PP-77-2

PECULIARITIES OF SHALLOWS IN REGULATED RESERVOIRS

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January 1977

ABSTRACT

This paper is concerned with the shallows of water reservoirs, which are located between the shore line and the deep water area. The intermediate location of these shallows is the reason that their formation, especially at large amplitude of water level oscillations, is a very complex process. At the same time the role of these shallows is subject to considerable discussion in the relevant literature.

Comprehensive investigations of water quality at present include not only the technological aspects of pollution control (waste treatment, water purification, etc.), but also the relevant ecological problems which in turn are closely related to social problems and to the conditions of human life.

This paper describes the role of reservoir shallows, taking into consideration the entire spectrum of the above mentioned aspects. Special stress is given to the filtering role of shallows; they act as natural filters protecting water in the reservoir against the nonpoint source pollutants of agricultural origin which are difficult to control.

The degree to which the reservoir shallows can act as the "natural filters" depends on their structure, which in turn depends on the regime of water level oscillations in the reservoir. This dependence makes possible the control of natural processes which occur in the reservoir shallow's ecosystem by the appropriate control of the reservoir water levels.

Peculiarities of Shallows in Regulated Reservoirs

There are two factors whose interrelationship determines the nature of artificial reservoirs on plains rivers: (1) natural processes, and (2) artificial regulation of water volume (whether due to the functioning of an entire water resources complex or only part of it). Naturally, as inland bodies of water exhibiting slow water exchange rates, such reservoirs have much in common with lakes. In this sense lakes and reservoirs may be considered analogous. Significant fluctuations in reservoir water level over the course of a year or more create, however, special conditions--analogues which do not occur in nature. In this respect reservoirs differ sharply from lakes and may be considered as separate entities.

Substantial differences between lakes and reservoirs are also manifested at present by the difference in their ages. Lakes, even the very youngest (as a rule, postglacial ones), have existed for quite long periods of time and are objects with already-formed natural complexes. Reservoirs, on the other hand, are created only by men and we believe that in order to understand the peculiarities of their associated shallows specifically (not the shallows of all inland bodies of water generally), consideration must be given to time factors--the time required for reservoir development, the stage a reservoir is in at the moment we encounter it.

1. AGE

Undoubtedly, age in many ways determines the specific features of reservoirs as natural bodies of water. Reservoirs are among the few natural objects whose developement may be traced from the very moment of their inception. In the USSR, large-scale dam construction began in the 1930's (Ivankovo Reservoir, 1937) and developed particularly rapidly in the postwar years, during which the major river systems of the European and Siberian parts of the USSR were transformed into reservoir cascades. Practical experience accumulated over these years plus observation and theoretical studies, have all allowed for the singling out of those stages in the process of reservoir formation where (1) natural coastal and reservoir complexes adjust to new hydrological conditions and (2) a reservoir has been fully formed, i.e., after a relative adaptation of the reservoir's natural complexes to new hydrological conditions has been achieved. Due to the fact that most major hydroengineering activities have been undertaken in the last 10-15 years, publications on reservoir-related issues have focused mainly on the first stage--the period of reservoir formation. The problem is complicated even more by the fact that reservoirs currently not in isolation, but as specific steps in cascades and, consequently, must be examined not independently but in connection with the entire hydrological system. Observations on reservoirs over a ten-year period give sufficient data to suppose that the presence of regulated reservoirs in a cascade postpones the emergence of the "final stage" of bank-and-bed formation to such a great extent that, according to V.M. Shirokov (1970), it lies beyond the boundaries of the reservoir's entire operational period.

Usually, the first stage in a reservoir's formation occurs violently and may be likened to an explosion. The flooded river valley abruptly changes character. Intensive washing-away and collapsing of slopes takes place with all the undesirable after-effects. Coastal forests and shrubs, submerged at the roots, form entirely unique aquatic biocoenoses, without analogues in any other natural freshwater bodies. From the newly inundated soils of various terrains an intensive leaching of nutrient substances occurs which leads to a drastic increase--"a biological explosion"--of planktons (Priimachenko, 1961, 1966; Morkukhai-Boltovskoi, 1965) and benthos. Among the benthos, the oligochaetes predominate along with soil fauna (Mordukhai-Boltovskoi and Dzyuban, 1966). They serve as a food reserve for phytophile fish and, first of all, for young fish, the first-year's yield of which is connected with the existence of new spawning grounds in flooding areas (Platonova, 1964). The appearance of the high-yield generation of the first year* or years facilitate the formation of the fish population, determining its composition and high numbers for several years to follow (Sharonov, 1966).

The most abrupt changes take place in the coastal areas of newly created reservoirs. Former riverside coastal formations in the reservoir's lower and middle zones[†] are flooded to a considerable depth and are never dry, even during periods when the water level is at its lowest (during periods of maximum utilization of water capacity). In the reservoir's upper zone and its zone of minimum backwater where the floodplain is not inundated to a significant depth, wide areas of shallow water develop which we characterize as "inherited", i.e., formed on the existing "amphibious base" of the river's former flood plain.

Completely new formations appear in the lower, deep parts of reservoirs where the water level, raised by the dam, reaches land never before subjected to flooding. In such vast shallows, specific formations appear--natural complexes of the reservoir's shallow waters.

2. WHAT DETERMINES THE EMERGENCE OF SHALLOWS

First, the peculiarity of the morphological structure of the reservoir's bed. As a rule, reservoirs are constructed on large rivers with well-developed valleys. With the rise in water level, tributary valleys, gulches, ravines, riverside lowlands, river terraces, etc. are suddenly located in the

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*The role of the first year in determining fish stock for the Tsimlyanskii and Kakhovskii reservoirs was pointed out by I.I. Lapitskii (1961) and N.E. Salnikov (1961).

†Division of reservoirs into hydrological zones is done here on the basis of work by S.L. Vendrov (1955).

flood zone and cause areas of shallow water to appear. Where there used to be river valleys, ravines, gulches, riverside lowlands, now bays are formed that vary in both shape and size. When the river floodplain or terraces are not inundated to a significant depth (i.e., only to 1.5-2.5 m) high formations such as dunes, sand ridges, channel banks, etc. occur above the water level. These are transformed into archipelagoes and are typical, first and foremost, of the upper zones of reservoirs, where water is less deep. Archipelagoes are also encountered in the deeper water of a reservoir's middle and lower zones at places where river terraces have been inundated. In the majority of cases these archipelagoes are made of easily eroded soils (sand, sandy loam, gravel) and actively disintegrate as a result of wave action. Their material, together with that from collapsed banks, is transported by coastal flows to the reservoir's lower parts and in turn forms bars, sand ridges, shoals and accumulates in depressions in the riverbed. At the Tsimlyanskii Reservoir, after twelve to fourteen years of existence, there predominates in its lower and middle zones bottomland covered with 10-40 cm of silt, whereas the upper zone is silted mainly due to the heavy flow of the Don River and its tributaries (Klyueva, 1969).

Observations over the course of ten years at the Kuibyshev Reservoir have shown that of a total of 234.3 million m^3 of soil washed away, 46% have gone into coastal zone accumulations and 54% into suspension or accumulation in the reservoir's bed. (Shirokov, 1969).

On the basis of information gathered by flights over the Kuibyshev Reservoir before the springtime water increases (Shirokov, 1964a) and when the water level had fallen to 4.5-5.5 m average level for this period on the basis of readings taken over many years, we have compiled a comprehensive map-diagram (Figure 1). From this map-diagram one can clearly see the well-coordinated distribution of main archipegaloes along the aquatory, as well as the shift pattern for sand drifts along the coast and the distribution both of newly accumulated forms and of relief elements inherited from the former river valley,

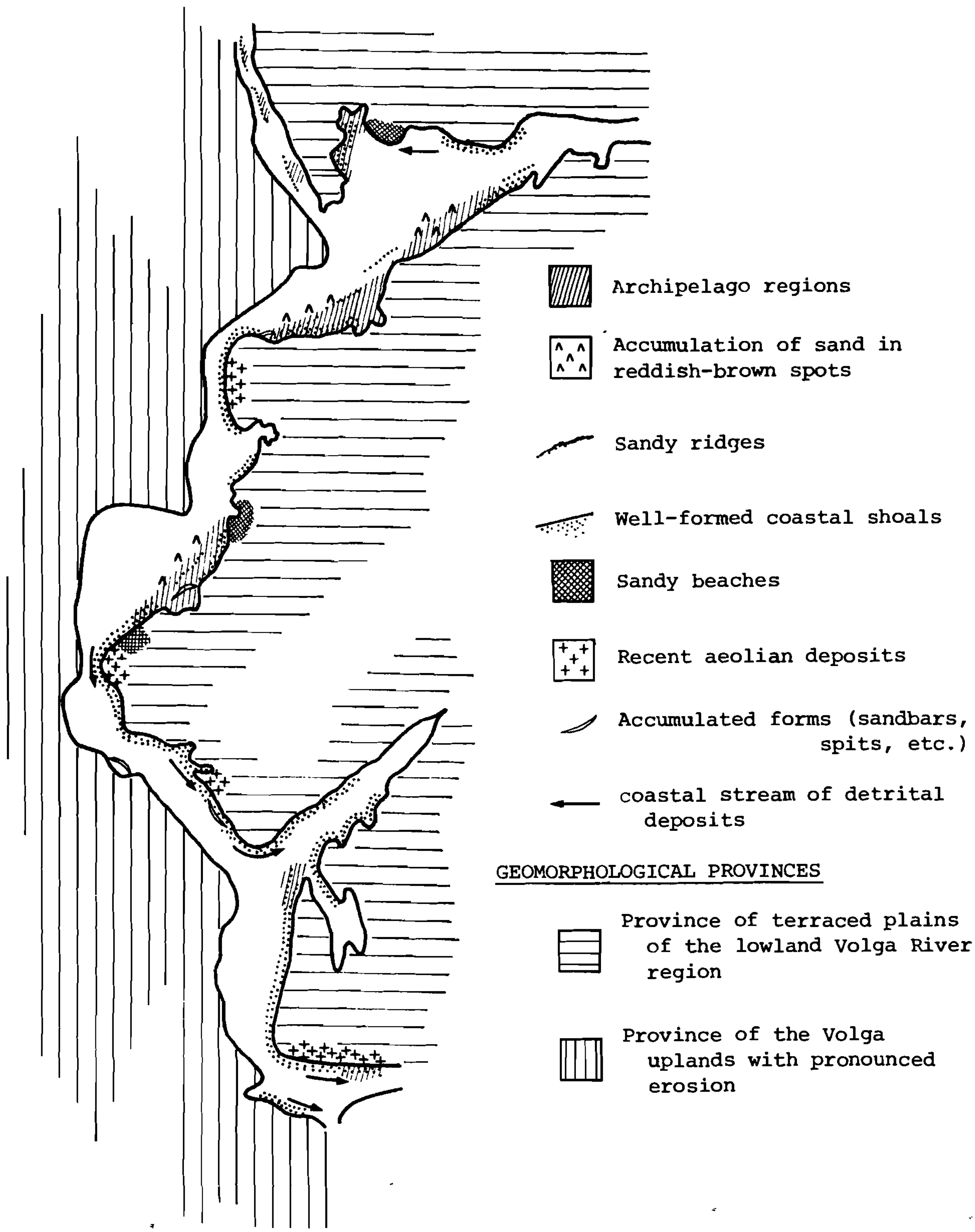


Figure 1. Geomorphological provinces and some elements of the present-day submerged relief of the Kuibyshev Reservoir.

i.e., sand ridges, dunes, etc. From this diagram one can see the clear correspondance of shallows along bays and behind islands with gullies and ravines of the left bank.

In the Ivankovo Reservoir where a wide terrace of the Volga River has been flooded along the left bank near the dam, wide shallows have appeared behind islands and along bays. In instances where a tributary that is located within a dam's backwater lies in a wide valley or extensive lowlands, considerable expanses of shallow water occur.

In the Gorky Reservoir, for example, Kostroma Bay was formed along the valley of the Kostroma River at the place where the well-known Kostroma Lowlands are located--a depression in the topography that has existed since pre-glacial times. This depression is bounded by a well-defined ledge running up to 60 m in height and at present is linked with the main body of the reservoir by a narrow passage.

In the Ivankovo Reservoir the aquatory along the Shosha River was formed in the valley of an outwash plain. In the upper reaches of this flooded area there emerged a whole archipelago whose islands differ from each other in form and size--the remnants of the highest elements of the valley. Among the peculiarities of the Shosha's shallows is the fact that the general shallowness of the flooded area hinders the development of intensive wave action. A consequence of this is a low rate of disintegration for islands and bottomland. According to the data of V.P. Kurdin (1961), uneroded bottomland already begins at a depth of 2.7 m and the entire soil complex of the upper reaches of the flooded area consists of inundated soils.

The connection between the distribution pattern of shallows and the structural peculiarities of a flooded valley may be seen very clearly in reservoirs which "cut across" different geomorphological regions. Let us take, for example, the Sheksna Reservoir. In this reservoir, two parts are clearly distinguished: a river part (the valley of the Sheksna River) and a lake part (White Lake and the mouth of the Kovzha River) (Figure 2). The upper reservoir occupying the low part of the White Lake-Kovzha depression is uniform in its morphological

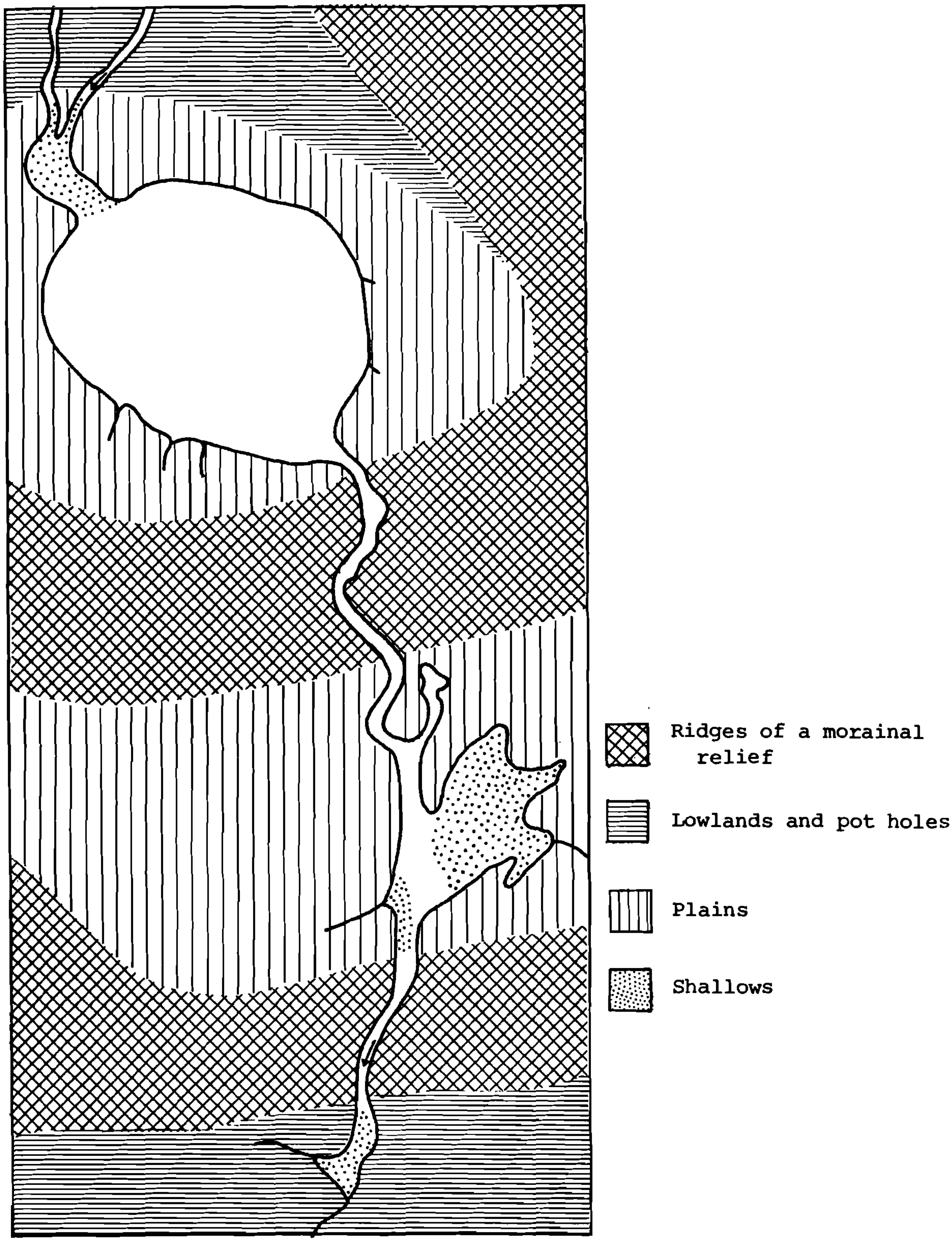


Figure 2. Scheme of the geomorphological regions of the Sheksna Reservoir and principal regions of shallows.

aspect. On the other hand, the valley of the Sheksna River which crosses moraine ridges, lowlands and hollow, has distinct, identifiable parts.

