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FISH PRODUCTION IN IMPOUNDMENTS

a report[1] by

Gerald P. Cooper

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A BIBLIOGRAPHY WITH ABSTRACTS OF THE LITERATURE ON ECOLOGY OF IMPOUNDMENTS

by

Grace G. Hubbell

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1 Paper presented by Gerald P. Cooper at the Eleventh Pacific Science Congress, Tokyo, Japan, on August 25, 1966.

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FISH PRODUCTION IN IMPOUNDMENTS IN THE EASTERN UNITED STATES OF AMERICA

By Gerald P. Cooper
Michigan Department of Conservation, Lansing, Michigan

The primary aim of this paper is to review the production of sport fishing in impoundments in the U.S.A., with special reference to the northeastern states and particularly to Michigan. First, I give a general review of the status of impoundments, of the factors affecting their productivity, the role of impoundments in sport fishing, and some of the possibilities of management of impoundments for fishing. Then, I give something specific about sport fish production in impoundments in Michigan.

My general remarks are based on a review of the very extensive North American literature on impoundments. (The able assistance of Grace G. Hubbell in this literature review is gratefully acknowledged.) This paper is documented only to a few major sources of information.

The Waters

In North America there are hundreds of huge impoundments, and at the other extreme in size there are literally millions of small farm ponds which would classify as impoundments. The real giants are reservoirs in the Mississippi, Colorado and Columbia river drainages which are for flood control, hydroelectric power, water supply and irrigation. Sport fishing is an incidental, rather than a primary aim for these waters. The myriads of 1-acre to 5-acre "farm ponds" throughout the midwest and south have fishing as one of their primary purposes.

Back to the large reservoirs, the largest include: (a) Garrison Reservoir, on the Missouri River, in North Dakota, 390, 000 acres; (b) Oahe Reservoir, on the Missouri River, in South Dakota, 376, 000 acres; and (c) Kentucky Reservoir, on the Tennessee River, in Kentucky, 261, 000 acres. The states of Montana, Texas, Oklahoma, Tennessee, California, Arizona and Washington also have very large impoundments.

The glaciated northeastern states are generously endowed with natural lakes, also have a considerable number of relatively small hydroelectric impoundments (of 2, 000 to 10, 000 acres), but have almost no large impoundments and relatively few farm ponds. Michigan for example has 73, 000 acres of impoundments, as contrasted with 250, 000 to 700, 000 acres for each of the states cited above (Thomas and Harbeck, 1956).

Their Productivity

In new impoundments the water gets a large amount of nutrients (nitrates, phosphorus, other elements) from the newly flooded substrate. The result is a system essentially like a hay infusion in the culture of bacteria, algae and protozoa. New impoundments have a high production of plankton, consequently a good survival of fish fry and young, very fast growth of fish, a high production of fish, and therefore good angling. The simplicity of this generalized statement is somewhat misleading, however, for there is great variation in the productivity of impoundments, depending upon a wide variety of conditions.

Temperature and nutrient content of inflow: An impoundment on a spring-fed trout stream typically has cold water which is low in elements of organic fertilizer. The watershed may be mostly of sand plains, or bogs and swamps, or of igneous rock in mountain terrain, but is typically forested and with little or no agriculture or livestock grazing. Such impoundments represent a very early stage of eutrophication; initially they are not very rich, they do not readily undergo a limnological stagnation in the hypolimnion, they remain suitable trout habitat for many years, and they do not become highly productive.

In contrast an impoundment on a warm stream which drains rich agricultural land is highly productive and immediately is in an advanced stage of eutrophication.

Depth, mixing, and draw-off: A deep impoundment stratifies in summer, and nutrients including organic detritus accumulate in the hypolimnion. Plankton production in the epilimnion is dependent upon recirculation and mixing of these nutrients from the hypolimnion back into the epilimnion. A draw-off of water at the dam from the bottom of the impoundment depletes these nutrients from the basin, and also adds to the lowering of the thermocline which further helps to trap the remaining nutrients in the deep water (Murphy, 1962).

Turbidity: Some reservoirs are unproductive because of high turbidity, which eliminates algal photosynthesis. The clay (turbidity) may come in with tributary inflow, or from wave erosion of clay banks of the impoundment itself, or from bottom feeding activity of fish like the carp. The inflow of a turbid tributary may drop down and "layer out" at an intermediate depth level in the impoundment if conditions of temperature and density are right; the turbidity, if restricted to some deep level in the reservoir, would not interfere with photosynthesis in the epilimnion. The level at which water is drawn from the impoundment may be the determining factor in whether a turbid tributary will flow onto the surface of the impoundment or seek some lower level.

Rate of displacement: A considerable number of medium-size impoundments are little more than a modest widening and deepening of a river, produced by a small hydroelectric dam. Such waters are not really biological impoundments, for water and nutrient flow are entirely in one direction and there is no time for lentic production. Such an impoundment probably makes a more significant contribution on a trout river, than one on a warm-water river, because trout prefer rivers as a physical habitat more than do most warm-water game fish.

Fluctuation of level and exposure of benthic soil: In the nutrient cycle, dead plankters settle to the bottom and the basic N, P, K and other elements are added to the bottom muds. These nutrients are re-cycled into the system at the fall and spring overturns to the degree that they are not "held" by the bottom mud. Typically the surface layer of the bottom is a colloidal substance, of decomposed organic material, which has a strong affinity to adsorb nitrogen, phosphorus, potassium and other nutrients. This retention of nutrients by the bottom soil is believed to be a main reason why impoundments regularly undergo an early decline in productivity.

It seems to be well established that an impoundment can be rejuvenated if the water is drawn off and the dry basin left fallow for several months to a year or so. The colloidal bottom mud is dried and oxidized to the point where it readily releases its nutrient elements when the impoundment is refilled (Neess, 1946; Kadlec, 1960).

The concept that a fish pond (or impoundment) will be more productive under a system of water-land crop rotation has been recognized for a thousand years in Europe and here in the Orient (Neess, 1946). In the U.S.A. we have not made much progress in rotating ponds and small impoundments, although a start has been made, particularly in managing impoundments for waterfowl.

Decline of productivity with age: It is generally believed that production of game fish in impoundments declines greatly with time. The loss of nutrients to bottom soil and to outflow is the primary reason for the decline. This loss is both substantial during the early life of the reservoir, and continuous, if considerably diminished, over an extended period of time. The time factor is affected by a number of variables. Some large impoundments remain highly productive for 10 to 30 years (more or less), whereas smaller ponds are often very productive for only 5 to 10 years. Natural beaver ponds on trout streams in Michigan, mostly 1 to 10 acres in area, are initially very productive, but limnological deterioration occurs early, mostly within 2 to 4 years. There is stagnation, with a loss of dissolved oxygen, a drop in pH, and a decline in the trout population. Thus a feature of beaver-trout management has been to encourage beaver activity and trout fishing during the first 4 years of life of the pond, and then about in the 5th year to remove the dam so that the stream returns to its original channel (Salyer, 1935).

