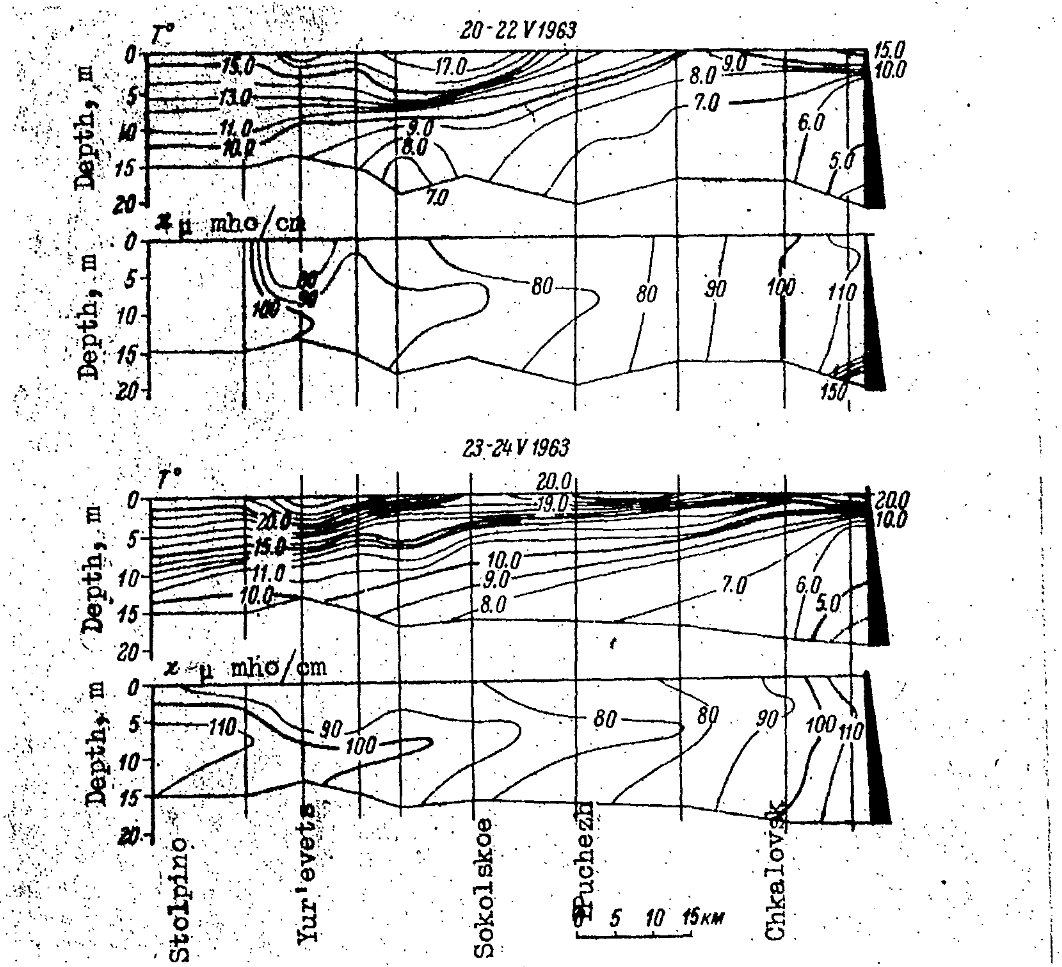

Fig. 25. Temperature and electrical conductance of water in longitudinal sections of the lake part of the reservoir (along the flooded Volga channel).