The reach of the reservoir nearest the dam, situated on a plain of the glacial epoch, has an average width of about 2 km. This section of the reservoir has several large bays such as Ust-Ugolskii along the right bank and the one along the left bank located on the site of the flooded terrace of the Sheksna River.

The reservoir attains its maximum width in the regions of its hollows, where the river--its water level raised by the dam--floods the depression in the region of the village Nilovets (the "Sizmenskii Expanse") and forms a vast area of shallows. In the backwaters of the dam are White Lake and the mouth of the Kovsha River; these flood the terrace of White Lake (Photo 7) and the Kovzha Lowlands. Large and small bays have appeared in the marshes along the Kovzha River (the river itself has a maximum depth of only 3 m in its fairway, which by the third year of the reservoir's existence were overgrown with aquatic plants, including marsh varieties. Menyanthes trifoliata has formed entire floating islands, as has Polygonum amphibium and, more rarely, Sagittifolia. This situation has been encouraged by the former marsh-like character of the valley: marshland meadows acting as a reserve for marsh vegetation, the inflow of pigmented and weakly mineralized waters from Kovzha Lake with significant amounts of organic substances, oxidation at the rate of 12.8-13.6 mg o/l (Fedorova, 1964).

The shallow waters of the Sheksna Reservoir reach their maximum extent in the region near the village Nilovets (the "Sizmenskii Expanse") when crossing the Svirsko-Kovzhinskii Depression. Here ox-bow lakes, floodplain lakes, marsh areas (Sokolskii Marsh, Zybin Marsh and others), lowland forests of birches and willows--all have disappeared under the reservoir's waters. In their place a great flooded area has appeared with many bays which at present are heavily overgrown. In contradistinction to what happens when crossing depressions, the reservoir's valley narrows considerably during the crossing of moraine ridges. Here the steep banks remind one more of the slopes of artifically created canals than those of natural slopes. Particularly of note is that part of Chernaya Gryada (Black Ridge) where the Sheksna River cuts through a ledge of the terminal moraine (Figure 2, the part of the river above the reach of the reservoir nearest the dam). The examples cited show how the morphological character of the flooded valley determines the surface distribution of shallows. In addition, it has been noted how shallows differ according to peculiarities of location: shallows occur along bays and where the valleys of tributaries and coastal depressions are flooded; they occur behind islands and where there are river terraces, coastal slopes, heights flooded to a slight depth, etc. Other formations are directly associated with shallows: shoals, bars, spits, sand ridges--all which emerge while coastal slopes and beds undergo transformations. Naturally, qualitative and quantitative characteristics of coastal slopes and beds change noticeably in the process of a reservoir's formation: there is a straightening of coast lines; a cutting off of the tops of underwater ridges; a forming of new submerged slopes, etc. On the other hand, one may point out as a peculiarity of shallows behind islands and along bays their relative stability. The severing of bays from reservoirs due to the emergence of sand ridges, i.e., as part of coastline straightening processes, does not eliminate these shallow waters but only gives them a new characteristic: a bay as part of a reservoir ⟶ an autonomous body of water (lake). On the basis of a great deal of factual material already accumulated from hydroengineering projects in the USSR, the following general scheme for the spatial distribution of shallows may be discerned.

In northern zones and primarily in areas of Quaternary (young) relief, shallows along bays and behind islands tend to be in depressions, hollows, interridge depressions and in the valleys of outwash plains. For examples one need only look to the basin of the Volga River: in the Ivankovo Reservoir, shallows lie on the site of the Shosha and Sozz Rivers valleys; the basin of the Rybinsk Reservoir is an ancient lacustrine hollow wherein the Mologa and Sheksna Rivers developed their valleys; and it was in interridge depressions where the Chernaya Zavod (Black Creek) Bays of the Gorky Reservoir emerged. The previously mentioned bays in the White Lake and Svirsko-Kovzhinskii Depressions of the Sheksna Reservoir also emerged in a similar fashion.

In southern zones the distribution of shallow water is different. Here shallows tend to appear in terrace depressions and in areas with gulch and ravine reliefs. As a result of this close connection between valley morphology and the distribution pattern for reservoir shallows, one is able to foresee at the planning level those places where major shallows will form in future reservoirs.

3. Linked with the problem of their distribution pattern is the question "HOW WELL ARE THE SHALLOWS PROTECTED FROM WIND-GENERATED WAVE ACTION?"

It is a known fact that in reservoirs, as in any other inland body of water, wind-generated wave action is the main dynamic factor influencing the formation of shallows as natural complexes. Let us take as an example two shallows formed on a terrace of the Volga River in the lacustrine section of the Gorky Reservoir. In the submerged areas of the mouth of the Yachmenka River the ledge of the river terrace facing the open part of the reservoir has been extensively eroded. Even stumps, snags, and driftwood do not protect the coast from erosion caused by waves. However, simultaneously on the same terrace, but behind the ledge in a bay 200 m from the mouth, in a place large waves do not reach, shallows are overgrown with luxuriant varieties of grasses. Among these grasses even marsh varieties occur. The front part of the growth, consisting of Potamogeton, extends gradually along the bay's aquatory. In contrast to open stretches, which consist of sandy soils, the soil complex of protected shallows is 19% sand, and more than half (55.8%) silt. From the example it is clear that the absence of wave action is quite clearly manifested by the appearance of aquatic vegetation. It may even be said with certain reservations that such vegetation may serve as an indicator of the hydrodynamic state of the aquatory. It is precisely for this reason that botanists subdivide the phytocoenoses of reservoirs into those formed in protected areas and those subjected to wave action ("exposed" ones). Thus A.D. Priimachenko (1959), divides all shallows into two categories: exposed and protected, pointing out that the latter is characterized by a large variety of aquatic plant forms, 84% of which are encountered only in coastal zones. A.A Potapov (1962) has stressed that one of the basic factors leading to concentrations of hydrophytes must be the the presence of shallows protected from wave actions. In the work of V.A. Ekzertsev (1960, 1962, 1966, 1973), it has been demonstrated that the nature of a shoreline's vegetation is determined by soil peculiarities, but also by the degree to which the shoreline is sheltered. Observations by zoologists of aquatic invertebrates have shown that many animals inhabiting shallows and feeding as filtrates are encountered chiefly in areas protected from winds. One example is the Asplanohnidae family--A. priodonta and A. herricki-- which concentrate mainly in bays (Mordukhay-Bultovskaia, 1965).

The formation of new elements in the topography of a reservoir's basin--spits, sand ridges, bars, wide shoals, steep submerged slopes, etc.--is directly connected with wind action and accompanying coastal flows of detrital deposits, discontinuous currents, etc. which are typical for the open parts and are rarely found in protected bays, or behind island archipelagoes (Ikonnikov, 1972; Kaskevich, 1969; Churinov *et al.*, 1972).

In shallows where the aquatory is small, where broken coastline, islands, aquatic vegetation, etc. hinder wave action, calm conditions exist. As a consequence of such conditions thermal and chemical stratification of the water occurs, and a settling to the bottom of heretofore suspended detrital material that waves have carried in, plus organic and mineral complexes are formed in these deposits. Here there is intensive development of amphibious vegetation and the dense growth of accompanying biocoenoses.

For shallows not protected from wind-generated wave action, the water's mass exhibits dynamic (active) processes. The leading factor determining the character of open shallows is such wave action. In certain cases, however, when a reservoir is narrow, for example, waves from ships may play an important role. Reservoirs in the USSR lie along busy commercial routes and therefore in narrow and winding stretches where conditions suitable for development of wind-generated waves are absent, wave action from ships becomes the main dynamic factor determining the formation of shallows. Ship-generated waves which have, as a rule, a height of no more than 0.5 m and a length of 1 to 2 m begin to dissipate along the bottom at depths just slightly exceeding 0.5 m. When waves reflect back from a coast a percentage of the larger suspended material is carried to great depths. The nature of small (ship-generated) wave action in open shallows is such that while not acting to erode submerged slopes and coastal features, it does (like wind-generated wave action) keep the water's mass in a dynamically active state, mixing and equalizing it thermally and chemically, redistributing mechanical fractions along the profile. Under such conditions the spread of those aquatic plants most resistant to wave action is also possible. Both Schoenoplectus lacustris, and Potamogeton are "pioneers" in this regard. Potamogeton pectinatus, which usually grows on sandy shoals, exhibits excellent resistance to wave action. These same properties are shared by Potamogeton perfoliatus and Potamogeton lucens, both of which usually form homogenous communities in areas subjected to wave action (Ekzertsev, 1966). According to our observations at the Gorky Reservoir in July 1965 dense growths of Potamogeton pectinatus occupy the entire submerged part of the coastal slope from the water's edge to a depth of 50-60 cm, forming, together with the floating leaves of Butomus umbellatus, a clearly discernible border that marks the place where small ship-generated waves begin to break.

We devote attention here to ship-generated waves since wind-generated waves on elongated "fluvial" areas of water do not develop as fully as they do on broader, lacustrine areas. Up to the present time the attention of researchers has been devoted mainly to wind-generated wave action and its manifestation in shallows on bodies of water where waves may gather momentum and have considerable energy. These researchers, however, have not taken into account the fact that shallows are encountered not only in lacustrine areas but also in the narrower parts of reservoirs. In connection with this, the presence of a wave-absorbing barrier, either natural (as for example, a wide shoal or submerged bank) or artificial, may have substantial and at times a decisive influence on the development of natural complexes in shallows which, in spite of their "open" position are protected from wind-generated wave action. So it is that in the Gorky Reservoir near the towns of Puchezh and Yurevets along the right bank of the reservoir's lacustrine reach, a 5 kilometer stretch of river terrace is flooded to a depth of 1.5-2 m (Figure 3). In this stretch of water (in spite of the aquatory's considerable dimensions) waves have not worn the shore. Here the wave-bearing action of the shoal is reflected both in the distribution of bottom deposits (where 20 m from the water's edge at a depth of 50 cm the proportion of fractions less than 0.1 mm is 75%), and in the distribution of aquatic plants. From the shore to a depth of approximately 80 cm Potamogetonae (Potamogeton pectinatus predominating) have spread, forming homogeneous communities in elongated patches 45 m long by 25 m wide. In inundated floodplains besides Potamogeton there have appeared Glyceria aquatica, Butomus umbellatus, Sagittaria sagittifolia, Alisma plantago aquatica. And at the former peat excavations at the mouth of the Orekhovka River near the village of Obzherikh these forms are joined by Calla plaustris, Menyanthes trifoliata and Stratiotes aloides. On the floating peat many sedges can be found. One may suppose that in open expanses of shallow water protected by large wave-bearing shoals, aquatic vegetation

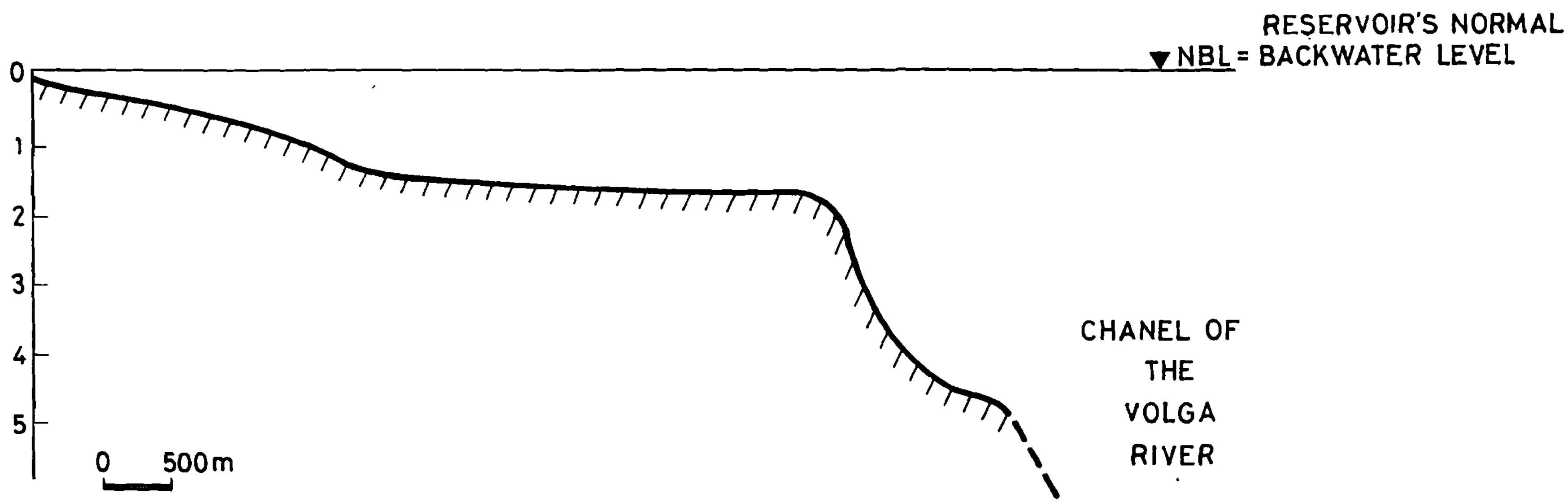
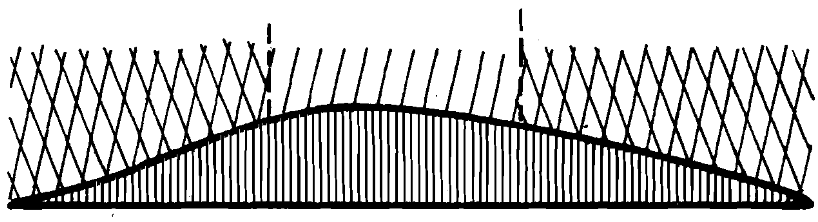


Figure 3. Longitudinal profile of the submerged terrace of the Volga River near Puchezh-Yurevets.

continues to advance and that there is an accumulation of minute particles (a silting process) from the coastal area in the direction of the open aquatory.

As a special case, but one characteristic of all our northern reservoirs formed over peat lands, we may examine the impact of peat islands on wind-generated wave action and on the growth of aquatic vegetation in open aquatories. Clumps of peat which have floated to the surface during the first years of the reservoir's existence contain in their mass the seeds of former forest and marsh plants. On such masses of floating peat occur associations of marsh varieties. In Figure 4 such an "island" is illustrated, one which floated to the surface during the first years of a reservoir's existence. As a rule, these masses have a lens-like shape. This is because with erosion their outermost parts become thinner and, while allowing waves to pass through themselves in a sieve-like manner, still retain mineral suspensions. Under such conditions of excessive moisture, lowland marsh plant associations form on the peat and mineral substratum. The emergence of a ring of marsh vegetation--a "marsh ring"--along the periphery of the peat "island" retards the rapid disintegration of the peat mass due to wave action and promotes the development of upper-marsh associations in the central, higher (convex) part of the mass.

For all practical purposes, peat which rises to the surface after having been submerged seven to nine years contains neither seeds capable of germination, nor plant organs capable of vegetation. On such peat masses vegetative cover to block destructive wave action does not form and, therefore, a large number of such islands fragmentate during storms, ceasing to exist. Their remnants settle to the bottom as small pieces in the shoals of open aquatories. These remnants, in turn, while damping part of the surf action are covered by suspended material and are overgrown by marsh vegetation; in this manner, they promote the emergence in the upper parts of sloping shoals of natural complexes similar to those found in lowland marshes. This process whereby shoals are overgrown as the result of the peat settling, may be noted in every reservoir where peat bogs are flooded.