The concept that impoundments decline in productivity is most often associated with the production of sport fish, often of predatory species. Many investigators, concerned with species composition, have stated that the decline in fish production in impoundments is due largely to changes in species composition--from an early population of mostly predators and other game species to a population predominantly of worthless species. It is easy to find evidence supporting the two ideas:--production related to nutrient fertility, versus production related to species composition.

Productivity of impoundments compared to natural lakes: It is suggested, but not too firmly established, that impoundments are generally more productive than natural lakes. Carlander (1955) summarized much of the American literature on the subject of lake productivity. He gives summary figures for the standing crop of fish at about 200-400 pounds per acre in reservoirs and farm ponds, as compared to 125 to 150 pounds per acre in warm-water natural lakes. Rounsefell (1946) generalized that impoundments should be less productive than natural lakes, except for the initial period of high productivity of impoundments. The difference in productivity between impoundments and natural lakes is perhaps of less magnitude than the change in productivity of impoundments with time.

We have some biological information on two Michigan impoundments (Fletcher and Haymarsh) which are quite different in conditions affecting productivity.

Fletcher Floodwater

Fletcher Floodwater, a 9,000-acre 35-year-old impoundment on the Thunder Bay River was built for hydroelectric water storage. For the first 15 years it provided outstanding sport fishing for northern pike, but since 1948 the game fish population has been deteriorating and quality of fishing has declined. We have various types of population data over the past 20 years.

In 1956 a mark-and-recapture population estimate gave a figure of 97,000 pike over 14 inches, or about 10 pike per acre. Fishing is both open-water with hook and line, and winter fishing through the ice with either hook and line or spear. Total fishing effort in 1955-56 was about 250,000 angler hours per year; these anglers caught 37,000 pike, or about one-third of the population. This harvest of one-third of a standing population in one year represents, for angling, a high rate of exploitation. The above annual fishing effort and catch convert to about 25 hours of angling and 4 pike per acre per year. In contrast to an intensive farming of fish in small and fertile ponds, the production of 4 fish per acre per year is almost no production at all. But in production of game fish, Fletcher Pond is probably typical of other large lakes in forested lands of low fertility at the latitude of northern Michigan.

The decline in fishing for pike and other game species in Fletcher Pond during the past 20 years has come about because of a great decrease in size and age of pike, and a decrease in numbers of other species. In spite of the heavy fishing pressure and the angler removal of one-third of the population each year, the pike has retained its abundance and depleted most of its preferred food supply of forage fishes. The result has been a great decline in rate of growth and in survival, so that the pike population is now mostly small and young fish. Direct evidence of these changes was provided by studies made in 1948 and repeated in 1955. Pike in age groups II and III made up 65% of the angler catch in 1948, and then 94% in 1955; age groups V to VIII made up 25% in 1948, but only 3% in 1955. The average length of pike taken by anglers dropped about 2 inches during the period. The average size has dropped to the extent that the state-wide legal length of 20 inches on pike is too high for efficient utilization of the population.

The extent to which the pike has depleted its preferred supply of forage fish (suckers, minnows, and other large-size kinds of food fishes) is seen in a study of stomach contents of pike. In earlier years the pike fed largely on suckers, minnows, perch and other preferred items; now these species are rare and the pike is feeding mostly on crayfish, darters and leeches, all of which are considered to be low on the preferred list.

The decrease in average age of pike, the decline in growth rate, and the change in feeding habits, all point to the one conclusion that pike in Fletcher Floodwater are now mostly dying of starvation at the end of 2 or 3 years, whereas many of them should survive to an age of 5 to 8 years and to a much larger size.

Haymarsh Lake

This 375-acre artificial impoundment was formed by an 8-foot dam installed on the headwaters of a small stream in 1949. Within the basin of the lake there were six bog lakes with a combined area of 81 acres. Thus the flooding added about 294 acres of shallow water over muck soils and marshy or low brush vegetation.

The original six bog lakes had a variety of warm-water game fish typical of the area: pike, largemouth bass, bluegill, pumpkinseed sunfish, perch and rock bass. The fish present were sufficient to populate the new reservoir very quickly, and the new impoundment produced good sport fishing for the first 4 or 5 years, after which fishing quality declined.

In 1958 an attempt was made to rejuvenate the fishing. The lake was lowered about 6 feet early in the spring; then millet was sown and a crop was produced on the dry lake bed. The impoundment was refilled in late summer, which meant flooding a good stand of green millet plants.

The drawdown and flooding of millet had several effects. The number of fish was reduced, obviously because of the considerable reduction in lake area which prevailed for several months. There was a severe winterkill of fish the first winter after drawdown, and another kill the second winter after, both apparently reflecting the increased biological production after the reflooding. Haymarsh Lake has 1 to 2 feet of ice for 3 months each winter. There was some improvement of growth of fish after reflooding, but the cause here may not be too obvious. An increase in fertility and a reduction in population numbers would contribute to better growth, but a major disruption of benthic fauna (fish food) by the drawdown would operate toward slower growth.

Haymarsh Lake offers a marked contrast to Fletcher Floodwater in time lapse for marked changes in fish growth and production. The 9,000-acre Fletcher, with pike the predominant fish, has taken 25 years or so to pass through a cycle of productivity. The much smaller Haymarsh, with more bluegills, perch and other small pan fishes rather than pike, has much shorter cycles of ups and downs in the fish population.

Pike Marshes at Otsego and Houghton Lakes

A somewhat different type of fish impoundment is represented by pike spawning marshes which have been developed on lakes which lack good pike spawning grounds. The pike spawns in shallow, warm marshes in early spring. An artificial marsh is created by a low-level dam which floods 2 to 3 feet of water over a flat, marshy area which can be drained into the lake. The marsh may be fertilized. Adult pike are transferred into the marsh in April, the adults spawn, and the young pike are flushed from the marsh into the adjoining lake when they are about 2 inches long (2 months old).

The principles of fertility of water in a system of periodic flooding is much like the same principle operating in larger impoundments with fluctuating levels.

Role in Sport Fishing

According to R. H. Stroud, writing in the Sport Fishing Institute bulletin (Dec., 1965), there are 10 million acres of man-made waters in the U.S.A. These waters are mostly used for sport fishing, and their yield of fish to anglers is about 15 pounds per acre per year. Of something over 1 1/3 million farm ponds and reservoirs which were constructed with financial help from the U. S. Department of Agriculture, about half of them are good fishing ponds.