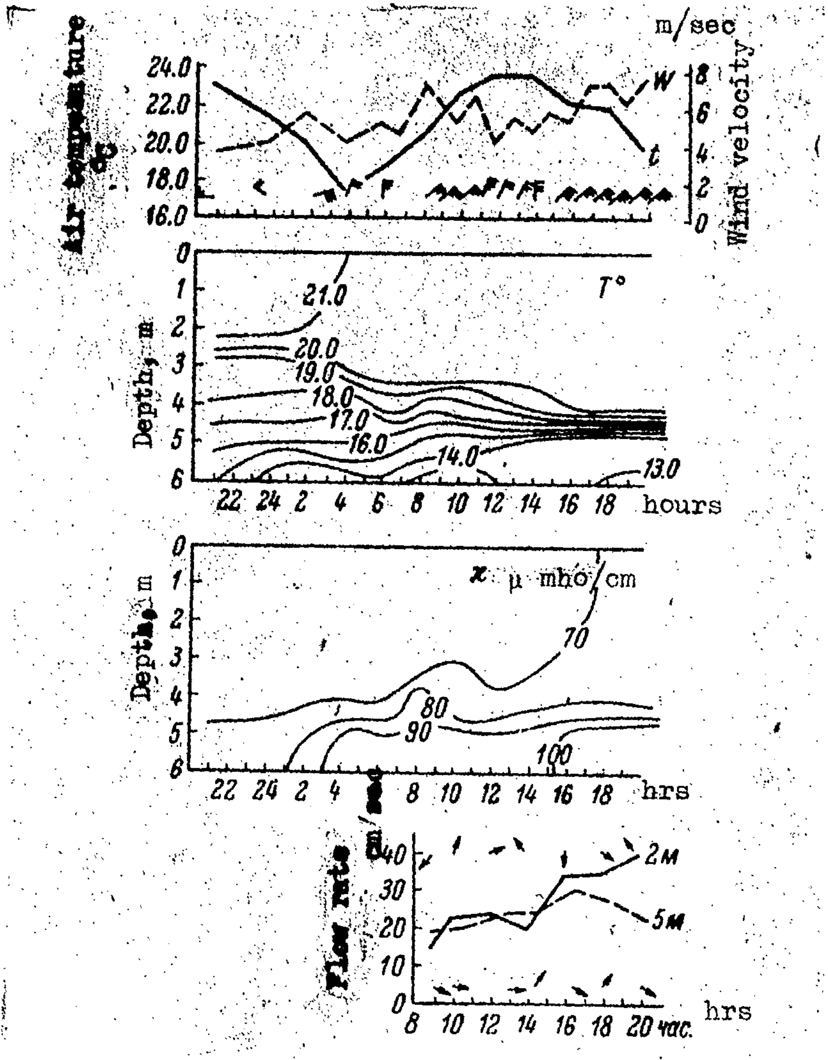

Fig. 26. Variations in: t - air temperature; W - wind velocity and direction; T - water temperature, and x - electrical conductance; of water; rate of flow and its direction at the depths of 2 m and 5 m. Data of the 24 hr, station at the Yur'evets expansion, May 24 - 25, 1963.

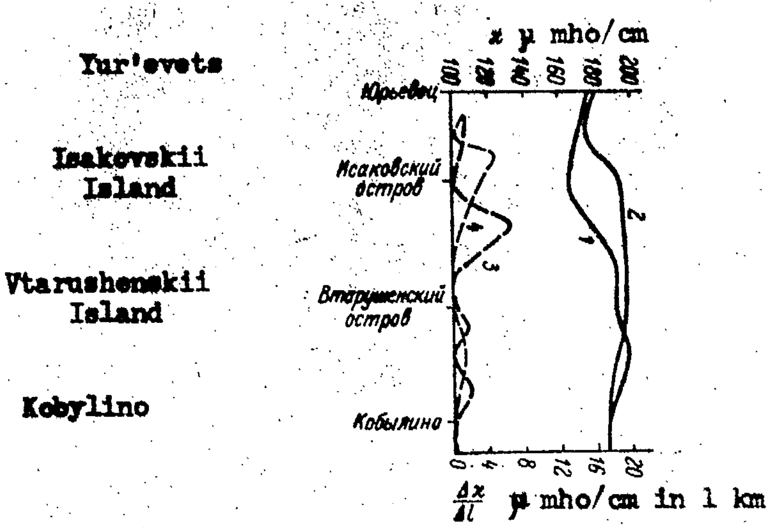

Fig. 27. 1 - Electrical conductance between 10 and 12 a. m., and 2 - between 8 and 9 p. m. on July 22, 1962; 3 and 4 - its horizontal gradients in surface waters from the section Yur'evets- Kobylinoé