- "body" of the floating peat

- "zone" of plant associations indigenous to upper marches

- "zone" of plant associations indigenous to lowland marshes

Figure 4. A cross-sectional diagram of a floating peat mass ("island") which rose to the surface during the first years of a reservoir's existence.

3.1. It is only in reservoirs that we encounter such a phenomenon as a submerged forest. Besides the fact that submerged timber influences water quality in many ways, e.g. changing its color, imparting unpleasant smells and tastes, increasing the level of dissolved and suspended matter (Potapov, 1962), it also plays a wave-dampening role. Under the protection of a former forest in the newly emerged "wave shadow" of open shallows, natural complexes begin to form similar to those found in sheltered aquatories. Depending on how long the wave-dampening role of the submerged trees continues, the "protected" shallow-water area continues to exist in the open reaches. We encounter no similar such paradox in any lake.

How long the submerged timber lasts depends both on the composition and the age of the forest and on the destructiveness of the wave action. With flooding, tree root systems are partially or completely deprived of oxygen for a long period of time. This causes the dying off of, first, young trees (Afanasev, 1966; Kurzhakovskii, 1953), and the immediate destruction of pine seedlings. The ability of the willow, however, to form adventitious aerial roots makes this plant the most resistant to flooding. In this same category may be included Populus nigra, Fraxinus pennsylvanica, and Populus tremula.

In our northern reservoirs, flooded forests consist chiefly of birches, aspens, firs and willows (Bobrovskii, 1952, 1957). In the open coastal shoals of the Rybinsk Reservoir, forests consisting of birches and firs have, in the course of two decades, been almost completely destroyed. On the other hand, a submerged larch is able to exist for many years, a fact testified to by the submerged forests in Lake Khubsugul. According to Tomilov and Doshidorzha (1965), the forests there have continued to survive for over forty years.

In the Sheksna Reservoir, the main tracts of forest are in the valley of the Sheksna river. Here the negligible width of the river bed hampers the acceleration of wind-generated waves. For this reason the chief destructive forces are ship-generated waves and biological processes which lessen the durability of the timber. The mechanical effect of wave action is seen most clearly along the forest's frontal belt, which has a width of 20-50 m, at most 80-100 m. Usually, by going deeper into the submerged forest, 25-30 m from open water, one begins to find floating aquatic plants, such as Ceratophyllum demersum, Hydrocharis morsus-ranae, Utricularia vulgaris, and duckweed (Lemna). Here large hummocks are found to be overgrown with Cicuta virosa.

Continued investigation of the Sheksna Reservoir has shown that even after the forest completely died out*, its wave-bearing effect continued and under this protection groupings of hydro-hygrophyletes developed at a depth of 20-60 cm, namely Elodea canadensis, Ranunculus circinnatus, Potamogeton perfoliatus, and P. obtusifolius. Of the floating varieties, there continued to appear, as in previous years, accumulations of duckweed and Hydrocharis morsus-ranae.

Even from these few examples it is apparent that during the process of a reservoir's formation, especially in its first stage of development, submerged forests play a significant role in retarding destructive wave-action. They permit shallows to develop in their "shade" (i.e., from wind-generated waves) and thereby permit features to appear, which are uncharacteristic for open aquatories.

Of the factors which determine the specific nature of reservoirs and their associated shallows we have examined: (1) structural peculiarities of flooded river valleys which predetermine the position and distribution of shallows, whether along bays, behind islands, over flooded river terraces, etc. or whether in upper, middle, or lower reaches, etc.; and (2) hydrometrical impacts. However, the main factor determining the character of shallows in man-made reservoirs is fluctuation of water level.

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*According to the observations of V.A. Ekzertsev and A.P. Belavskaia (1970), in the sixth year of the reservoir's existence one encounters only isolated willows, mainly Salix pentandra, in the dead forests.

4. Types of Reservoir Regulation

According to how their discharge is regulated, reservoirs can be divided into two categories: (1) those which regulate over multi-year periods, and (2) those which regulate seasonally. In the first instance, the normal backwater level (NBL)* is reached once every several years in connection with the natural peculiarities of the basin and the demands placed upon it by various industrial and public consumers. In the second instance the NBL is reached every year through maintenance of all anticipated norms for water consumption by the networks of users dependent on the given reservoir or (with known deviations) as a function of a specific year's average water conditions and operational requirements.

Coastal stretches of open water, of course, are the first to experience the impact of fluctuations in water level. When the level drops, they become dry; when the level is driven up, they submerge to a level deeper than originally planned and experience somewhat different, deeper conditions than those associated with the usual (normal) water level.

Depending on the kind of reservoir and the needs of its consumer, a reservoir's water level may fluctuate over different periods at varying rates. If the water fluctuates around a mean level over a fixed period of time, as for example in the upper reaches of the Gorky Reservoir (where daily fluctuations reflect the rhythm of work at the Rybinsk Hydroelectric Complex) then such changes do not substantially modify the natural complexes in existing shallows. This is so since complexes are constantly being formed which adapt well to the most frequently occurring water level. Quite another situation occurs where there is a seasonal drop in water level e.g., from the NBL (or maximum level for a given year) to the minimum levels which precede spring increases. Such fluctuations easily have amplitudes which are measured in meters, reaching, for example,

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*This is the optimal high water level for which a reservoir is designed. (Translator's note.)

6.5 m in the Kuibyshev Reservoir, 7 m in the Kamsk Reservoir, 10 m in the Bratsk Reservoir and 15 m in the Krasnoyarsk Reservoir. Naturally, fluctuations of this dimension radically influence natural complexes occurring in affected areas. Such processes have no analogues in nature. Water fluctuations (both multi-year and seasonal) in major lakes are of an entirely different magnitude, for instance Lake Balkhash, 25 cm; Lake Ladoga, 38 cm; Lake Pskov-Chudskoe, 56 cm.

In reservoirs that have seasonal fluctuations in water level--where high water is regularly reached in the spring following yearly minimums due to ice formation--the characteristics of shallow-water complexes depend on the nature of water fluctuation specifically during the "ice-free" period. Regardless of differences in the length of time that various reservoirs maintain water at the NBL (i.e., at the high-water level for a given year), one may distinguish three types of water-level regimes. Reservoirs may be divided according to the times when low water occurs during the "ice-free" period:

Type I - Low-water level at the end of fall and in the winter.

Type II - Low-water level at the end of summer, in the fall, and in the winter.

Type III - Low-water level in the summer, in the fall, and in the winter.

If we take the full amplitude of fluctuation to be A, the low water level in the "ice-free" period to be a_I, and the low-water level for the period when ice is present to be a_2 (i.e., $A = a_I + a_2$), then for each type of water-level regime we have:

Type I $a_2 > a_I \cong 0$ $A = a_2$

Type II $a_2 > a_I$ $A = 3\text{-}4\ a_I$

Type III $a_2 \geq a_I$ $A = 2\ a_I$

In the Volga Cascade there are reservoirs for seasonal regulation that represent all three types. As an example, let us introduce several of them, using averages completed on the basis of observations made over several years (Butorin, 1969) and presented in Table 1.

TABLE 1

Water Level Fluctuations in Reservoirs of the Volga Cascade

Reservoir	Amplitude of Fluctuation in Meters			Type of Water Level Regime
	a_I	a_2	A	
Ivanovsk	0	6	6	I
Gorky	0	2	2	I
Kuibyshev	1.5	5	6.5	II
Rybinsk	2	3	5	III

This classification reflects only average yearly water conditions and must be corrected for changes caused by hydroelectric power operations, the effect of input of water, etc.

Prolonged maintanence of water at the NBL during "ice-free" periods (Type I) occurs usually in regulating reservoirs. These reservoirs as a rule are filled by the waters of a primary river, and tributaries have no decisive influence on water level. In the Volga System of cascades such a water-level regime is manifested by the Uglich, Gorky, Saratov, and Volgograd Reservoirs. At the present time the Ivankovo Reservoir is included in this group. This reservoir was planned as the chief water-control work of the Moscow-Volga River System. Thus it is designed for intensive water intake during warm periods of the year, and for a drop in water level at the end of July or in August and for a continued low level until the beginning of spring floods (Gaveman, 1955), i.e., for a Type II regime. However, in connection with the summer floods of 1949, 1950, 1953, 1960, 1962, and the fall floods of 1952-1954, 1956-58, 1960 etc., measurements of water level since 1948 have shown insignificant fluctuations in the NBL during "ice-free" periods (Emilianov, 1965). Thus, we deem it more appropriate to treat Ivankovo as an example of a Type I reservoir (Figure 5).

If a reservoir is fed not only by one river but by two or three, the basins of which are located in different natural zones, then maintenance of water at the NBL is associated with problems of balancing input and output. There must be regulation of water flow in light of disparities between the amount of water entering the reservoir and the demands of an associated hydroelectric station. Here, utilization of water accumulated in the spring usually begins soon after the reservoir's basin has been filled (Type III water level regime).

An analysis of observations made over the course of many years on the Rybinsk Reservoir (Butorin, 1969; Savina, 1965; The Rybinsk Reservoir, 1972) has shown that in spite of the whole complexity of problems involving artificial regulation of water flow in years of varying water conditions, one may note over the course of many years a mean trend for water level (Figure 6)--a trend which has, in fact, determined that specific nature of this reservoir's shallows. Deviations from this mean have lead to shifts in the composition of natural complexes. Thus, in the summer of 1972 when the water level was significantly below this mean, the upper part of the shallows was not inundated. This had disasterous effects for invertebrates, which perished in great numbers (Semernoi, 1974).

The suggested three types of water level regimes represent, in fact, a hydrological mathematical series in respect to the stability of water level in "ice-free" periods. Type I ($a_I \rightarrow 0$) and Type III ($a_I \rightarrow \max.$) are the extremes: the most stable and the most unstable. Type II occupies an intermediate position, since in the first half of summer it is characterized by its stability, however, in the second half of the "ice-free" period (primarily in the fall) a gradual decrease in water level occurs (Figure 7).

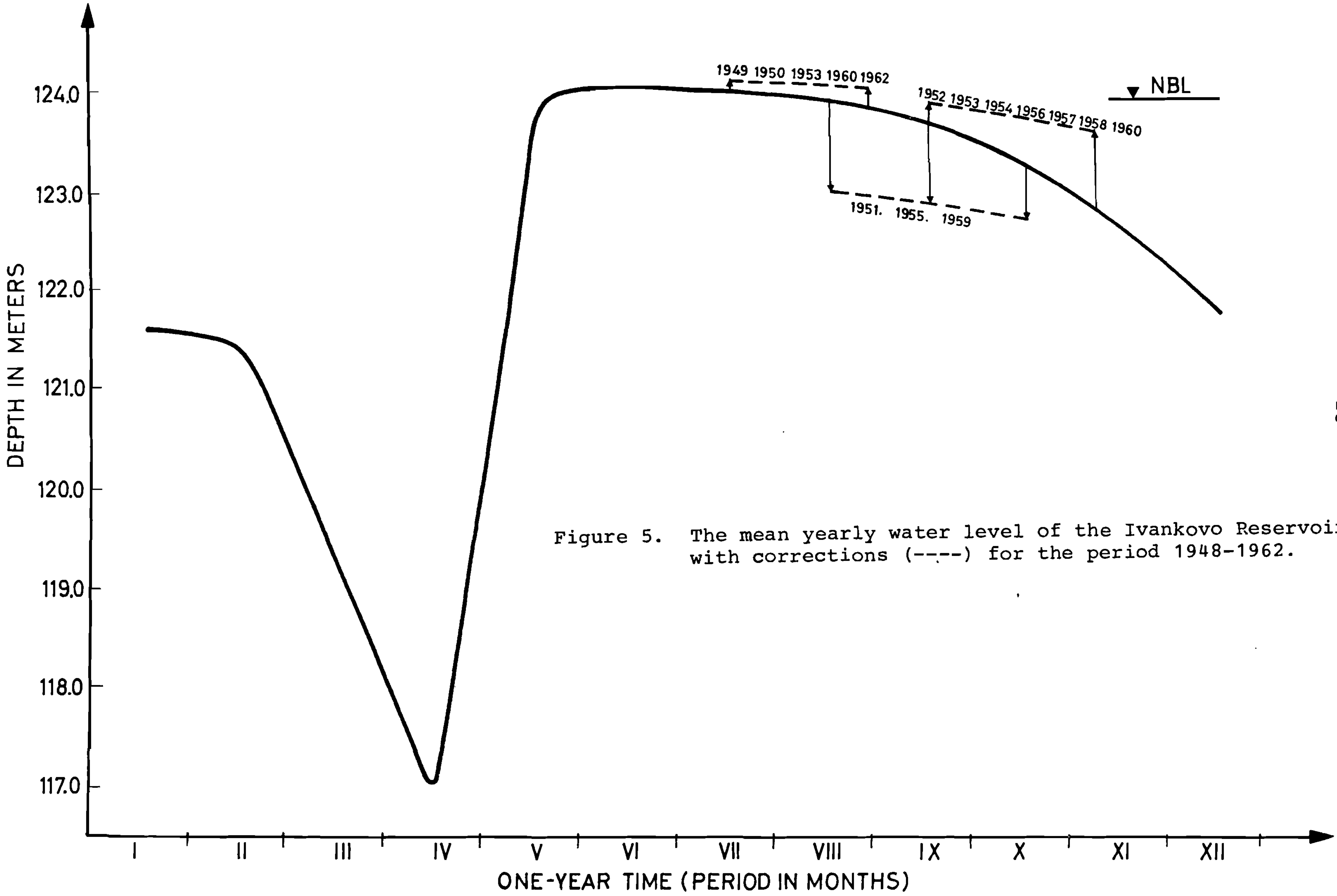

Figure 5. The mean yearly water level of the Ivankovo Reservoir with corrections (--.--) for the period 1948-1962.

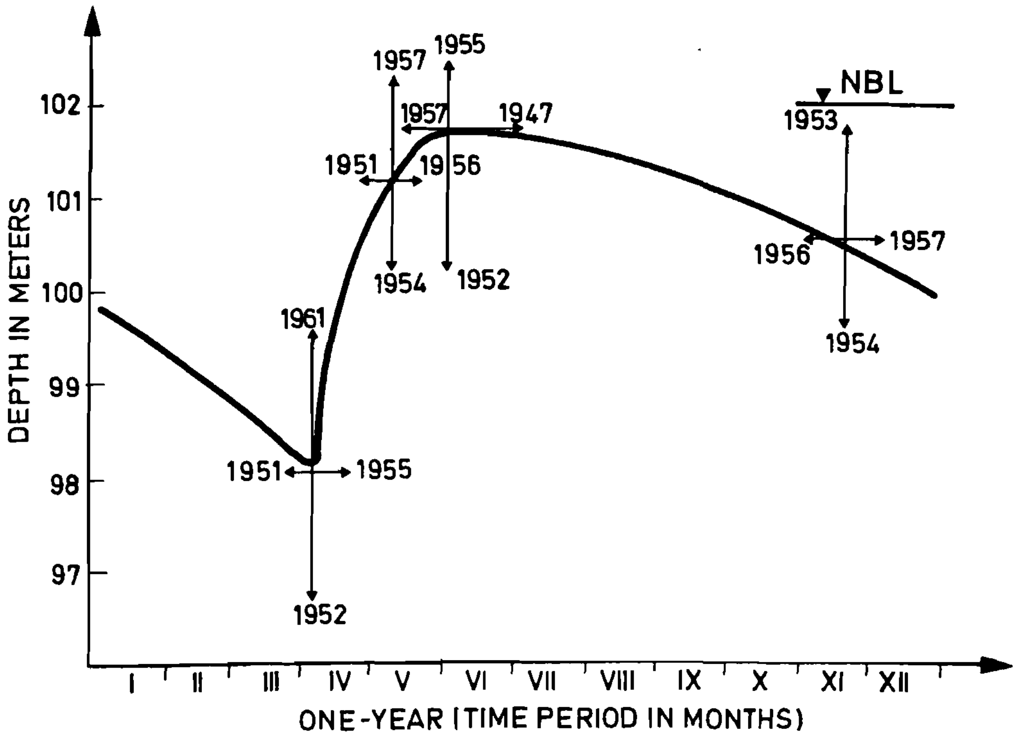

Figure 6. The mean yearly water level of the Rybinsk Reservoir for the period 1945-1961 (Savina, 1965).