Seven Impoundments with Angling History

Seven impoundments in Michigan were selected because of a long record on sport fishing which provides a basis of judging the relation of angling productivity to size and age of the impoundment and to geographical location. Data on these waters are given in two accompanying tables, along with data for comparison of angling quality in all (thousands of) natural lakes in the State.

The first table gives catch of fish per hour as a simple average for a 22-year period. The figure on angling hours in the sample gives an idea of the adequacy of the sampling. These records were collected by Conservation Officers in line of general duty. In natural lakes, the more northern waters are the least productive. This applies also to impoundments but there is more uncertainty about impoundments because of small sample size. The smaller impoundments are generally the more productive.

The second table was prepared to see if fishing quality in these impoundments declined over a period of years. The same impoundments are listed in the two tables. There is hardly a well defined downward trend in angling here, since three of the impoundments did not change, three went down and one went up. For all other lakes in the State (Table 2) there was likewise not a uniform change from one decade to the next. Fishing improved in the north part of the state, but declined some in the other two parts.

This analysis of seven Michigan impoundments does not support very well the generally accepted ideas that fishing quality in impoundments declines over a period of years, and that impoundments are more productive than natural lakes.

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Table 1.--Creel census of game fish by angling, on selected impoundments and all Michigan lakes, 1943-1964

Part of state	Impoundment: Name	Area, acres	Year[1]	Angling hours in sample	Fish per hour	Species
North	Michigamme	5,220	1940	21,200	0.50	*
	Peavy	2,673	1943	7,240	0.62	*
	Seney	2,000	1935	2,450	0.35	Mostly pike
		All other lakes		260,000	1.06	*
Middle	Fletcher	8,970	1930	97,000	0.50	Mostly pike
	Reedsburg	1,151	1940	3,000	0.69	*
	Haymarsh	375	1949	1,720	3.04	*
		All other lakes		1,000,000	1.10	*
South	Pontiac	585	1924	5,800	1.72	*
		All other lakes		837,000	1.42	*

1 Year of construction of dam.

* Mostly sunfishes, perch, bass, pike, walleyes.

Table 2.--Catch per hour of game fish by angling, on selected impoundments and all Michigan lakes, comparing two decades, 1943-1964

Impoundment	Decade	
	1943-53	1954-64
Michigamme	0.50	0.51
Peavy	0.67	0.57
Seney	0.35	0.35
Fletcher	0.50	0.50
Reedsburg	0.61	1.29
Haymarsh	3.79	2.29
Pontiac	1.77	0.97
All other lakes, in parts of State		
North	0.91	1.18
Middle	1.15	1.07
South	1.56	1.33

Following are author's abstracts of seven papers (in addition to the one by G. P. Cooper, given on preceding pages) which were given in a symposium on impounded waters at the Eleventh Pacific Science Congress, Tokyo, Japan, August 25-26, 1966. They give considerable insight on biological thought about impoundments in countries surrounding the Pacific.

Impounded waters
("A changed aquatic environment")

By A. Dunbavin Butcher
Melbourne, Victoria

A discussion on impounded waters must logically include the waterway downstream from the impoundment and upstream, even beyond the limits of the backwaters.

A full consideration of impounded waters in relation to the aquatic fauna requires pre-impoundment studies, studies of the changed environment, of the indigenous fauna, of exotic fauna, should the latter be present and of the inter-relationship of these several factors.

Impoundment walls present physical barriers to fish movement; impoundments bring about temperature changes which may be upwards or downwards; they function as flood control devices and change the normal river cycle; they produce physical and chemical changes with concomitant biological effects; they control the rise and fall of a river; they may destroy zoo-geographical boundaries.

It is the Australian experience that, generally, impounded waters (as defined above) favour introduced species of fish. At best, residual populations of indigenous fish are found in impounded waters.

A limnological survey on Shihmen Reservoir

By (Mrs.) Yanung Chu Wang
Taiwan

The Shihmen Reservoir is the largest of its kind ever built in Taiwan. It covers an area of 8.15 square kilometers in a length of 16.5 kilometers. Its effective storage capacity is 251,000,000 cubic meters irrigating about 58,000 hectares of farm land and furnishing a potential power capacity of 87,000 kw.

Having its dam site located about 52 kilometers south of Taipei City this multipurpose reservoir is becoming a recreation center in Taiwan ever since its building in 1963. As it furnishes an ideal place to study population and community growth, a project of constant survey on the physical, chemical and biological characteristics of this reservoir water has been going on under the direction of Dr. T. S. Miu and the present writer. The following is the preliminary result of this long range observation:

Oxygen	4.165 ml/1000 ml
Carbon dioxide	2.3 ppm/1000 ml
Hydrogen sulfide	0.9296 ml/1000 ml
pH	6.2
Rotifer	3 species
Ciliates	4 species
Flagellates	3 species
Algae	4 species

Biology of studies on an impoundment in East Pakistan

By F. A. Sandercock and C. C. Lindsey
University of British Columbia, Vancouver, Canada

A highly dissected reservoir of about 60,000 hectares was created in 1961 by damming the Karnaphuli River. Maximum depth is about 50 metres but much of the reservoir occupies flooded valleys with gentle gradients; in these, extensive delta flats covered with decaying vegetation and flooded trees are exposed annually during the drawdown of 10 metres in June. During the winter of 1964-1965 the reservoir was isothermal. In summer a temperature gradient of 6° C was established, but no distinct thermocline. In mid-May, cold rainfall caused a brief mixing. Oxygen was uniformly 5-6 p.p.m. in January; by summer, an oxygen-free zone existed below 10 metres. Bottom fauna was extremely sparse, probably due to a combination of exposure of the littoral zone during drawdown and periodic oxygen depletion in deeper water. Mean secchi disc reading was 4 metres; dissolved solids were 90-95 p.p.m. Between January and May the average number of plankters in the 0-10 metre zone strained by No. 10 bolting silk was 7.8 per litre. About 60 species of fish have been identified, of which 28 are of commercial importance. Annual removal, largely by gillnet, is now about 25 kg./hectare. Intense experimental netting of a 22.6 hectare bay for 7 days showed a standing crop of fish of catchable size of only 9.3 kg./hectare.

On the problems of Lake Succession

By Shoji Horie
Kyoto University, Otsu, Shiga-Ken, Japan

In Japan, there are about 600 lakes of natural origin. Some of them had been transformed to impoundment by gate in order to regulate water discharge for the purpose of irrigation, water-power electricity, and industrial water.

The writer has been interested in the limnetic history, paleolimnology, confirming the fluctuation of trophic stage.

In a 10-m core from Yogo-ko (1.63 km^2, 14.5 m of maximum depth), one conspicuous point is the limnetic accident. It is correlated with an inter-stadial between two expansions of glaciers in Japanese high mountains. The other notable point is that ages of low lake levels are correlated with the recurrence surfaces in Northern Europe. These facts suggest that the trophic stage is controlled by the climatic change. Such features are shown by the studies of wet weight, dry weight, ignition loss, calcium carbonate, residue, nitrogen, phosphorus, and carbon.