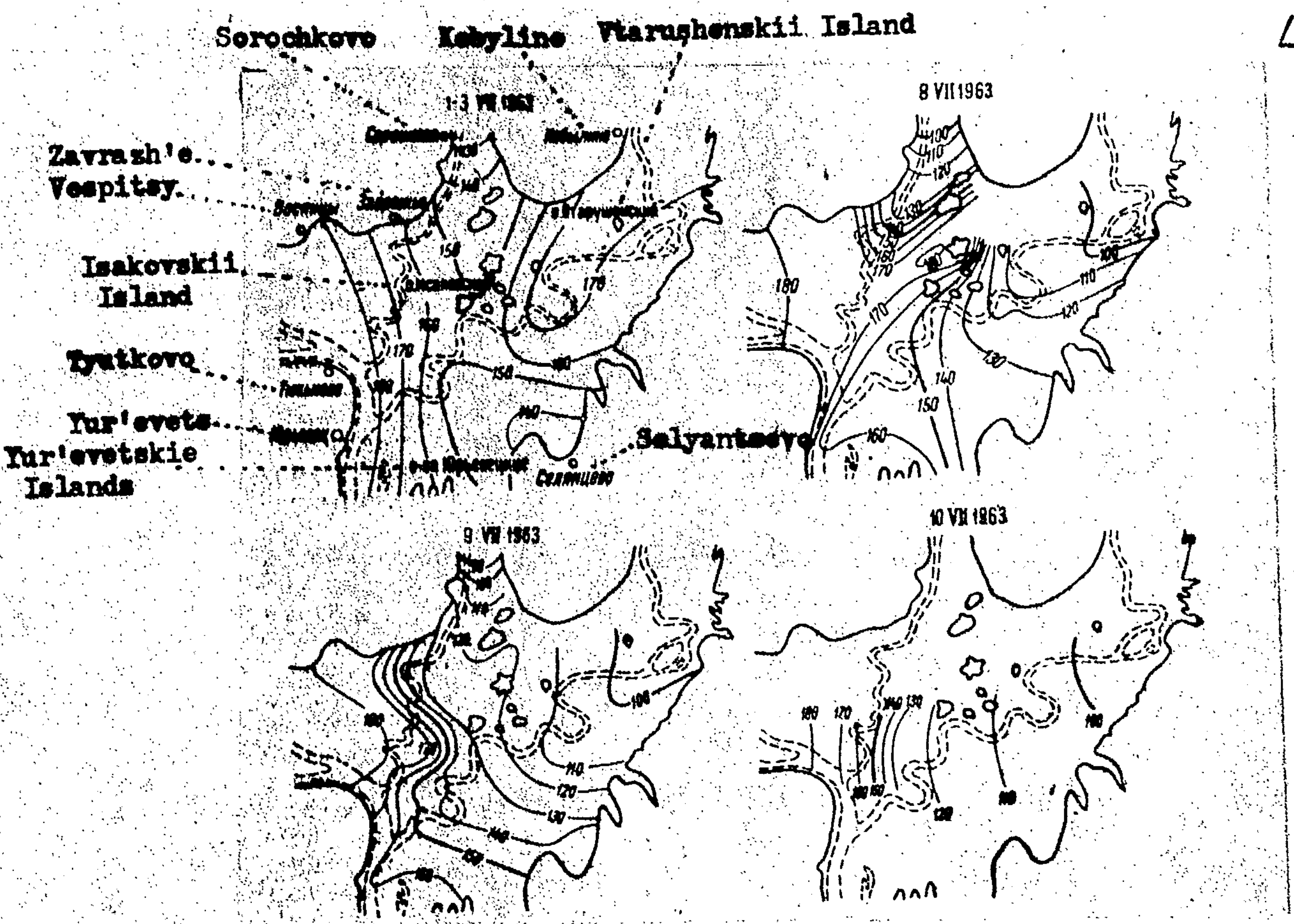

Fig. 28. Distribution of electrical conductance (μ mho/cm) in surface water layer at the Yur'evets expansion.