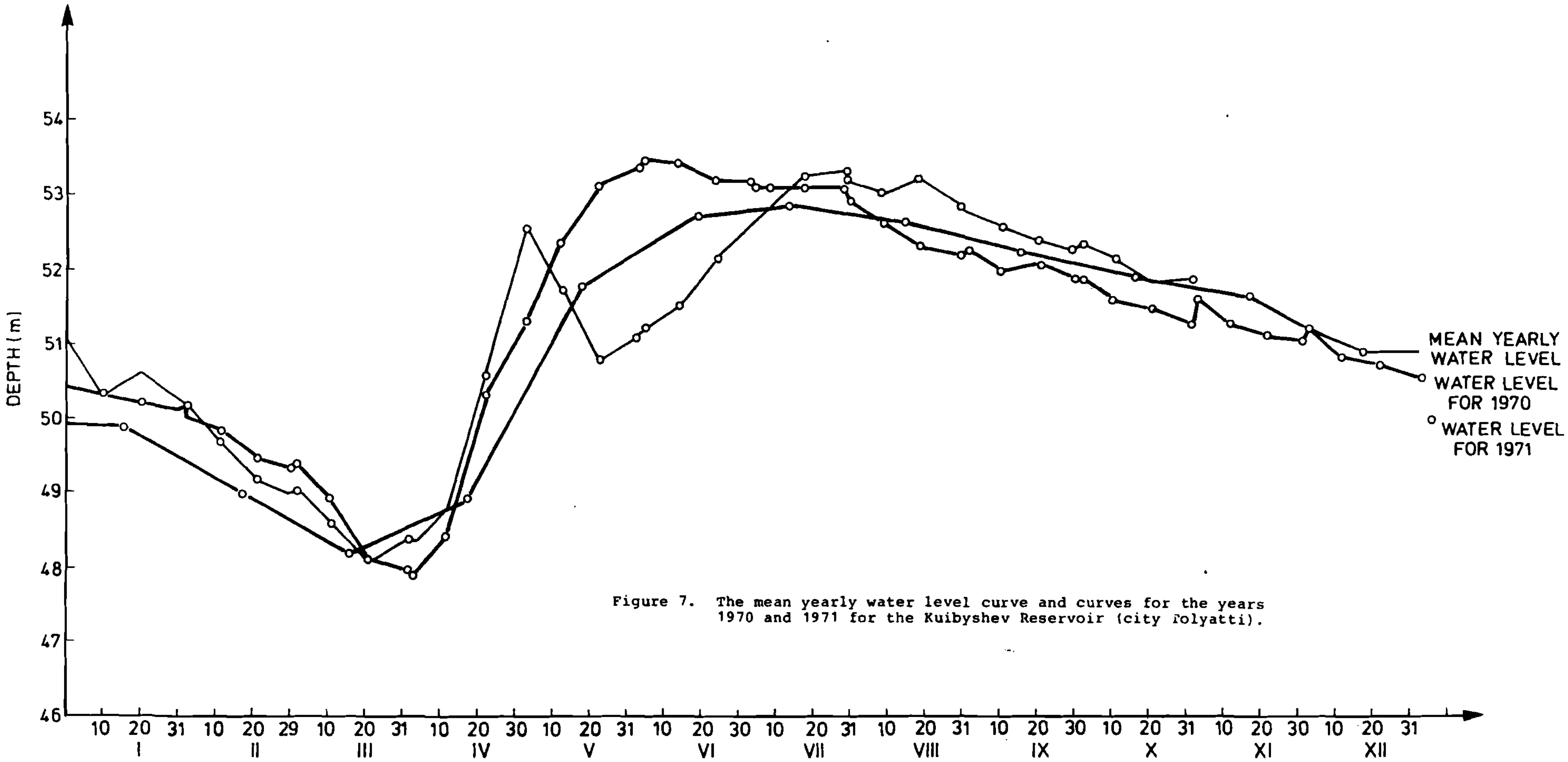

Figure 7. The mean yearly water level curve and curves for the years 1970 and 1971 for the Kuibyshev Reservoir (city Tolyatti).

The Kuibyshev Reservoir may serve as a representative example of a Type II water-level regime. In 1962, a year with average water conditions, the rate at which the water level dropped after reaching the NBL is as follows: the zone which was submerged (when the high water mark had been reached) to a depth of 0.25-0.50 m remained under water for 32-37 days; the zone which was submerged to 0.50-0.80 m remained under water for 37-55 days; and the zone which was submerged to 0.80-1.25 m remained under water for 70-78 days (Liakhov, 1972). In other words, if the NBL is attained in the middle of June, then by the end of July the entire upper part of the shallows which had been submerged to a depth of one meter or more remains under water. The consequence of this pattern of water fluctuation during the "ice free" period (a_I) is a gradual replacing of aquatic conditions by dry ones. This causes the drying-off of aquatic organisms, the intensive oxidation and mineralization of organic residues and their transfer from the dry stretches of land to the reservoir's aquatory and, as many researchers believe (Krasheninnikova, 1958; Kuznetsov, 1961, 1970; Mikheev, 1966; Feniuk, 1958), it is precisely in connection with these coastal processes that autumn (secondary) flare-ups in the number of bacteria occur in reservoirs.

Recently, we have develped the ability to re-allocate reservoir discharge for the msot effective utilization possible--it is especially important to anticipate the consequence of water level fluctuation on reservoir coastal zones. Let us illustrate this fact using an event which occurred on the Kuibyshev Reservoir in 1971. In Figure 7 alongside a curve of the mean long-term level, is a curve of the water level for 1970 (when there was an excess of water), as well as for 1971, which was atypical (anomalous). It is evident from the graph that in the spring of 1971, after the reservoir had filledin early May (in an unusually short time period), there was a release of water into the tail waters. Over a ten-day period beginning May 20 this release led to a two-meter decrease in the reservoir's water level. The usual pattern (of the curve for the mean long-term average) was for the NBL to be reached by the middle of June. Natural shallow water complexes forming in this reservoir had, therefore, adapted to this rhythm.

However, in 1971 the water level at this time was two meters lower than usual. On the dessicated parts of the former reservoir bottom, destruction of the above-mentioned complexes occurred and spread. Especially rapid was the destruction of a previously-formed underwater ledge in the zone subject to breaking waves. This ledge was located above the water's edge until the middle of July. Figure 8 presents the results of measurements carried out on a stretch of the main reach near the dam of the Kuibyshev Reservoir. Here, four different water levels are given for May and July 1 of 1971, for the mean long-term average and for the mean 1970 average (when there was an excess of water). For the first half of the summer of 1971, a large part of the ledge was dry. The sands were desiccated and exposed to the wind. With the water's gradual rise, new destruction began in accordance with the hydrodynamic circumstances of the period ravine which, with standard NBL conditions, was submerged to a depth of 1.0-1.2 m (Figure 8). By 1971, water meadow plant communities had managed to form along the ravine's edge despite existing conditions. In the low-water period of 1971 these communities were in a depressed state, not having experienced the flooding customary for this area in average years.

We observed analogous patterns of destruction for coastal complexes, the depression of coastal biocoenoses, etc. also in other parts of the reservoir during the low-water period.

The example of an anomalous pattern of water level fluctuation in the first half of the summer demonstrates that shallows react very quickly to changes in water level. From this we may infer that in connection with another reallocation of reservoir discharge, a similar situation reoccurs. This, in turn, will lead to a rearrangement of currently existing natural complexes. This is because it is precisely the yearly pattern of water level fluctuation which determines the specific characteristics of the shallows of man-made reservoirs.

5. The seasonal character of the processes in shallows.

In shallows where there is an accumulation of relatively small quantities of water and, thus, little heat-retention capacity, all processes have a pronounced seasonal character. The

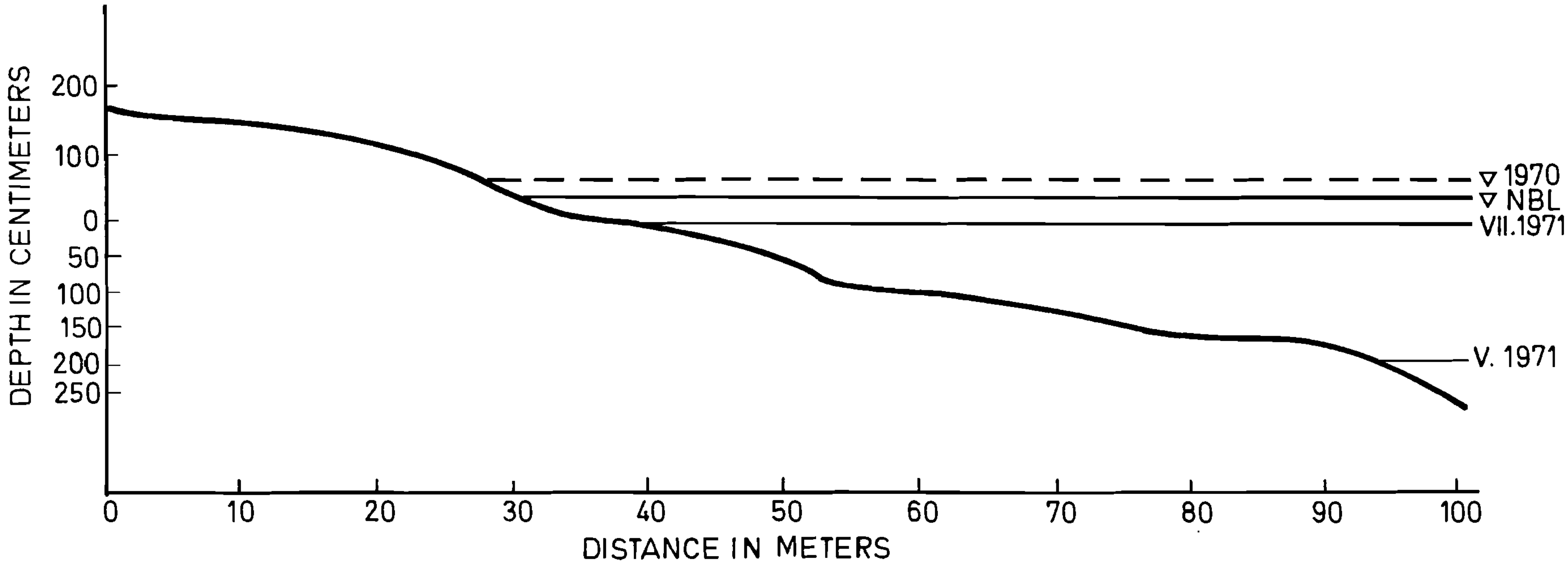

Figure 8. A cross-section of open shallows (village Stepan Razin) on the basis of measurements taken in July 1971. The main reach by the dam of the Kuibyshev Reservoir.

peculiarities of yearly "cycles" exhibited in reservoirs are predetermined by the pattern of water fluctuation. These peculiarities are defined first of all by the magnitude of such fluctuations in the "ice-free" period (by the value a_I); therefore, in examining the seasonal dynamics of natural conditions we will concentrate on the "ice-free" period.

Winter and early spring (prior to the filling of a reservoir's basin) are for all reservoirs, the time when the drop in water level is most significant and when there is a maximum exposure of dry bottomland. The term "dry bottomland", however, is more figurative than exact. Shoals are, in fact, usually covered by accumulated ice or snow and are in a relatively humid state. In the forest and forest-steppe zones the earliest floods occur when temperatures first rise above freezing--in March, and in some years, in the beginning of April. Snow and ice begin to melt first in coastal areas with a southern exposure as well as in small basins. Waters from the thawing tributaries and runoff from melting slopes facilitate the break-up of ice which has accumulated in shoals and in open aquatories. The ice cover disintegrates and freshets occur first in small tributaries and then in the major river (or rivers). The nature of the spring floods, dependent as they are on snow levels in river basins and on the entire European territory of the USSR, are determined by atmospheric processes that have occurred during the preceding winter (Afanas'ev, 1967).

The more southerly the reservoir, the more pronounced the interval between the onset of spring floods in tributaries and the rivers and the filling of the reservoir. Thus, in the case of the Volgograd Reservoir, freshets occur in small rivers at the end of March, but the reservoir's basin is filled only by June. This interval is 65-70 days. In the Kuibyshev Reservoir, freshets occur 20-30 days earlier than in the Volga and Kama systems (Borovka et al., 1962), but in the Gorky Reservoir system the peak for spring floods occurs on the average, at the end of April or early May while the NBL is reached in the middle of May.

How is this interval in the spring flooding process reflected in the nature of reservoir shallows? In the early spring, i.e., the pre-flood period, shallows in all reservoirs are located above the water line and are dry. Depending upon the utilization of the reservoir's capacity, i.e, its type of water-level regime, its coastal parts will be covered either with accumulated ice and snow, or only with snow. Therefore, in early spring the processes of melting, erosion, etc. will occur with varying intensity for different reservoirs.

With a Type I regime, ice formation begins when water levels are high. In winter, with utilization of capacity, ice settles down onto bottomland which is saturated with water. How far down freezing continues under this "roof" of settled ice depends on many factors. Two examples are: winter temperature conditions and the thermal reserve of the soil itself. For shallows protected from direct wind-generated wave action (shallows along bays and behind islands), it is customary to encounter a great variety of soils and plant life--from submerged varieties to those growing in moderately humid habitats. A significant portion of bottom deposits in such areas consists of silts of diverse origins. Many of these deposits have a significant thermal capacity, for example, decay ooze with 92% humidity has a thermal capacity of 0.95 (Forsh, 1965), and prevents the deep freezing of areas from which waters have withdrawn.

Since shallows are overgrown with vegetation when wide submerged shals are present to dampen wave action, they are usually covered with ice which settles directly onto their bottomland--the result of having no protective layer of plant remains. The surface layer of sandy soils, which predominate in open shallows, is often frozen to the underside of accumulated ice and in the spring are washed away by flood waters. Such "ice erosion" is unfavorable for the future development of bentos organisms which, for the most part, pass the winter in the upper 2-3 cm. of soil (Greze, 1960). However, the breaking away of large pieces of ice from shoals is first observed when there is a very rapid rise in water level, i.e., when the spring filling of the reservoir occurs with air temperatures only slightly above freezing and the ice is not subject to prolonged melting periods. Usually, the melted surface water begins to flow into a reservoir, especially during daylight hours, well before the reservoir water level begins to rise. Accumulated ice partially protects areas of the exposed bottomland from the erosive effects of streams.

During this phase flood waters may form detrital cones of eroded material above the ice. Ice and snow which contain soil melt more quickly and soils saturated with water undergo weathering when subjected to sharp 24-hour fluctuations in water level. Such weathering processes are particularly intensive in clayey shoals, and in sandy shoals there is the added factor of aeolian fanning of bottomland (Ikonnikov, 1972). Thus, even before the onset of high water (i.e., even in the pre-flood period) processes take place in open shallows which make it difficult for plant and animal organisms to exist.

With water regimes Type II and Type III, the water level drops during warm periods, and in shallows located along bays and behind islands plant communities cover a significant portion of bottomland. Under thick layers of snow there is usually a dense layer of vegetative remains, sod, etc. serving to block deep freezing of bottomland. For example, according to observations on the Rybinsk Reservoir (Luferov, 1965), bottomland was frozen only to a depth of 7.5-8 cm. under such conditions. Below-zero temeratures are registered to a depth of 10 cm. and more only in those years when highly humid soils freeze. It should be emphasized here that one of the main elements of the benthos, and a food source for benthophagous fish, i.e., the moth larva Tendipes, withstands freezing well. A survival rate of up to 60-70% is also displayed by aquatic sow-bugs (Asellus), leeches, grubs, and many gastropods (Mordukhai-Boltovskoi, 1965). Thus, in winter temperatures, conditions for organism survival are more favorable in shallows with a developed plant cover than in open (exposed) areas.