In a 8-m core sample obtained at the center of Suwa-ko (14.5 km^2, 7.0 m of maximum depth), the writer discovered peat layer at 6 m depth. It indicates the existence of two limnetic cycles interrupted by that layer which is correlated with extremely low lake level age in Yogo-ko.

The significance of such fluctuation of trophic stage is that the succession of lake is not simple. It has been said that initially oligotrophic lake type transits towards eutrophic lake type. We must, however, consider some important factors interfering that transition. Although we recognize high fish productivity in Suwa-ko, it might be created during last 3,000 years. Most important factors seems to be climatic change and crustal movement both of which regulate water volume, i.e. morphometric features of lake and therefore, lake typology and productivity.

Fish production in impounded water in Japan

By Y. Shiraishi
Freshwater Fisheries Research Laboratory
Tokyo, Japan

The impounded waters, mostly constructed with multi-purposes, now outnumber the natural lakes, and further increase of the numbers is expected. The general features of the reservoirs in the country is first expressed as to their geographical distribution, area, altitude, depth, etc., in comparison with natural lakes.

Fish fauna of these waters are then discussed as to its formmes, warm-water and cold-water type. The amount of fish catch is then explained with relation to the artificial stocking, a managemental procedure taken at present.

By taking up a few examples of surveys, the role of crustacean plankton which is believed supplying basic food source to the fish is discussed. The location of fish population and their moving within the water are explained as the result of surveys which were conducted by the use of echo-sounding machine.

The present knowledge on the limnological conditions as well as the occurrence of fish population in the mainflow reservoir suggests the concentration of fish population falling on the middle and lower parts of the water, where emphasis should be placed as to commercial, and sport fishing as well as fish culture in floating cages.

Plankton control in reservoirs

By Sadao Kojima
Japan

Tokyo Metropolitan Water Bureau had experienced considerable trouble of filters being clogged with plankton algae, growing in Murayama and Yamaguchi Reservoirs for more than 20 years.

Then the Water Bureau decided in 1947, to control the plankton growth in these reservoirs, and to explain, in the first place, the hydrology of reservoir and the ecology of plankton.

We were successful in explaining the stratification of impounded water, the current of water, especially the density current, the periodicity of plankton growth, and the vertical and horizontal distribution of plankton, as well as the correlation between the plankton and the filter clogging, which were the essential knowledge for plankton control.

From these studies, mentioned above, we can establish a way of observing and forcasting the plankton growth. We, also, developed the measures of controlling plankton by spacing the depth of outlet gate, and made an improvement on copper treatment method of control.

The filter clogging decreased year by year, and finally disappeared entirely in 3 years after our plankton control was started.

Comparing each decade before and after the plankton control, we found 26% reduction in total of operating labor for filter plant, and 13% increase of filtered water per year. And these correspond, at least, to 200,000,000 yen per year, balancing the cost of doing the control.

Plankton and benthos of some Japanese impounded waters

By Matsunae Tsuda
Women's University, Nara, Japan

On the basis of our biological studies of the reservoirs in Japan I want to report following items.

1. The typical examples of water level change of Japanese multiple purpose reservoirs.
2. Annual temperature stratification in reservoirs.
3. Lack of submerged higher plant.
4. Dominant phytoplanktons in various reservoirs.
5. Dominant zooplanktons in various reservoirs.
6. Benthic fauna (Chironomidae, Oligochaeta, Asellus, etc.).
7. Occurrence of fresh-water medusa in Asahigawa Reservoir.
8. Change of fish fauna by the impoundment.

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(Abstract)

Fish Production in Impoundments of North America

By Gerald P. Cooper

Impoundments in temperate North America are of all sizes from 1-acre farm ponds to 1,000-acre hydroelectric and recreational impoundments to very large flood control reservoirs of 500 square miles or more. These waters are open to sport fishing; a few of the largest are also open to commercial fishing.

Productivity of a reservoir depends on: (1) nutrients in inflow waters; (2) nutrients from reservoir basin soils; (3) rate of volume displacement in the reservoir; and (4) character of the plant-animal food chain which is dominant.

Reservoirs lose their high initial fertility in 5 to 10 (up to 25) years. Nutrients in the new impoundment become locked up in bottom deposits or are lost to outflow or to fish harvest. Or deterioration may be toward acid bogs, as with some beaver dams. Or the fish population usually changes, from good fish growth and a favorable predator-prey ratio, to poor growth and a decline in predator fish.

Reservoirs produce more fish than do natural lakes. The standing crop of fish averages 50-150 pounds per acre in natural lakes, 200-400 lbs/acre (2 to 8 times as much) in impoundments. A large part of the food chain is from plankton and insects to centrarchids and perch; less is from plankton to minnows and suckers to large predators. Best predators are the northern pike in the northeast, the largemouth bass and white bass in the south, and large salmonids in the west.

Periodic drawdown may be the best way to manage impoundments for fish. Aeration of basin sediments helps to keep nutrients in the food chain. Any crop of herbaceous terrestrial plants is good organic fertilizer when that part of the basin is reflooded. Disruption of rooted aquatic plants releases nutrients which might better go into other links of the fish food chain. Fluctuation of level dislodges prey species from ecological niches, resulting in more predation, lower population density and better growth rate of sunfishes and perch; this improves the sport fish population.

THE LITERATURE ON IMPOUNDMENTS

By Grace G. Hubbell

The following bibliography of literature on impoundments includes first, on this page, a list of published bibliographies plus extensive bibliographic compilations on the subject of impoundments which have been published. Then follows the bibliography and abstracts, under author names in alphabetical sequence.

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The bottom fauna of 10 streams in the Beaver Reservoir basin, northwest Arkansas, was studied previous to impoundment. The streams were grouped according to size and seasonal pattern of flow. Small spring-fed streams produced the most bottom organisms per unit area, large tributaries produced less, and small streams subject to surface drying produced least. Riffles were much more productive than pools in the spring-fed streams and in larger tributaries; but in streams subject to drying, pools produced almost twice as much as did riffles. No satisfactory sampling technique was developed for deep pools in the larger tributaries. Bottom organisms were most abundant in water of temperatures below 65 F.

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1937. Management of impounded water in Iowa.
Trans. Second N. Amer. Wildl. Conf., 1937: 424-427.

If a lake is intended primarily for fishing, the dam should produce enough water to cover at least 30% of the lake bed to a 5-foot depth. In southern Iowa it has been found that an impounded area having less than 30% of shallow depths resolves itself into a v-shaped trough. In such a mud-bottomed lake having a large amount of deep water, fish yield would be slight as shallows are the spawning areas of game and forage fishes. Erosion control is essential to prevent silting. Studies of 17 reservoirs with an average age of 28 years, with an average volume of 378 acre-feet, showed an average volume of 23.5% siltation had occurred. This is 88.83 acre-feet of silt or a yearly volume of 3.17% in acre-feet.

Andrews, Ted F., and John Breukelman
1952. Studies in Kansas limnology. I. Survey of the Kansas State lakes.
Trans. Kansas Acad. Sci., 55: 315-529.

The Kansas lake system was started in 1927. By the end of 1938 dams had been built or were under construction in five counties. These impoundments were opened to fishing in 1929 and thereafter. The lakes range in size from 25 acres to more than 3,000 acres; in depth from 6-70 feet; in capacity from 300 to 10,000 acre-feet. They are situated in areas of less than 20 inches of annual rainfall to more than 40 inches; in areas of sandstone, limestone, shale, chalk, sandy loam and glacial drift. The temperature of the water ranged from 15 to 31 C; pH from 5.9 to 8.1; turbidity from less than 5 to 200 ppm; carbon dioxide from 0 to 55 ppm; and oxygen from 0 to 9.8 ppm.

Armitage, Kenneth B.
1961. Species composition and seasonal distribution of limnetic crustacean zooplankton of northeastern Kansas.
Trans. Kansas Acad. Sci., 64(1): 27-35.

Author's summary [in part]
A study of the species composition of 17 samples from 6 lakes showed an average of 23 species of copepods and three species of cladocerans present in any single sample. In 11 of the samples, two or more calanoid or cyclopoid copepods or daphnids were found. Interspecific competition in these situations is discussed. It occurred in the same lake, Laboratory Lake. Each species is an invader of a new environment. Quite possibly sufficient time has not elapsed for the characteristic species composition of limnetic zooplankton to have become established.

Bates, John
1962. The impact of impoundment on the mussel fauna of Kentucky Reservoir, Tennessee River.
Amer. Mid. Nat., 68(1): 232-236.

Collections made in Kentucky Reservoir during 1958 indicate that the pre-impoundment assemblage of species, characterized by a preponderance of species belonging to the Unioniae, is doomed. Only Quadrula quadrula has adapted to the altered ecological conditions. This species, along with two species of Leptodea, one species of Carunculina, and three species of Anodonta comprise the dominant assemblage in post-impoundment habitats. More recently, and since these collections were made, an introduced Asiatic clam Corbicula fluminea has invaded these portions of the Tennessee River. It is apparently spreading very rapidly. These data indicate that as man continues to tamper with the ecology of rivers, additional changes will take place in the original mussel fauna. It is likely that this early natural assemblage may suffer to the point of extermination.

Bell, Hugh Stevens
1942. Stratified flow in reservoirs and its use in prevention of silting.
U. S. Dept. Agr., Misc. Publ. No. 491: 1-46.

The menace of sediment depleting the capacity of reservoirs of all sizes is not generally understood. Many dams that impound water have been built with no provisions whatever for discharging water and silt at low levels. Stratification that results when dissolved or suspended material produce the essential difference in density is less familiar than stratification due to differences in water temperatures; but the former is of great economic importance. During this investigation density currents were studied in glass-walled flumes and in Lake Mead. A complex stratification is the usual condition in Lake Mead: warm surface layer; cool at depths from which water is withdrawn, but some of the coldest water is slightly brackish and forms a distinct stratum beneath which is a submerged and very muddy lake. Sediment-laden streams tend to build deltas when they enter a body of still water. Deltas are composed of coarser particles; most of the finer are held in suspension. Under such conditions the Colorado

River water entering Lake Mead plunges beneath the surface and continues to flow along the sloping bottom (as far as 100 miles) as a submerged, sediment-laden stream, a moving stratum that is frequently able to keep fine particles in suspension until it comes to rest as a muddy lake in the deepest part of the reservoir. It is estimated that density currents in Lake Mead are transporting material sufficient to completely fill the reservoir in 200 years. It was concluded from this study that properly placed outlets at low levels might remove from 75 to 90% of the sediment by carrying it beyond the dam. In some reservoirs the problem of removal of salty water from the submerged pools near the dams is difficult to accomplish without loss from more desirable layers, because density differences are not very great. Over a long period, it is economically unsound to store salty water in a reservoir from which fresh water must be wasted.

Bennett, George W.
1954. The effects of a late-summer drawdown on the fish population of Ridge Lake, Coles County, Illinois.
Trans. 19th N. Amer. Wildl. Conf., 19: 259-270.

Ridge Lake is an artificial impoundment of 17 acres used as an outdoor laboratory for the study of largemouth bass. Prior to this investigation it had been studied for 10 years in a series of 2-year periods during which water levels were relatively stable. The 2-year periods were delimited by lake drainings and fish censuses, followed by return to the lake of selected marked fish and subsequent population adjustments. In September of 1951 and again in 1952, following summer fishing, the level of Ridge Lake was lowered by 15 feet, reducing the lake area from 17 to 5.25 acres, and the maximum depth from 25 to 10 feet. In both years the lake level remained low until December when runoff water began to refill the lake; in both years the lake basin had nearly refilled by early March. Results. The September drawdown exposed the entire bottom of the littoral plant zone, at a time of year when it was filled with dense stands of potamogetons and other submerged aquatics. Small fishes and aquatic invertebrates inhabiting this zone were forced to move out of the vegetation into the open water or become trapped in plant mats, and in small depressions that were completely dry in 3 or 4 days. This concentration of aquatic animals in a reduced volume of water made these food resources more readily available, but probably caused marked reduction in the numbers of such food animals. Largemouth bass--there was no reduction in the numbers of individual fish, but there were fewer large fish and more small fish; by weight the catch amounted to 15.8 pounds per acre which was larger than the yield of 1946 (14.6 pounds per acre) but smaller than that of 1948 (25.6 pounds per acre). Bluegills--considerable reduction in numbers, but with the large bluegills outnumbering the small ones. The drawdown was too severe from the standpoint of the bluegill population. It was suggested that the optimum drawdown for individual lakes must be determined by testing.

Brasch, John G.
1958. Drawdowns: fish management tool.
Wisconsin Conservation Bull. 23(12): 25-28.

In the early 1940's research on TVA waters suggested that drawdown had a controlling effect on the abundance of rough fish, with little or no serious injury to game fish. Most drawdowns occurred in winter when spawning of fish was over and presumably destroyed the bottom organisms on which carp feed. Stable-water-level reservoirs usually produce good fishing for bass and panfish for several years after stocking. Then bass harvest declined and panfish were small and stunted. This sequence was believed to be a "normal" ecological succession, probably caused by competition for food and space. The species least able to compete well (the bass) gives way to panfish and rough fish. A research reservoir built and stocked in Illinois in 1941 has been under continuous observation since that time. Using controlled-water-level fluctuations the research pond was drawn down one September and refilled the following March. Bluegill numbers were decidedly reduced with no comparable loss of bass demonstrated. [See Bennett, George W. 1954, for an account of the work referred to.]