Considerable accumulations of organic matter, however, consume oxygen during the oxidation processes and thereby cause a sharp deterioration in a reservoir's gas regime. Thus, due to structural peculiarities, the Shoshin Reach on the Ivankovo Reservoir contains vast shallows (previously discussed) with a multitude of islands to which already-found coastal-aquatic plant communities have gravitated. These plant communities produce organic matter at the rate of up to 75.8 gr/m^2 or, in other words, 4.5 t/ha of macrophytes per vegetative period (Ekzertsev, 1961, Ekzertsev et al., 1971). With the sharp drop in water level in February-March before spring flooding, the oxygen content falls from 1.2 ml/l to 0.2 ml/l (Meisner, 1971). And even after the reservoir begins to refill in the spring, intensive oxidation processes still continue in water lying near the bottom, causing an oxygen deficit (Sappo, 1973).

In the spring, refilling of the reservoir's basin begins with tributaries in whose reaches flooding occurs (by a measurable interval) prior to flooding in the main river (or rivers). The length of this interval varies for different regions: in forest zones it is 10-12 days, in forest-steppe zones, 20-30 days. The spring flow into the Gorky Reservoir is 65-70% of the total runoff into the reservoir in a year's time. The major part of the yearly flow into the Kuibyshev Reservoir is yielded in April--whereas for the remaining months the total inflow of water is less than 3% of the total volume of water received per year.

Shallows in bays formed along tributaries are flooded by the spring waters of small rivers. Backwater from the reservoir holds back the flood waters of these bays for a long period of time. Thus, the blocked waters of the tributaries preserve for an extended period their low (spring) mineralization level and low pH. For example, in May 1958 the level of mineralization in the main basin (Volga River water) of the Gorky Reservoir was 97.3 mg/l, whereas in the bay formed along the tributary Unzhe the level was 43.8 mg/l; at these two places the pH level was 7.0-7.9 and 6.5-6.6 respectively, and only by August, when rivers are fed by groundwaters mineralized by the soil, were these indicators equalized.

In areas protected from wind action, and hence water agitation, the waters begin to warm rapidly. On the basis of observations made in shallows lying behind islands of the Rybinsk Reservoir, the water temperature by early May was found to reach 5-12°C, and by the end of the same month, 16-23°C (Bakulin, 1974). Such favorable temperatures, together with water illumination (when waters are still) and the presence of nutrient substances (primarily detritus carried in by spring floodwaters) all promote the early (two or more months earlier than in open reaches) development of phytoplanktons (Guseva, 1965). With activization of photosynthesis, the oxygen regime is improved. As already mentioned, prior to spring this situation tends to become extremely critical.

The characteristic biological chain for reservoirs: organics ⟶ bacteria ⟶ animals (Sorokin, 1966) in the spring, in the flood period, is based on allogenic substances (Kuznetsov et al., 1966; Sorokin, 1971). Therefore, one may expect the most favorable conditions for the development of aquatic organisms in places where these substances accumulate, primarily in bays. This assumption is substantiated, for example, by the presence of two peaks in the seasonal reproduction curve for most kinds of reservoir zooplankton--one in spring, the other in fall (Rybinsk Reservoir, 1972). The spring (May) peak in the number of bacteria is related to the improvement of trophic conditions. According to the data of I.V. Mikheeva (1966), in the Kuibyshev Reservoir, this peak reached 3.2 million cells/ml as compared to an autumn level of 2.3 million cells/ml (September-October).

Gradually, with the water's general warming trend, a maximum number of phytoplankton move out into the open aquatory in July and August, while in the shallows a high level of aquatic vegetation creates favorable conditions for the large-scale development of imnophyte varieties. The abundance of such forms in protected shallows attracts fish, especially young fish. Most varieties of fish in the reservoirs spawn in the spring and, for the most part in shallows, where they find the most suitable substrate.

When making further generalizations regarding the major role played by spring floods in the formation of reservoir shallows, the following should be emphasized. The most important factor is the correlation over time of the temperature of incoming flood waters and that of bottomland and in the area being inundated. If the waters flood frozen or only slightly frozen bottomland, i.e., T^o of the water $\geq$ T^o of the bottomland following a quick warming of the protected shallows, conditions become quite favorable for the development of aquatic organisms. This is the situation when flooding takes place in April or early May. If flooding occurs at a later time, the end of May or in June (in reservoirs at the lower end of a cascade or in circumstances when the water level rises slowly), and T^o of the water $<$ T^o of the bottomland, and bottomland is dried up and cracked due to sun and wind, then the spread of aquatic organisms is very slow, attributed to a lack of adequate biotopes. As examples, we may use the shallows of the Volgograd Reservoir and, in part, those of the Kuibyshev Reservoir (Ekzertsev, 1963). In addition, the coastal shoals of Sylva Bay on the Kama Reservoir are flooded by the waters of the Sylva River only during the early part of June (Ovesnov and Aristova, 1962). In this situation most plant embryos of aquatic vegetation fail to survive extended drought and are unable to germinate, especially when subjected to the low temperatures of spring flood waters inundating soils which have already been warmed. Drought also adversely effects hydrobionts, causing greater destruction than freezing (Mordukhazi-Boltovskoi et al., 1958). Consequently, a protracted "surface" period (i.e., of exposure to air) in shallows prior to spring refilling is harmful for the formation of phyto- and zoocoenoses.

If one conducts a time analysis of spring-like conditions beginning from the moment temperatures rise above $0^{o}C$, comparing shallows exposed to wind-generated wave action and those with no exposure, then it is clear that such conditions manifest themselves at the earliest in the shallows of bays. Depending on the extent to which the water level falls ($A = a_I + a_2$), these shallows become completely or almost completely dry. An early passing of spring floods in tributaries and a location within the "shadow" of direct winds facilitates rapid warming of the waters and reduces the time for the onset of summer conditions. Although shallows located behind islands in a main reach are submerged by waters of a main river, their sheltered position causes faster warming trends than are possible in open reaches. In shallows which are unprotected from winds and where waves warm slowly, spring-like conditions prevail the longest. Consequently, the more shallows are isolated from winds and waves, the faster the waters are heated and the faster the transition from winter to summer conditions.

In the summer, the intensity of the warming process is, of course, a result of the weather conditions for a given year. Under calm conditions and when the water is still, thermal stratification occurs, manifesting itself particularly in shallows along bays and behind islands. The results of observations carried out on the Rybinsk Reservoir in 1966 are presented in Tables 2 and 3. Measurements of water temperature in the main reach of the Mologa Reservoir in an open area of the reservoir are shown in Table 2.

TABLE 2

Depth cm	Water Temperature in °C	Remarks	Time
20	14.6		7:00
350	14.6		
680	14.6	Bottom, ledge, submerged terrace	
720	14.7	Bottom, bed of the Mologa River	

In the presence of intermixing caused by winds, a homothermal condition is established throughout the water's entire mass to a depth of several meters. At the same time, in the bay where there is no wind action and consequently no intermixing, a thermal stratification is noted (Table 3).

TABLE 3

Depth cm	Water Temperature in °C	Remarks
20	17.2	Surface layer
120	14.2	Bottom, former floodplain
250	13.2	Submerged tributary bed

In the summer, most rivers are fed by groundwater. Consequently, in shallow water bays formed along tributaries, two areas may be discerned characterized, respectively, by different temperature distributions:

1. In the area where groundwaters enter and pass along the bay, some smoothed thermal stratification is in evidence. This area is found primarily along the submerged bed of the tributary.
2. In the area of the shallows proper, which have emerged on the floodplain, thermal stratification is sharply pronounced and may be traced through the entire aquatory. Table 4 shows the results of temperature measurements made in the Chernaia Zavod Bay (Gorky Reservoir) on July 12, 1965 when the air temperature was 22.8°C.

TABLE 4

H_{cm}	Water Temperature in °C	Remarks
20	20	Submerged bed of the Chernaia River
80	19.2	
20	24	Submerged floodplain
60	19	

During prolonged hot weather, the temperature differential between surface and bottom water levels may be still greater and reach 7°C (as in the Sylva Bay (Gromov, 1962), or 9°C (as recorded in Cheremsha Bay (Sorokin, 1961)).

Shallows located behind islands are not only in the "shadow" of wind-generated waves because the frontal chain of islands serve as a natural barrier against the propagation of waves deep into the archipelago. They are in a "shadow" also because the islands themselves, in effect, "break up" the water's surface and thus prevent large waves from gathering momentum among narrow channels. When there is a weak intermixing in these areas, warming occurs quickly, and when waters are strongly pigmented, thermal stratification intensifies due to the water's optical properties.* For example, at the Gorky Reservoir in July 1965 in shallows located behind the islands, we recorded a temperature differential between surface (20 cm) and bottom (100 cm) layers of 2.7°C. However, in protracted hot, calm weather, this differential can increase to 6°C.

In open shallows subject to direct wave action, homothermal conditions are customary. Even in still weather, ship-generated waves, a constant factor in the reservoirs, prevent thermal stratification. An example of this is demonstrated by the following results of observations made on the Gorky Reservoir during a period of stable high pressure (prolonged calm weather).

With an air temperature of 32°C (as noted above), variation in water temperature at a depth of 150 cm was 6°C in shallows located behind islands. However, in open shallows during the same weather conditions and at analagous depths, the water temperature differential was only 1.5°C.

Intensive warming of water in summer stimulates the development of animal and plant organisms. Thermal stratification is one of the causes of the accumulation of phytoplankton in the warmer and better-illuminated upper layer, which through photosynthesis becomes enriched with oxygen (Stroikina, 1960; Sorokin, 1961). Later, when masses of plankton die, activization of bacteria occurs. This, in connection with the oxidation of organic substances in the absence of active intermixing, leads to an oxygen deficiency in layers of water near the reservoir's bottom (Ivatin, 1973; Romanenko et al., 1969). Especially lethal are summer moraines with hydrogen sulfide contamination which may be observed in shallow bays that have been fed by groundwaters with a high SO_4'' ion content. As a result of the joint activity of thionic

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*Measurements show that pigmented waters of stagnant reservoirs which contain insignificant levels of suspended matter retain 70-75% of solar radiation in the uppermost layer 20-25 cm deep. In less pigmented waters, the absorption rate of the surface layer averages up to 47% (Aleksandrova, 1966).

and sulfide reduction in the Kuibyshev Reservoir ranges from 0.2-0.7 mg/l per twenty-four hour period to 1.6-3.0 mg/l, whereas in the shallows of Cheremsha Bay it is 288 mg/l in twenty-four hours (Kravtsov and Sorokin, 1959).

The shallow water stratification process under consideration is a peculiarity not limited to reservoirs. Such a situation may arise in lakes as well as in reservoirs with weak water-level fluctuations in the "ice free" period (Type I regime where $a_1 \cong 0$). However, only in man-made reservoirs does the water level drop in the warm period (Type II and III regimes) as a result of artificial regulation of river flow, thus leading to a drying up in shallows which never occurs in deep water. Following summer drainage, the exposed bottom dries up quickly. The replacement of aquatic conditions by surface conditions demands plasticity of organisms and adaptability in surviving unfavorable conditions. Macrophytes requiring a relatively long "aquatic" period of development, grow slowly during the steady drop in water level over the summer (Type III). Thus, in the Rybinsk Reservoir, a good representative of reservoirs of this type, high aquatic plant forms are poorly developed and do not play an essential role in the total production of organic substances. Hydrobionts also strive to adapt themselves to unusual conditions. According to the data of L.N. Zimbalevskaia (1967), in the Kremenchug Reservoir shallows (Type III), over 15 varieties have been isolated which, during the bottom's dry period, burrow deeply into the ground and survive the "exposed" period. Some varieties exhibit an accelerated development cycle. A gradual drop in water level in the warm period (Types II and III) causes a shift of the period of maximum development of the biomass. Organisms in shallow waters reach maximum growth in the first half of the summer whereas organisms in deep water achieve maximum growth in August-September.

With the drop in water level in these shallows a current begins which leads to the disruption of stratification and promotes intermixing and the arrival of oxygen at a reservoir's bottom. The simultaneous dying off of organisms (which results from the dessication of coastal areas) and arrival of oxygen both stimulate oxidation processes and the mineralization of organic remains. It is precisely in connection with this fact that, along with the destruction of organic matter, the second peak is highly characteristic of reservoirs with a summer drop in water level (Romanenko et al., 1969). In summing up the seasonal peculiarities of reservoirs, one can see that in spring and the first half of summer the bulk of the organic matter arrives with runoff from the coast, i.e., allogenic, and in summer and autumn autogenic matter predominates, most of which is produced in shallows.

The rapid drop in water level in autumn often leads to a separation of shallows from deeper areas of water and the death of fish left behind in hollows (holes) of the bottomland. In this period, many young pikes and perches perish whose instinct for descending into the deeper waters of the reservoir along with the current is weaker than that of breams, ides, roaches and white breams (Kusnetsov, 1973).

A continuing drop in water level after the onset of ice formation often leads to the death of fish in wintering holes. Here they are crushed by ice from above.* Additional causes of massive losses of fish are winter moraines, connected both with depletion of dissolved oxygen through oxidation of organic remains as well as with the arrival of groundwaters of a different chemical composition. As noted above, in the Ivan'ko Reservoir a sharp oxygen deficit in winter of 0.5 mg/l is caused by the oxidation of organic matter under an ice cover (Sappo, 1973). Field observations in January 1962 in the Cheremshan Bay (near the town of Melekess) also yielded similar readings--about 1 mg/l (Guseva and Sharonov, 1962). A rise in the mineralization of organic matter is also characteristic of winter, especially along shallow bays. This fact is related to the mineralization of allogenic and autogenic organic matter (the former arriving first in bays along tributaries). With the gradual drying up of coastal areas in the "ice free" period when temperatures are above zero, there is sufficient time for organic substances to mineralize. This process is accompanied by the formation of various nitrogen compounds and their accumulation in places where the greatest accumulations of organic materials have occurred, i.e., in shallows. To prove

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*The yearly loss of fish in wintering holes in the Bolshoi Cheremshan and Suskan Bays of the Kuibyshev Reservoir has been recorded at 222,000 (Guseva and Sharonov, 1962).

this, one need only consider the results of long-term obervations on the organic content of bottom deposits of the Kuibyshev Reservoir for different stages in its development. By the fifth and sixth years of the reservoir's existence with a general rise in the level of organic material in the reservoir bed, the lower reach (by dam) and the bays display higher concentrations than elsewhere. Here, most often dark grey and dark brown silts are found with their plant residues. The C/N ratio in bottom deposits with a mean value of 10.0 (ranging from 4.0-16.5) is close to the C/N ratio found in silt deposits of the most entrophic lakes i.e, with a range from 7-11 (Guseva and Maksimova, 1971).

As a rule, two peaks may be observed in the seasonal growth pattern for biogenic elements: a spring peak associated with surface flow from a natural drainage system; and a winter peak, associated with the mineralization of organic residues. The summer depression in this activity is a result of intensified consumption of aquatic organisms. Increased mineralization, with higher iron and manganese concentrations (Khrustaleva, 1973) occurs in shallows and, initially, in aquatories--partially or fully sheltered from wind-generated wave action--where most allogenic and autogenic organic substances settle to the bottom.*

Undoubtedly, the earlier after the establishment of the summer water-level regime that a reservoir's capacity begins to be utilized, the faster this utilization proceeds, and the greater the amplitude of water level fluctuation (i.e., $a_I \geq a_2$), then the fewer are the conditions for the development in the shallows of specific winter processes. Processes associated with intensive oxidation of organic substances include deoxidation of the water and an increase in mineralization; the accumulation of groundwater of varying composition, etc. Of the three types of water-level

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*One of the indicators of change in water quality is color (Fortunatov, 1959). If one compares colorimetric indicators (in degrees on the Pl-Co scale) at different times of the year for shallows of the Shoshia Reach of the Ivankov Reservoir, the following is apparent: In the summer (according to observations made in July) the level is 80°-120°, whereas in the winter it is over 165° (Trifonova, 1961). This illustrates the "accumulative role" of shallows which contain primarily biogenic components.

regimes singled out by us, the one manifesting most unfavorable conditions in winter is regime Type I, i.e., $a_I \cong 0$. The water-level regime manifesting the least favorable conditions is regime III--($a_I \leq a_2$)--where water has almost entirely left the shallows by the time rivers become icebound. Therefore, in order to improve winter reservoir conditions, it has been suggested that water levels should be lowered and shallows be dried before rivers become icebound. This would also help to preserve young fish which have fed in the spring and summer periods in shallows (Poddubnyi and Il'ina, 1965; The Rybinsk Reservoir, 1972). Depending on the nature of the ground runoff by which rivers are fed, they bring waters either similar or different in chemical composition to those of the reservoir into which they flow. The "lethal wave" of chemically harmful waters which can emerge as a result of this may "roll" into a reservoir's open reach and contribute to the formation of winter reservoir conditions.