Briggs, John Carmon
1950. The quantitative effects of a dam upon the bottom fauna of a small California stream.
Trans. Amer. Fish Soc., 78(1948): 70-81.

Stevens Creek is a small but permanent stream. The effect of the dam upon bottom fauna production was tested for a 9-month period. Production of bottom organisms, both in number and weight, was much greater in the area below the dam than above. A sharp spring peak of production occurred both above and below the dam. The period of minimum production in both areas coincided with the period of greatest fluctuations in flow and water temperature. The greatest extremes took place above the dam. The population above the dam fell to a much lower point during the period of minimum production than did the population below the dam. Caddisfly larvae (45.1%); mayfly larvae (25.8%); stonefly larvae (10.4%) formed 81.3% of the total number of organisms taken. Mayfly larvae showed remarkable resistance to the floods and lower temperatures above the dam and were taken in greater numbers in this area. The caddisfly larvae accounted for most of the increased faunal production below the dam. Numbers and weights of animals from the riffle areas greatly exceeded the numbers and weights from the pool areas. The percolation dam (to stabilize water flow) on Stevens Creek seems to have had a beneficial effect in increasing the fauna of the stream bottom.

Buck, Homer, and Frank Cross
1952. Early limnological and fish population conditions of Canton Reservoir, Oklahoma, and fishery management recommendations.
Rept. Oklahoma Fish and Game Council. Reproduced by the Research Foundation, Oklahoma A. and M. Coll., 1952: 1-110.

Canton Reservoir is an impoundment of the North Canadian River. In January, 1949 the water level was raised gradually to 1,605 feet (5,400 surface acres).

With great rapidity the preimpoundment species of fish were able to populate the reservoir. These were: white crappie, largemouth bass, bluegill, and green sunfish. Rough fishes also increased rapidly in numbers and forage fishes were abundant in the earliest stages of impoundment. It was proposed that a 2-year cycle of rising and receding water levels be instituted, starting drawdown in May or June. This level was to be maintained until the following spring, then only a moderate rise was to be allowed until after a vegetative cover had developed on the exposed area. In the second year, beginning in July, the water level was to be raised as high as inflow and flood control limitations would permit, retaining this high level until the following spring. It was predicted that these measures would: reduce spawning, increase predation, and facilitate the harvest of fish in the diminished lake volume. Refilling the lake the next summer would enhance spawning and survival to offset the lack of reproduction in the preceding year. The end product should be a population dominated by 1- and 3-year-old individuals.

Buscemi, Phillip A.
1961. Ecology of the bottom fauna of Parvin Lake, Colorado.
Trans. Amer. Microscop. Soc., 80(3): 267-307.

Parvin Lake was created in 1927 by building two earthen dams across the South Fork of Lone Pine Creek. Annual water fluctuation is never more than 60 cm; inflow and outflow are continuous throughout the year. Bottom contour is that of the original stream bed--a gradual slope from the shallow southwest bay to the deep northeast portion where the dams are located. The dimensions of the impoundment are: length--760 m, width--400 m, area--20.75 ha., maximum depth--11.1 m, mean depth--4.4 m, developed shoreline--2.01 m, length of shoreline (includes island shoreline)--3,252 m. Elodea canadensis was introduced in the 1920's and in 1955 massive amounts of Elodea inhibited water circulation, and the shading effect greatly reduced photosynthesis in the water below these plants. It also caused a serious oxygen depletion in near-bottom water in summer. Windblown masses carried many macroscopic invertebrates into the deep water in September, resulting in a spotty distribution of the fauna in sublittoral and profundal zones. The animals present were: Hydra pseudoligactus, Lumbriculus inconstans, Hyalella azteca, caddisfly larvae, Chironomous larvae, Glyptotendipes, Tanytarsus, Hydrobaenus larvae, Calopsectra spp., and Pisidium, which is very susceptible to oxygen depletion. The mean 11-month standing crop, 99.8 kg. per ha. dry weight (roughly 582 kg. per ha. wet weight), is considerably higher than published estimates for Mendota, Weber, and certain other North American and north German lakes.

Byrd, I. B., and D. D. Moss
1955. The production and management of Alabama's state-owned public fishing lakes.
Trans. Amer. Fish. Soc., 85: 208-216.

Alabama has 11 managed lakes constructed by the State Department of Conservation to provide fishing in areas lacking sufficient fishing waters. They contain a total of

591 acres that have been open to fishing for 2 to 5 years. The sites were carefully selected and efforts were made to eliminate all native fish from the streams, ponds, and pot-holes prior to stocking with bluegill and largemouth bass. To keep these lakes in balance and producing high annual yields of fish, it was necessary to employ various management techniques, including fertilization, fish-population control, corrective restocking, and control of aquatic weeds and algae. These lakes provided an annual average of 189 fisherman-trips per acre and an annual average catch of 642 fish weighing 180.9 pounds per acre. The average catch per fisherman-trip was 3.4 fish weighing 0.96 pound.

Campbell, Robert S., and John L. Funk
1953. The Black River Basin in Missouri.
In The Black River Studies I, p. 11-21. Univ. Missouri Studies, 26(2): 1-136.

Clearwater Lake is a flood-control impoundment on the Black River in Missouri. It was filled during June 1948. At conservation-pool level the reservoir has a surface area of 1,650 acres. During the period of spring rainfall, water levels as much as 40 feet above the conservation-pool level may exist for several weeks. The reservoir is shallow so that only a very limited area is sufficiently deep at conservation-pool level to fall within 50-foot contours. Summer turbidity readings were less than 7 ppm in the headwaters and ranged from 16 to 24 ppm on the alluvial plain reaches. Net plankton showed a predominance of phytoplankton. Net plankton did not exceed 80 organisms per liter in summer samples.

Carlander, Kenneth D.
1955. The standing crop of fish in lakes.
J. Fish. Res. Bd. Canada, 12(4): 543-570.

To determine whether certain environmental factors may affect standing crop, an analysis was made, primarily by regression methods, of the published estimates of standing crops of fish in lakes and ponds. Standing crop estimates derived by draining and those by poisoning appear to be equally accurate, but marking and recovery estimates may not be directly comparable with the other two. Average standing crops in river backwaters and oxbows were almost 500 pounds per acre; in midwestern reservoirs, almost 400 pounds per acre; in other reservoirs and ponds, 200 to 300; in warm-water lakes, 125 to 150; and in trout lakes, less than 50 pounds per acre.

[Summary] Analysis of the standing crop estimates indicate:
1. No correlation between area of a body of water and the weight of the fish crop per acre.
2. A negative regression of standing crop per acre on the maximum depth of the body of water.
3. A positive correlation between carbonate content of the water and the standing crop of fish per acre.
4. Greater standing crops for species with short food chains than for species with predatory food habits.

5. An increase in the standing crop of a body of water as the number of species of fish increases, but maximum crops of selected species in lakes or ponds with not more than one other species.
6. Tendencies for some species to have smaller standing crops in the presence of certain other species (competition) and larger standing crops in the presence of other species (protocooperation).

Clark, John D., et al.
1938. Chemical and biological studies of the waters of Elephant Butte Reservoir as related to fish culture.
Univ. New Mexico, Bull. No. 330, Chem. Ser., 2(6): 1-39.

Elephant Butte Reservoir impounds the entire flow of the Rio Grande River. When full it extends a little over 40 miles and has an area of over 39,000 acres. When the reservoir is full extensive shallows exist at the north end; at the south end the shores are precipitous. The fish include: largemouth bass, white crappie, yellow perch, blue catfish, yellow catfish, channel catfish, bluegill, gizzard shad, carp, smallmouth buffalo, carp sucker and Gambusia. Salmon trout were planted--none has been seen since the first year. The upper layers of water have oxygen at all times but the lower layers in late summer and fall have too little oxygen to support fish. At times of flood, the amount of silt added to the reservoir has been enormous. Suspended silt not only interferes with the production of plankton but limits the range of some of the better species of fish and interferes with their spawning. The reservoir also has the disadvantages of scarcity of shore and shoal vegetation, low quantity of plankton, and a scarcity of bottom-living organisms.

Clark, Robert N.
1948. Bacteriological studies of Fort Loudon Reservoir.
Amer. J. Publ. Health, 38(3): 342-350.

This study was undertaken to determine the density of coliform organisms and suitability of various parts of the reservoir for bathing. Fort Loudon Reservoir is a TVA reservoir on the main channel of the Tennessee River. The Tennessee River is formed by the confluence of the Holston and French Broad rivers, and there is a deep storage reservoir on each of these tributaries. These reservoirs provide storage capacity enough to protect the streams below the dams from the effects of upstream pollution. During the summer when surface temperatures in Fort Loudon Reservoir are comparatively high, the denser cold water flows along the bottom, leaving the surface stream relatively undisturbed. During the period from May through July, the temperature difference between the epilimnion and the hypolimnion remained fairly constant at about 8 C. In August the difference dropped to about 2 C, and there was a definite tendency in the stratified section for coliform densities at the surface to exceed average values during the latter part of August and September. It is believed that the lower temperature differentials, which reduce the sharpness of stratification, were responsible for most of the observed tendency. As factors vary, the relatively unpolluted epilimnion may expand, contract, or disappear altogether. It is estimated that with the temperature differentials prevailing during the summer, the epilimnion will be completely eliminated by discharges in May through July of 28,000 c.f.s. and in August of 24,000 c.f.s., and in September of 17,000 c.f.s.

Cook, Arthur H., and Charles F. Powers
1958. Early biochemical changes in the soils and water of artificially created marshes in New York.
New York Fish and Game J., 5(1): 9-65.

Marsh soils tend to accumulate and become richer in plant nutrients than the surrounding uplands. Analyses of soil samples following flooding suggest that substantial amounts of nutrient salts were lost from bottom muds, presumably by going into solution above the mud-water interface. In such cases, except for the portion removed by vertical and horizontal water movement, the loss would be represented by the total amount in the water. This, in turn, would be that in solution, in suspension, incorporated into living tissue, and adsorbed on colloids dispersed throughout the water column. Thus, rapid removal of water (i.e., drainage) would carry with it much of its total load of nutrient salts. It was found that when drainage took place in summer, the magnitude of the change in essential elements was much greater than when drainage occurred just prior to ice formation. Oxygen demands for the first year after flooding were found to be much higher than those for the second. This is to be expected as much organic matter submerged at flooding uses up much of the available oxygen. This is no time to plant fish. Drainage to assist in establishing a balance of nutrient salts must be complete--the water must be removed from over the soil.

Cooper, Gerald P.
1960. Fish productivity of lakes and streams in the midwest.
Midwest Wildl. Conf., Toronto, Dec. 5, 1960 (not published)

"There is a great range in fish productivity of lakes and streams in the Midwest, and productivity is affected by a variety of factors: the character of soils, the rainfall-runoff ratio as it affects the accumulation of nutrient salts, morphometry of lakes and streams as it affects biological productivity, geographical location as it affects mean temperature and rainfall, distribution of fish species in relation to ecological conditions, and competition among fish species. Further, fish production in terms of angler harvest depends on fishing pressure, on standing crop exclusive of rough fish, and on the proportion of standing crop made up by species most desired by anglers.

"Present fish-management practices in the Midwest are concerned mostly with: (1) planting preferred species, (2) eliminating undesirable species, (3) thinning populations of stunted pan fish, (4) partial control of rough fish, (5) retaining a few restrictive regulations on some of the preferred and highly exploitable species such as trout and pike, (6) liberalizing regulations on pan fish, and (7) creating new fishing waters."

Cooper, G. P., and K. G. Fukano
1954. Fishing values in impoundments, with special reference to shallow-water flooding projects.
Mich. Dept. Conservation, Inst. Fish. Res., Rept. No. 1420.

Impoundments	Average catch per hour	Average catch per hour in non-trout lakes, by Region	
Michigamme	0.50		
Peavy	0.67	Region I	0.91
Seney	0.35		
Fletcher	0.50		
Reedsburg	0.61	Region II	1.15
Haymarsh	3.78		
Pontiac	1.77	Region III	1.56

Fishing quality in terms of catch per hour in the three large power-project impoundments (Michigamme, Peavy, and Fletcher) has been poorer, on the average, then for all non-trout lakes in the respective regions. In the four, smaller flooding projects (Seney, Reedsburg, Haymarsh and Pontiac), fishing quality has varied from much poorer (Seney and Reedsburg) to better (Pontiac) and much better (Haymarsh) than in non-trout lakes generally. An important factor also to be considered is the species composition of the catch. In Fletcher the catch has been mostly northern pike, and in Seney it has been almost entirely that species. Since pike taken by anglers are considerably larger, on the average, than fish caught in non-trout lakes generally (the latter being predominantly pan fish), the poundage of fish taken from Fletcher and Seney by anglers would compare more favorably (than indicated by the catch-per-hour figures) with the poundage taken from all non-trout lakes.