These examples of seasonal dynamics of natural conditions clearly show that they are specifically a function of water level fluctuation. A whole series of unfavorable phenomena, such as the winter "lethal wave", the death of hibernating organisms in holes under settling ice, etc., can be avoided through regulation and stabilization of the water level. At the same time one may accentuate positive effects by controlling the water level: stability at lower depths may be maintained, areas supporting aquatic vegetation may be inundated for necessary periods of time, etc. Consequently, reservoirs are natural objects for controlling an entire series of processes through the regulation of the water level. In this case the water level fluctuation proves to be the basic link that determines the course of natural processes in shallows.*

6. However, water level fluctuations in various shallows of a reservoir are manifested differently depending on the surface distribution pattern of shallows across the reservoir's aquatory.

*At the present time water level regulation is carried out in support of fisheries, land reclamation, etc.

As stated earlier, wind and wave action in all shallows can be divided into two groups: open and protected. Open shallows are subject to wind and wave action and include: aquatories over flooded terraces, coastal slopes, submerged sandbanks as well as newly formed embankments, sand ridges, bars, spits, etc. Protected shallows are sheltered by some kind of natural barrier located, for example, behind islands or along bays. Without touching upon questions regarding the classification of shallows with which we have dealt in detail in a number of works (Melnikova, 1967 a,b; 1970, 1972) we shall introduce here only concrete examples of various types of shallows dependent on their position along a given aquatory. From the multitude of possible forms we shall isolate the most typical: shallows along bays--A; shallows behind islands--B; and open shallows--C.*

6.1 Shallows Along Bays-A

Bays emerge in reservoirs where tributaries flood back on themselves, where flooding of deeply cut ravines, depressions, flood-plain lakes, etc. occur. Common to all of these formations in addition to shallowness, is the deep cut of the aquatory into the coast and, consequently, unfavorable conditions for the development of wave action and inter-mixing of water. As discussed above, a result of this stagnation is thermal and chemical stratification and a settling of deposits, mineral and organic, to the bottom. This in turn creates the peculiar conditions necessary for the existence of plant and animal organisms and allows us to view shallows along bays as unique biotopes.

In addition to mineral suspensions and detritus, river waters that flood the shallows of bays (A_I) also carry in embryos of aquatic plants, thus promoting growth of the shallows' plant cover. If in the first years of a reservoir's existence the determining factors in the growth of the shallows' plant cover are the presence of the embryos of aquatic plants and the nature

*The indexes A,B and C define types of shallows. Subtypes are given for each type by use of arabic numbers: AI are shallows along bays on tributaries; A2 are shallows along "blind" bays, i.e. those without tributaries, etc.

of the flooded areas†, then after the completion of this initial phase the situation changes. While these factors, along with the water level, continue to play a decisive role, trophic conditions and Phytocoenotic interrelationships gain in importance (Ekzertsev et al, 1971).

If we trace growth patterns in shallows along bays for all three types of water level regimes, i.e. examine vegetative changes for I-A, II-A and III-A, with water environments of similar chemical composition, then we see that the most dense and well-developed vegetation is ound in Type I reservoirs.

The bay along the Kovzha River above the river's mouth (Beloe Lake, Sheksna Reservoir) is an example of the first stage of plant cover formation, when a large role is played by the random transport of plant embryos into shallows by river waters. As a result of damming, fields covered with legumes and cereals were inundated as well as marshes and water meadows. Investigations conducted in the third year of the reservoir's existence revealed that with waters undergoing only weak inter-mixing the submerged soil of these fields and meadows was fully preserved on the river's alluvium (Figure 9, curves Ia,b,c). The uppermost layer of silt deposited during the three-year period of the area's submersion was so thin that it was difficult to distinguish. The entire strip of land next to the water's edge was overgrown by amphibious vegetation--predominantly Glyceria aquatica. The great variety of marsh species--Eleocharis palustris and Menyanthes trifoliata to Schoenoplectus lacustris--originated in the transport capability of the Kovzha from its upper reaches, where lowland swamps gravitate toward river valleys (Bobrovskii, 1957). Besides amphibious plants: Glyceria aquatica, Oenanthe aquatica, Alisma plantago aquatica, Sagittaria sagittifolia, Butomus umbellatus, Sparganium, Schoenoplectus lacustris, there were many plants with floating leaves and many underwater plants:

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†The role of submerged landscapes was examined in more detail in connection with stages in the development of reservoirs. It is precisely in connection with the presence of plant embryos and the embryos of animal organisms, i.e. with the "biofund" that a biological "explosion" occurs in reservoirs in the first years after they are constructed.

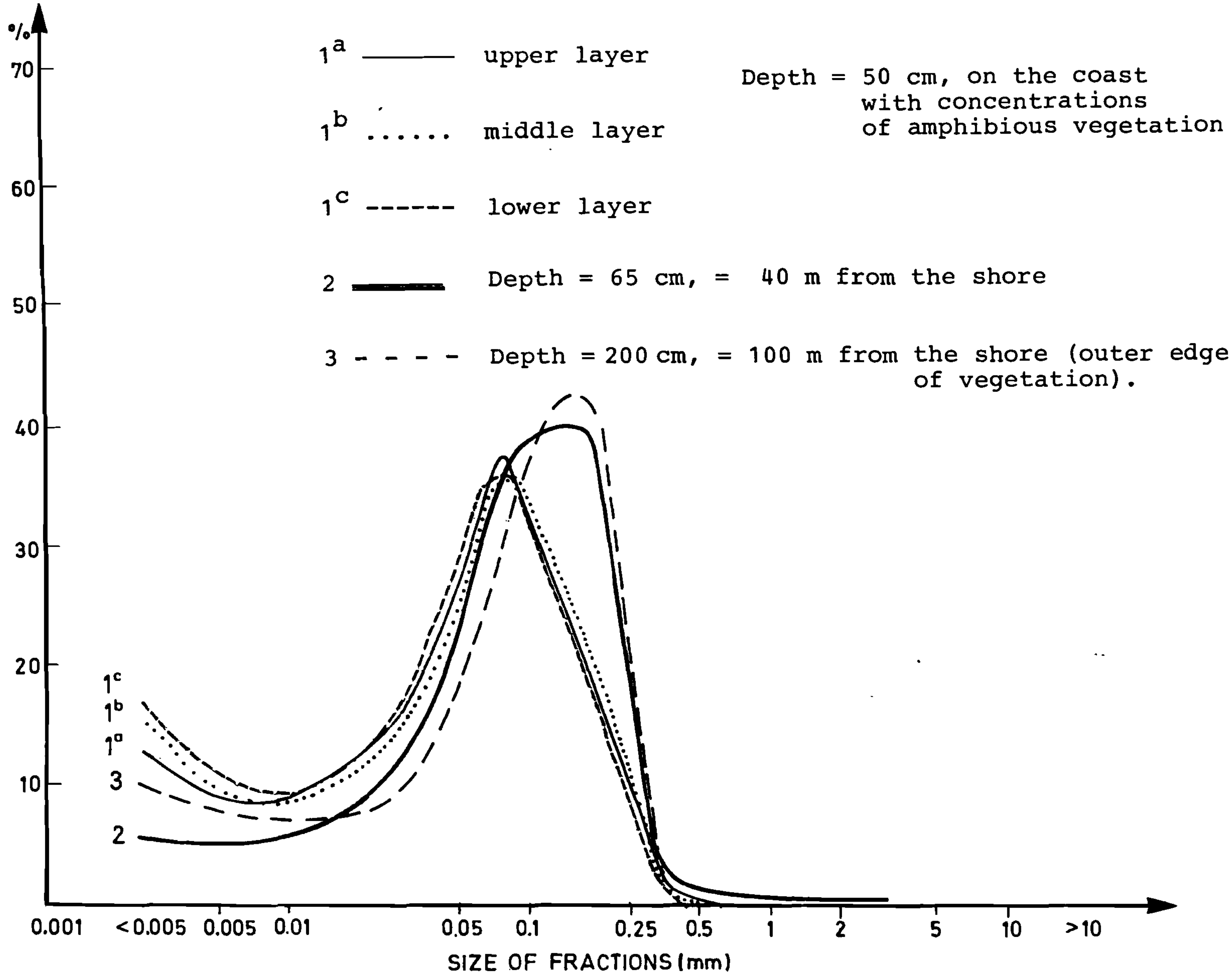

Figure 9. Kovzha Bay above the mouth of Belone Lake at a place where there was formerly marshland, July 22, 1966.

Potamogeton perfoliatus, Potamogeton crispus, Polygonum amphibiam, Hydrocharis morsus-ranae, Lemma minor and Lemma trisulca. The abundance of varieties undoubtedly was a result of the arrival at the reservoir of nutrient substances from recently inundated soils. Probably the large dimensions--165-175 cm. of Sparganium niglectum which occurred side by side with Sparganium simplex of a more ordinary size was a direct result of this fact.

Some washing out of soils was observed in the area of the bay in front of its mouth (Figure 9, curves 2 and 3). Here also however, only the uppermost layer of the inundated soil had been subject to erosion (the sod having been destroyed). Yet in all the lower levels the root remains of meadow plants as well as the dark coloration of the ground soils were still preserved.

In the upper layers all soil samples collected in the bay had a layer of undecayed aquatic plants. This fact was connected with the stability of the water level (i.e. at the NBL) for the entire "ice-free" period (Type I water level regime, $a_I \cong 0$).

Observations made during the sixth year of the Sheksna Reservoir's existence showed that in bays formed along streams and rivers, plant groupings had already formed. Alongside mixed concentrations of hydrophytes a belt of sedges appeared whereas Potamogeton perfoliatus, Sparganium niglectum and Simplex were encountered only in patches at a depth of 60-80 cm. (Ekzertsev and Belavskaia, 1970).

The above data regarding the Sheksna Reservoir reflects the first stage of reservoir formation. Over the course of decades yearly quantitative accumulations lead to significant qualitative changes. Thus, over three decades a unique complex of peat from plant remains that have decayed during winter periods of oxygen deficiency has formed in the Ivan'kovo Reservoir. While these plant remains hinder the outflow of minute mineral fractions (in the winter drainage period when reservoir capacity is intensively utilized) capture them and these minute particles upon settling to the bottom often serve to "cement" plant remains, thus facilitating the formation of organic-mineral deposits along the bottom.

The creation of peat-like formations is linked primarily with "hard" ("rigid") amphibious vegetation, whereas the creation of organically enriched silt is facilitated by the decay of "soft" submerged species.* Minute fractions which have been carried by rivers settle to the bottom when water is comparatively stagnant and lead to the rapid accumulation of silt deposits in bays. These silt deposits, according to V.P. Kurdin (1961), directly relate to the formation of reservoirs proper or to epigenetic terrains and become widespread after completion of the initial stage in a reservoir's formation. For this reason extensive growth of such species as Nymphaea candida and Stratiotes aloides, both requiring soil with a high organic content, is observed only after seven to fourteen years of a reservoir's existence (Ekzertsev, 1966).

In the bays of reservoirs with Type I or II water level regimes, certain processes characteristic for the "stagnant period" are disrupted by rain-generated freshets. For example sediment accumulation and decay of organic remains in the waters of a bay as a whole (or at the land-water interface for Type II regimes where exploitation of the reservoirs capacity begins in the summer) are disrupted when river waters in effect "wash out" the bay, carrying with them part of the bottom deposits. Therefore, in bays along tributaries, in their mouths and in areas where there is minimum backwater, i.e. where there is a transition from the bay to the flood plain of the tributary itself, sandy soils predominate--fluvial facies which reflect the presence of heightened water turbulence. Grey silts and organic-mineral complexes occur along former flood plains of these tributaries and here both peat and marsh formations are possible.

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*For purposes of comparison let us examine data obtained on the Ivan'kovo Reservoir (Ekzertsev, 1958) regarding the biomass of coastal-aquatic vegetation for air-dried weight (g/m^2). For Amphibious ("hard") vegetation the following values were obtained: Carex acuta 716; Phragmites communis 946; Equisetum fluriatile 604; Glyceria aquatica 719; Polygonum amphibium 187; Sagittaria sagittifolia 327; for underwater ("soft") species: Nymphaea candida 168; Potamogeton perfoliatus 223; Potamogeton lucens 216; Potamogeton pectinatus 165; Stratiotes aloides 521.

For shallows along bays without tributaries (A_2) a fluvial facies is not characteristic. In "blind" bays and shallow "lobed" bays stagnant water conditions persist for especially long periods of time and suspended particles settle to the bottom at the highest possible rates.

If "blind" bays of various sizes but of the same (Type I) water level regime are compared, then it is possible to note a common tendency in the formation of bottomland: in estuarine and pre-estuarine zones, i.e., those areas most heavily subject to wave action, sandy complexes with an insignificant proportion of organics are gradually formed from inundated soils.

In middle zones into which wind-generated waves penetrate only when maximum roughness occurs in the reservoir proper, minute fractions are deposited. The area above this "elutriation boundary" may be considered the true upper reach of the "blind" bay, with a pronounced degree of water stagnation and an active peat formation process. Figure 10 is a diagram of bottomland distribution in Obukhov Bay, which is located on the reach near the Ivan'kovo Reservoir Dam. This diagram was made on the basis of a survey conducted in the area in 1965. After many years the difference between the upper and the pre-estuarine zones has become sharply defined. Extending from the water's edge to a depth of one meter is a belt of *Carex acuta*, *C. vesicaria* and *Equisetum fluviatile* along with patches of reeds. The major part of the upper aquatory is covered by amphibious and underwater plant associations. The silts predominant in the bay's upper reaches contain organic substances which, according to observations made in 1965, are at levels up to 68% and according to the data of V.A. Ekzertsev (1963), reach 74%. In extensive areas of *Stratiotes aloides* losses due to soil performation exceed 50% since not only organic silts form here, but young peat as well.

At the present time, Obukhov Bay is characterized by the highest production rate of organic matter on the Ivan'kovo Reservoir: 350 g/m^2 as compared to the reservoir average of 75.9 g/m^2 (Ekzertsev, 1958; Ekzevtsev *et al*, 1971). Due to the reservoir's stable water level during "ice-free" periods the very slow out-

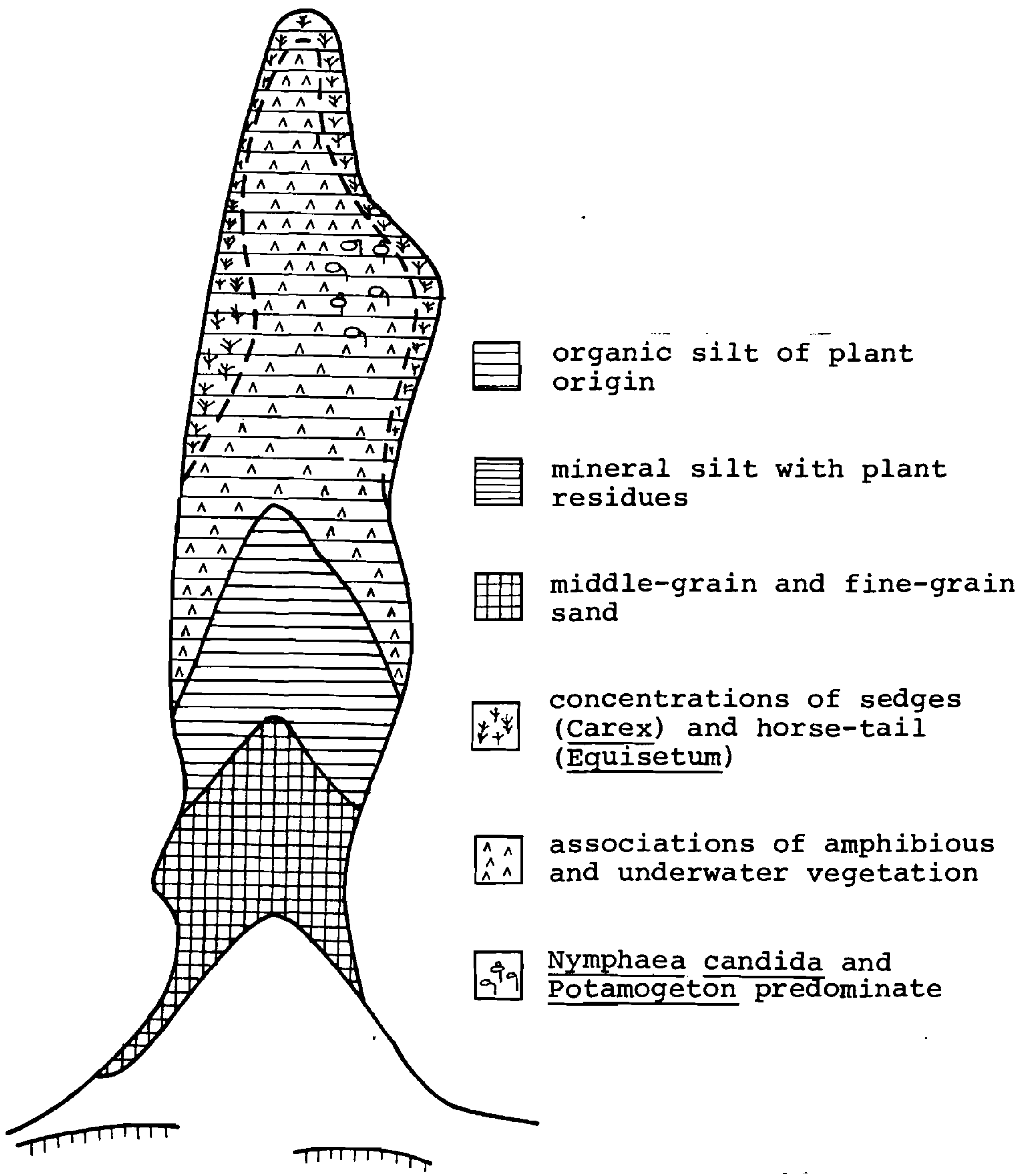


Figure 10. Diagram of the bottomland of Obukhov Bay (based on data from a 1965 survey).

ward flow from the bay when rivers are ice bound, this yearly production or organic matter should soon lead to the formation of a bog in the bay's aquatory from the upper reaches to its mouth.

Mineral components predominate in the silts of Obukhov Bay's middle zone. Here losses due to perforation range toward 25%, whereas in the pre-estuarine zone they are minimal, owing to the predominance of sand. In summarizing the characteristics of shallows in bays (both bays along tributaries (A_I) and "blind" bays without tributaries (A_2) during the stable water conditions of the "ice-free" period, i.e., for Type I and partly, Type II water level regimes, the following may be said. Such shallows are characterized by the accumulation of an organic-mineral complex of bottom deposits and the formation of plant associations which produce a maximum quantity of organic matter for a reservoir. This facilitates the rapid formation of bogs, especially in "blind" bays.

A completely different set of conditions exist for shallows subject to a Type III water level regime. In this situation dessication takes place gradually during the entire "ice-free" period. With time only those plant and animal organisms remain which can exist under amphibious conditions.

A vivid example of this is the Rybinsk Reservoir, in whose shallows have emerged phytocoenoses not encountered in naturally occurring bodies of water. Here species sharply differing from one another in their ecological characteristics are enjoying "equal rights" in one and the same biological community. The presence of hydrophilic, hygrophilic and hydratophic species provides a stable biological community in the face of the changing water level. Main concentrations of macrophytes occupy about 1.3% of the area of the Rybinsk Reservoir and gravitate toward bays located along streams and rivers (A_I). The water level regime of these shallows can be compared with that of a flood plain during a flood period with a somewhat extended time factor. In the bottomland complex one can clearly distinguish two facies--a fluvial one and one representative of a flood plain.

After being submerged for a short time flood plain soils (Figure 11, curve 1) fail to undergo significant changes and divide clearly into three layers: upper (sod), middle (dark colored, humus) and lower (silted, of a lighter color). In contrast to flood plain soil formations, fluvial formations are constantly under water. A gradual drop in water level leads to the constant, slow outflow of water from the bay into the reservoir's open reaches. A dying out of aquatic vegetation takes place in the autumn when water is low, but in the winter with the formation of an ice cover and the shift of tributaries over to ground sources, a sharp drop in the water's oxygen content occurs and dead aquatic plants together with forest foliage remain under ice without undergoing decomposition. In the spring however, after the breakup of ice and the passing of freshets, new plants begin to develop in the water. It is possible to observe in the fluvial deposits of forest tributaries of the Rybinsk Reservoir both the mineralization of forest foliage (which occurs slowly), and the remains of aquatic plants (which occurs much more rapidly). Figure 11, curves 2,3, and 5 depict the gradual change in the composition of a fluvial facies starting from the bay's upper reaches and proceeding to the pre-estuarine area--over a distance of 2-2.5 km.

In the deeper parts of the bay (curve 5) aquatic vegetation is absent. Plant remains brought in by the current either mineralize or are carried out of the bay. Those parts of the bay whose bottomland has been subjected to the greatest degree of washing out contain the least organic matter.

In connection with a belt-like distribution of bottom soils is a belt-like distribution of vegetation, the latter being most clearly evident in bays along tributaries. In the upper belt communities of Glyceria aquatica, or Carx, whose phytocoenoses consist of Carex inflata, C. vesicaria, C. acuta and C. aquatilis usually predominate. The belt of amphibious plants consists of mixed areas of Agrostis with Potamogeton heterophyllous and P. lucern, Alisma plantago-aquatica and Rozippa amphibia. As the water's depth increases phytocoenoses of Agrostis with Oenanthe aquatica or Butomus umbellatus appear. The belt of floating plants consists of separate patches of Polygonum amphibium.

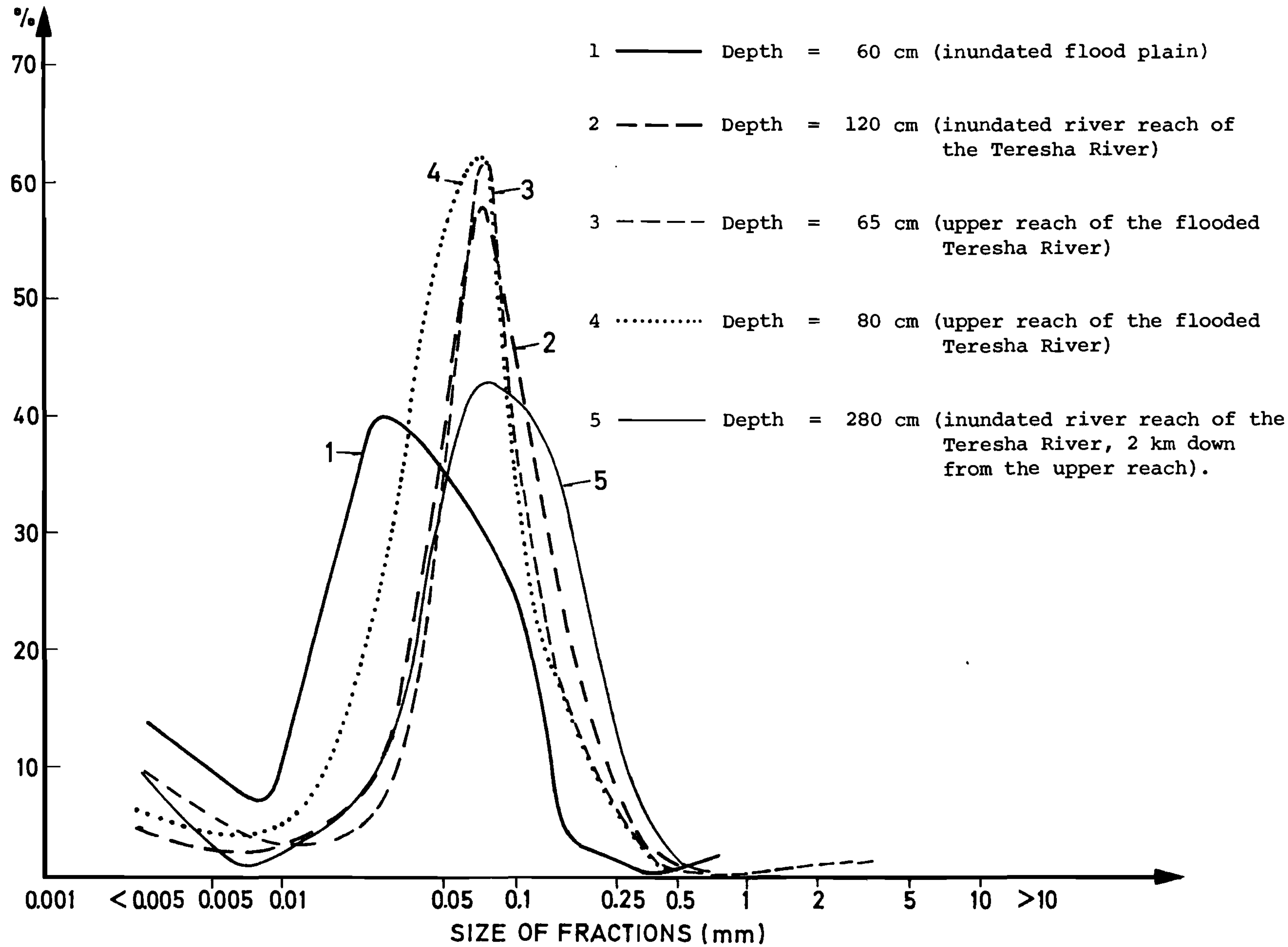


Figure 11. The upper reach of the bay along the Teresha River (Rybinsk Reservoir) June 2, 1966 (an analysis of the fluvial part of the bay).

"Blind" bays along the banks of the Rybinsk Reservoir merge very often in their upper reaches with swamp areas of a slightly submerged shoreline. Usually in such small swamp-like bays at a depth of 20-23 cm. the belt of Carex is replaced by concentrations of Equisetum together with Razippa. Sometimes in the open aquatories of such bays spots of Potamogeton amphibium or Nymphaea candida (Rybinsk Reservoir, 1972) may be found.

The above examples associated with the Rybinsk Reservoir show that in shallows with unstable (gradually falling) water, circumstances are not favorable for the developing of organisms, especially plant organisms. Although shallow bays exhibit a higher level of macrophyte development than other kinds of shallows, their annual production in air-dried weight does not exceed 8 g/m^2 (according to data from 1956). At the present time these figures are even lower.

If one compares these values with the annual production level of organic matter in Obukhov Bay (350 g/m^2) or with the average level for the Ivankovo Reservoir (75.9 g/m^2), it is evident how significantly fluctuations in water level influence the nature of shallows. This fact is evident merely on the basis of a single example--the formation of plant communities in shallows along bays (A).

With the second type of water level regime, depending on when utilization of water capacity begins, shallows may have affinities either with shallow bays which display a gradual drop in water level beginning in the summer months, or with shallow bays in which the water level remains constant or almost constant during the "ice-free" period.

6.2. Shallows located behind islands (B) like those along bays, have aquatories which are protected from wind-generated wave action. Here islands hinder wave action and the deep intermixing of waters by breaking up the water's surface. A direct consequence of the water's relative motionlessness, in addition to stratification, is the settling to the bottom of suspensions that have been brought into the shallows by tributaries, as well as the accumulation of organic remains, primarily of plants.

The rate at which these processes occur depends both on the quantity of autogenic and allogenic material and on the nature of a reservoir's water level regime.

Archipelagoes are most often encountered in a reservoir's upper reaches where backwaters from the dams decrease and rivers spread along flood plains leaving higher elevations dry. Waters in the upper reaches of a reservoir are in a higher dynamic state than in lower reaches. Thus, the shallows of archipelagoes of a reservoir's main reach (B_1) manifest greater fluidity in their waters than shallows behind islands in the upper reaches of bays (B_2).

If one compares reservoirs with identical water level regimes but different water exchange rates, i.e., compares the average yearly coefficients for water exchange, then it is possible to readily distinguish "stagnant" from "fluid" reservoirs. For example, for a Type I water level regime, the Gorky Reservoir with a yearly coefficient of 6,2 would be less "fluid" than the Ivankovo Reservoir with a coefficient of 13.6; consequently, shallows behind islands in the main reaches of the Ivankovo Reservoir are better "rinsed" (by a factor of two) than those in the Gorky Reservoir. Naturally the periodic change of water in shallows behind islands influences the accumulation rate of organic and mineral deposits, the formation of biocoenoses, etc.

When comparing shallows behind islands along the Volga Reach of the Ivankovo Reservoir with those along the Shosha Reach of the same reservoir (where the latter exhibits an average yearly water exchange rate three times less than the former), the following is found. The reduced "fluidity" of the Shosha Reach is explained by the accumulation of poorly mineralized residues and the formation of reed and cane peat (the initial materials for the latter originating in dense concentrations of Schoenoplectus lacustris, Glyceria aquatica, Saggittaria sagittifolia and Nymphaea candida). Here a slow water exchange rate facilitates the formation of bogs in shallows behind islands. On silt and peat bottomlands marsh-like plant groupings have formed which consists of Ranunculus lingua, Comarum palustris, and Calla palustris. The latter spread from swampy areas to the open aquatory in floating mats of Equisetum, Menyanthes trifoliata, Comarum and Rozippa.

In shallows behind islands in the Volga's main reach flow rates of more than 0.12 m/sec. have been registered during spring floods. A heightened flow rate increases the water's transport capability. In channel deposits between islands large fractions (fractions > 0.2 mm) have been registered, but minute fractions predominate. Bottom sediments formed in shallows behind islands in the main reaches of Type I reservoirs (where the water level remains constant over the entire warm period, $a_I \cong 0$) may be classified as organically enriched silts.

With a Type III water level regime ($a_I \to MAX$), gradual utilization of reservoir capacity results in fixed currents which carry minute fractions out from inter-island channels--fractions which, for the most part, are in a suspended state. Of course the accumulation of minute fractions (silting) is not as pronounced a process in this case as in situations where there is a fixed water level for a prolonged period of time. In samples collected in shallows behind islands in the Rybinsk Reservoir, the total portion of minute fractions (<0.005 mm.) did not exceed 10%. A lowering of the water level in the "ice-free" period leads to the replacement of aquatic conditions by aerial ones. Gradually, in areas of dried bottomland, wind erosion becomes a predominant factor, in particular with the blowing off of minute factions (<0.005 m.) and the redistribution of the coarser, sandy material. In the bottom soil of the area studied well-sorted-out, small-grained sands predominated which were inherited from the mother rock of the islands. With the retreat of water as early as the summer period, bottomland soil complexes remain intact only in the deepest, isolated areas "sanctuaries", while on the former bottomland amphibious plants (primarily annuals) spread: Bidens tripartita, Polygonum minus, Juncus bufonius, etc. From these remains a loose bedding forms which is covered by a mineral material (spring alluvium) during spring floods and with water at the NBL. These deposits occur only in shallows located behind islands, i.e., in those areas where the protective role of islands as barriers is most clearly manifested. Such areas may, with reservations, be considered as analogues to the upper reaches of bays. However, in the outermost areas of islands, where wave action is much more sharply felt than in the "shadow" of the islands, analogues may be found to the estuarine areas of bays.

Thus, in wave action in shallows behind islands (B), processes may be viewed as an intermediary (transitional) link between shallows along bays (A), where wave action is weakly felt, and open shallows (C), where wind-generated waves are constantly felt.

6.3. Open shallows (C)

Aquatories in the general class of shallows may be included over flooded terraces and coastal slopes, i.e., elements of the topographical relief inherited from former river valleys. Such areas also lie over new formations: sand ridges, bars, banks, splits, and shoals.*

Since open shallows are part of a reservoir's main reaches, they are exposed directly to waves which form in the reservoir's deep water areas. The effect these waves have on a shoreline depends on wind conditions (meteorological factors), the morphology of the reservoir's basin (surface peculiarities permitting waves to gain momentum) and on the position of the shallows in the reservoir (especially in relation to the angle of the waves' approach). The total effect of wave action is also dependent on the lithology of a slope and the profile of a shoreline. Observations in reservoirs have shown that sandy soil fractions play a leading role both in bottom areas which are abraded and those which are accumulated. The density of sandy alluvuim in sandy coastal choals and in formations built up by wave action is even greater than the density of sand in coastal shoals formed by this material when first deposited. On the other hand,

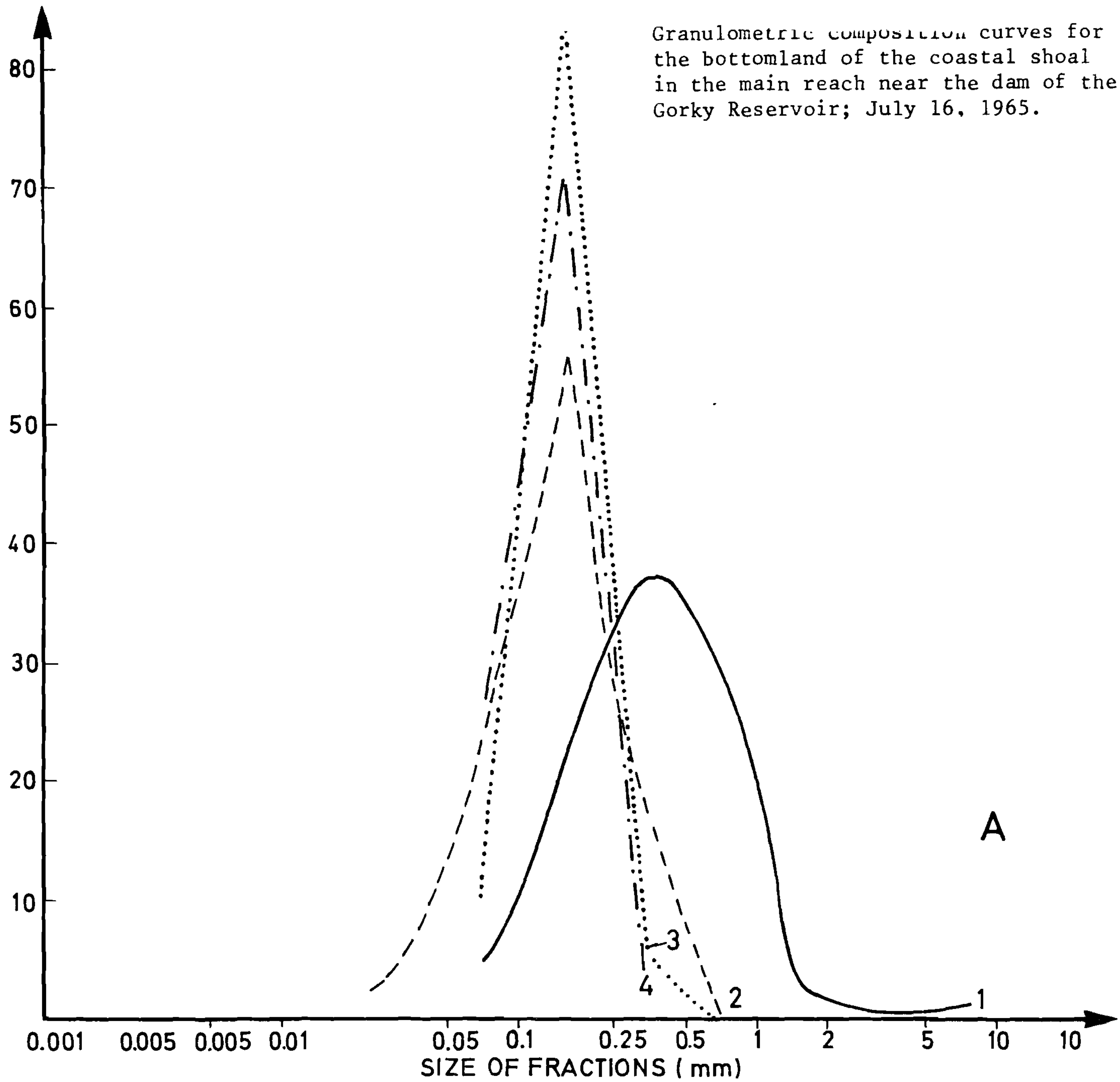
*At the present time there is a great deal of data available regarding the formation of the submerged reliefs of reservoirs under various hydrological conditions. Mechanisms and regulations have been brought to light regarding the formation of coastal shoals and new topographical features as a result of the movement of alluvial currents and the operation of wave processes.

new topographical formations of reservoirs--spits, sand ridges, bars--are formed from coarser material than mainland shoals. For example, the accumulated spit near the town of Puchezh (Gorky Reservoir) consists primarily of gravel (40%) and coarse-grain sand (25%)(Iaroslavtsev, 1966) whereas the shoals consist mainly of well-sorted-out small-grain sand. Figure 12 shows a family of curves for the granulometric composition of soil samples collected along the profile of a shoal at the mouth of a small bay on the lacustrine part of the Gorky Reservoir. It is possible to trace a natural sorting of material with decreasing degrees of coarseness from the water's edge (where waves break) into the open part of the main reach. This is tied to the role of wave action as a constant dynamic factor as well as the flow of alluvial material along the coast. This situation is common for reservoirs in their first ten years. However, this situation is significantly complicated; first by the lithology of coastal deposits*, and secondly by reservoir water level fluctuations which cause shifts in the zone where waves break along a shoal's profile. The magnitude of such shifts depends on the amplitude of water level fluctuation in the "ice-free" period (a_I) and on the width of the shoal.

With a Type I water level regime ($a_I \cong 0$) a stable profile for a shoal is quickly established. In the Gorky Reservoir there is a clear tendency for the slope of a shoal to decrease and for the shoal's width to increase. At the same time a slope will undergo "flattening"; its wave-dampering role will increase, and accelerate the spread of aquatic vegetation. Among the "pioneer" varieties that grow in open shallows subject to this wave action are: Potamogeton perfoliatus, P. lucens, P. pectinatus and Schoenoplectus lacustris; and as for trees, there are Salix alba, Salix rossica, Salix triandra and Salix pentandra (Afanas'ev, 1966). An accumulation of minute fractions occurs among dense

*L.B. Ikonnikov (1972) and N.A. Iaroslavtsev (1966) have pointed out the differences for shoals of sandy versus clay coasts in the Gorky Reservoir; V.M. Shirokov (1964 b) has made similar studies regarding the Kuibyshev Reservoir.

Figure 12A.



Granulometric composition curves for the bottomland of the coastal shoal in the main reach near the dam of the Gorky Reservoir; July 16, 1965.

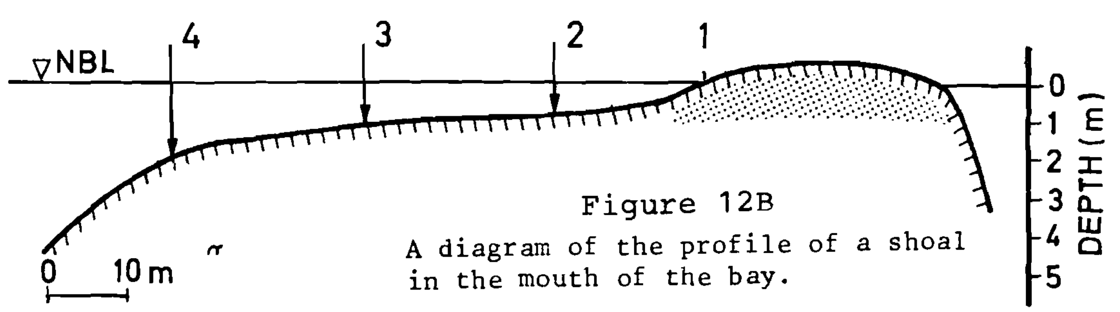


Figure 12B

A diagram of the profile of a shoal in the mouth of the bay.

Places where samples were taken:

1 - Depth of sample = 0 cm at a distance of 0 m from the water's edge

2 - Depth of sample = 75 cm at a distance of 20 m from the water's edge

3 - Depth of sample = 110 cm at a distance of 45 m from the water's edge

4 - Depth of sample = 170 cm at a distance of 70 m from the water's edge

concentrations of these plants and in the silted sands Equisetum will gradually appear along with Butomus and Glyceria aquatica. The rooting of macrophytes does not only depend on the presence of plant embryos and seeds, but also on the wave-dampening effect of shoals.

The following is an example of this situation. Near the navigation lanes in the Kostroma Reach of the Gorky Reservoir on a submerged bank near the channel, a sand spit has formed which is beginning to be overgrown with cane (Schoenoplectus lacustris). Near the shore in fine silted sand (fractions < 0.1 mm. predominate) concentrations of cane have a mature appearance. At 150 to 200 m. from the shore along the spit, the cane only begins to appear in clumps, with stems not exceeding 130-150 cm. in height. Here fractions of 0.1 mm. constitute $\sim$ 50% of the bottomland and 300 m. from the shore only young shoots (1-2 years old) rise above the water. Soil samples at this spot reveal fractions strictly within a 0.5 - 0.1 mm. range. One may suppose that on the basis of numerous observations made on the "mature" Ivankovo Reservoir that with the continued spread of macrophytes and the accumulation of silt particles the range of fractions necessarily widens. However, as shown by soil samples collected under analagous conditions on the Ivankovo Reservoir in well-developed concentrations of cane, aquatic plants, even when playing their full wave-dampening role, cannot completely change the nature of wave action, which remains a determining hydrodynamic factor in open shallows.

With a Type II water level regime where the shallows begin to dry out by the second half of the "ice-free" period, several stages in the formation of shallows may be observed, stages linked with the downward retreat of the zone where waves break. If, during the first half of the "ice-free" period (when a normal backwater level is maintained) there is a building up and smoothing out of shoals, during the period of heavy gales in the autumn the shoals shorten and become steeper. Since autumnal processes occur at a lower water level than summer processes, two "steps" corresponding to the two stages of this hydrodynamic activity can be distinguished in the shoals after many years: a summer step (at high water) and an autumnal step (at low water).

With a Type III water level regime a gradual shift of the wave erosion zone takes place along the slope of shoals, and the shaping of coastal profiles in response to new hydrological conditions extends over a long period of time. According to observations made on the Rybinsk Reservoir at its wide stretches, the "run" available for wave acceleration exceeds 20 km. and the depth to which waves have an erosive effect fluctuates from 1.0 m. to 2.5 m-- prolonging the time required for formation of shoals up to two decades (Kurdin, 1965).

Regardless of the time it takes, the process of forming a stable coastal profile is accompanied by a sorting-out of material. It is characteristic for the bottomland of open shallows to have a predominance of sandy fractions due to the evacuation of minute particles and their subsequent accumulation in calm areas. For example, according to measurements made in the open shallows formed on the steep river terrace of the right bank of the Mologa river (Rybinsk Reservoir), deposits consist of light colored sands. However, the narrow rifts of former ravines, cut deeply into the body of the terraces and free of wave action, are covered by a dark silt.

In addition to the fact that their sandy deposits are sorted out, open shallows are also characterized by their meager organic component--a reflection of the inability of plant and animal organisms to utilize these stretches.

Examples of the three basic types of shallows: along bays [A], behind islands [B], and open [C] for various water level regimes gives an idea of the present-day condition of shallows. At the present time, however, the majority of reservoirs cannot be dealt with as separate entities but only as specific steps in regulated river systems. According to present-day thinking on the subject* the presence of a reservoir in a cascade considerably delays the final stage of development. With relation to the stages in reservoir formation, it is possible to assert that with a Type I water level regime a stable profile is

*These reservoirs all manifest the same type of water level fluctuation and therefore may be compared with each other.

worked out faster than with a Type III regime where the water level gradually "slides" down a shoal's slope. Such constraints must be taken into account when forecasting the development of shallows as natural complexes or as a component of a natural complex. The short-term existence of reservoirs does not permit one to trace all reservoir developmental stages nor the developmental stages of associated shallows. We do, however, have the possibility of comparing reservoir processes for: 1) the first few years of their existence, 2) the first decade and 3) at the end of the third decade. For this we need only compare the Sheksna, Gorky and Ivankovo Reservoirs*. On the basis of collected materials an attempt has been made to trace the successive periods (stages) in the development of different types of shallows (Melnikova, 1967[b]). However, the proposed schema reflects only the general tendency in the development of shallows, and, of course, contains no time constraints for the separate stages. This is because at present we are not able to say with sufficient certainty how the rates of different processes--both in reservoirs generally and in shallows specifically--change depending on a reservoir's position in a cascade and in a total system for artifically regulating the runoff of a major river basin.

7. <u>The role of shallows in the natural filters</u>

All of the above-considered peculiarities of shallows are the result of processes which take place in reservoirs generally, and, of course, influence the related shallows. Positioned as they are around a reservoir's periphery, shallows are influenced not only by reservoirs but by coastlines (drainage from the shore) as well. This is to say, <u>shallows are the interface between reservoir and run-off</u> and all flows entering from the shore come first of all into the shallows zone which acts as a kind of natural filter. Both the quantitative and qualitative aspects of flows into the reservoir's deep part depend on the structure of this "filter".

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*These reservoirs all manifest the same type of water level fluctuation and therefore may be compared with each other.

Since they are not isolated from their environment, i.e., are not "closed systems" but have an "input" of light and allogenic organic material, reservoirs should be studied specifically as allogenic organic matter. Data from many years has shown that inland reservoirs have three sources of organic matter: 1) allogenic matter entering with incoming run-offs or from higher reservoirs; 2) organics produced by macrophytes in the shore zone; and 3) substances resulting from photosynthesis within the water's mass (Romanenko, 1967). Bacterial biomasses are produced as a result of allogenic organics, in other words, bacterial flora within the aquatic ecosystem exist due to sources of energy which are external to the system. A similar situation, characteristic for many inland reservoirs, is connnected with the enormour run-off areas on which flows form. Flows enter not only as the input of major rivers but as inputs of tributaries as well, and it is precisely in this connection that one may most clearly trace the link between run-off and shallows. Most reservoir tributaries are found in backwater areas, and in their lower (less frequently--middle) stretches, bays occur. Consequently the sharpest tie with run-off will be manifested in bays on tributaries. Here allogenic organics enter, precisely in the bays which are the main aquatories occupied by macrophytes. And in the general flow chart for aquatic ecosystem energy transfers, it is the allogenic organics and macrophytes along with phytoplankton and light which constitute the first trophic level (Rybinsk Reservoir, 1972). Consequently, shallows along bays (A) play a significant role in the cyclic exchanges of matter and energy in reservoirs.

Shallows behind islands (B) are flooded by main rivers and do not receive allogenic substances comparable to those found in bays. This is because main rivers either carry waters from a reservoir on a higher level of a cascade (and, consequently reflect processes occurring in these higher reservoirs) or as is usually the case, due to their considerable velocity, hinder the accumulation of material and, in fact, cause erosion.

As a rule, surface runoff reaches open shallows (C) only sporadically, with rains or in the spring with excessive melting of snow. Open shallows are therefore less affected by surrounding landscapes than are other kinds of shallows.

By examining the interaction processes between reservoirs and coastal drainage systems the existence of such differentiated reactions for different kinds of shallows allows one to predetermine where and how the impact of a coastal drainage system will manifest itself. At the present time there are already sufficient examples which permit one to record changes in shallows in connection with various kinds of land use on the shores of reservoirs. Let us introduce one example. In the bay along the Sacha River, whose basin drains farm lands (mainly meadows and cultivated fields) one encounters an abundance of macrophyte species: 15 species of amphibious plants; and 5 species of underwater plants. Among the latter is pondweed, Elodea which was first registered in the Gorky Reservoir in the first 3-4 years after it was filled (Ekzertsev, 1963). Spreading of this pondweed was connected with the leaching of nutrient substances from recently flooded soils. At the present time it is encountered only in those bays whose waters are enriched by biogenic matter--primarily bays along tributaries which drain farm lands.

Conclusion

When summarizing the characteristics of shallows in regulated reservoirs, it is desirable to stress the following:

1. The characteristics of shallows in such reservoirs are determined by the yearly water level and its inherent range of fluctuation--most importantly fluctuation in the "ice-free" period (a_I).
2. The connection between natural processes occurring in shallows and water level fluctuation permits one to have some control over the former through regulation of the latter.
3. The presence of a reservoir in a cascade (a water control system) changes the time constraints for the stages in its development, especially its coastal

development. This is because the attainment of the final stage in the working out of a stable coastal profile--the transformation of a bed in response to new hydrodynamic conditions--is postponed into the distant future, a future which lies outside the water system's anticipated period of operation.

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