Generally impoundments tend to be more favorable habitats for certain game species (especially for the northern pike and to some extent for the black crappie) and less favorable for certain other game species (especially the bluegill) as compared to natural lakes, and this difference has to be taken into consideration in any evaluation of fishing in impoundments as compared to natural lakes.

Dendy, Jack S.
1948. Predicting the depth distribution of fish in three TVA storage-type reservoirs.
Trans. Amer. Fish. Soc., 75: 65-71.

Depths at which largemouth bass, walleye and sauger were most abundant in Norris, Douglas, and Cherokee reservoirs were predicted on a weekly or bi-weekly basis during the summer of 1946. Netting records showed two things of importance to depth distribution: first, that in the presence of an adequate supply of dissolved oxygen the depth distribution of fish was related to thermal stratification; second, that the oxygen requirements of some species, notably sauger, are low--1.5 ppm or less in cool water (60-65 F). In early spring as well as in summer the water temperature is closely related to the quality of fishing. Because thermal stratification and the supply of dissolved oxygen differ in different impoundments, fish distribution could not be expected to be similar in any two impoundments.

Dugdale, Vera A., and Richard C. Dugdale

1962. Nitrogen metabolism in lakes. II. Role of nitrogen fixation in Sanctuary Lake, Pennsylvania.
Limnol. Oceanogr., 7(2): 170-177.

Abstract (Authors)
"A study of the rates of nitrogen fixation using N^{15} as a tracer was made in Sanctuary Lake, Pennsylvania. The rates of fixation in the lake were found to be considerable during the summer and appeared to be correlated with a dense population of Anabaena. Laboratory experiments supported the idea that photosynthetic organisms were responsible since a strong correlation with light was found."

From the discussion. "It is not possible to distinguish between direct utilization of the $N_2{}^{15}$ by algae and the nonphotosynthetic use of the carbon fixed by algae by nitrogen-fixing bacteria."

"It might be profitable to speculate on the conditions in Sanctuary Lake which support such an actively fixing population. Sewage from the town of Linesville entering the lake via Linesville Creek is undoubtedly important. . . The entering water carries a widely fluctuating but always considerable amount of soluble phosphate. The phosphate level in the lake itself is consistently low during the summer remaining around 10 $\mu g/l$, rising during the low Anabaena period, dropping again and finally rising rapidly in the fall. Nitrogen, however, is rapidly depleted from the lake water in the spring to a rather low level and then is apparently produced by the nitrogen fixing activity during the summer months. These facts in themselves do not reveal a definite causal relationship."

Eaking, H. M. (1936)
1939. Silting of reservoirs. (Rev., by Carl B. Brown, of the 1936 Bulletin)
U. S. Dept. Agr., Tech. Bull. No. 524, 168 p.

Silting of reservoirs is a practical problem of the first order of magnitude. The high rates of silting depend upon man-induced erosion and the general prevalence of these conditions over broad areas of the country. It is not unknown for clear waters which have deposited their load of silt in the reservoir to be wasted over the spillway, thus making room at the bottom for a new body of muddy water. The main reliance for permanent and material conservation of reservoir resources must rest upon control of sediment production at primary sources through widespread and effective application of established methods of erosion control.

Edmondson, W. T.
1956. The relation of photosynthesis by phytoplankton to light in lakes. Ecology, 37: 161-174.

It was noticed in limnological observations made on Base Lake, Kodiak Island that the rate of photosynthesis by natural populations of phytoplankton was frequently lower at the surface than at 3 meters depth, especially during periods of bright sunshine, even on occasions when the phytoplankton population was uniformly distributed. Such observations have been made on other lakes as well and are interpretable on the basis that the saturation intensity of light for photosynthesis by a number of algae is quite low relative to the intensity of full sunlight. Moreover actual inhibition due to photo-inactivation of the photosynthetic mechanism may take place in bright light (Rabinowitch). The inhibition is important in connection with studies of the productivity of lakes. Within a lake, the vertical variation in potential rate will be largely determined by the surface intensity of light and transparency of water. Variations in distribution of populations, nutrients and temperature will modify the basic pattern. An additional factor is the effect of stratification. If the epilimnion is thicker than a certain critical depth, the phytoplankton will be unable to grow. It is obvious that even with the most favorable natural media and temperatures, photosynthesis will not proceed without light and too much light will be inhibitory.

Eggler, W. A., and W. G. Moore
1961. The vegetation of Lake Chicot, Louisiana after eighteen years of impoundment. Southwestern Naturalist, 6(3-4): 175-183.

Lake Chicot, in Evangeline Parish, Louisiana, was formed in 1943 when a dam across Chicot Bayou was closed and the water allowed to rise flooding an area of 2,000 acres. At spillway level the lake averages about 7 feet in depth, with a typical channel depth in the old bayou of about 11 feet. The original vegetation was cypress-tupelo gum swamp bordered by upland hardwood forest. In 1943 bald cypress was the most abundant tree in deeper water and it still is. However, the mortality rate, which was only 3% during the first 4 years, has been 50% in the past 18 years. Most cypress trees have dead tops. Tupelo gum had a higher rate of mortality, only 28% have survived to the present. Most button bush died during the first 4 years, though water elm survived quite well during that period. Both died in deeper water. Some herbaceous aquatics have been introduced and are causing problems increasingly serious. Drawdown of the lake level has not solved the aquatic weed problem. The drawdown of August 1957 resulted in a heavy fish kill.

Ellis, M. M.
1936. Erosion silt as a factor in aquatic environments. Ecology, 17(1): 29-42.

"In various of the deeper power dam lakes, created by impounding rivers, as Lake Wilson, Tennessee River, and Lake of the Ozarks, Osage River, a very definite stratification of the erosion silt load was observed. In these river lakes stream flow and depth are such that during the summer months there is a definite thermal stratification of the water, with a well defined thermocline. In Lake Wilson during July and August extending from the surface to approximately the 18-meter level there is an upper mass of water in which the temperature declines gradually as the depth increases. This mass of water, the hyperlimnorrheum, flows steadily downstream. Below the hyperlimnorrheum is a second mass of water between the 18th and 21st meter levels, a true thermocline in which the temperature of the water drops abruptly. The water in the thermoclinal zone does not flow appreciably. A third mass of water extends below the thermocline, i.e. from approximately the 21st meter level to the bottom of the lake. This mass of water is quiet during the summer and is a true hypolimnion. A set of m.i.d. determinations at station 385 in Lake Wilson on August, 24, 1931, will suffice to show the vertical distribution of silt in these three masses of water. The surface m.i.d. on that day was 1,147 mm. It decreased progressively to 1,070 at the 15 meter level, and rose to 1,127 mm at the 18 meter level, the bottom of the hyperlimnorrheum. At the 21st meter level, the lower limit of the thermocline, the water had cleared so that the m.i.d. was 4,143 mm and from the 24th meter level to the bottom, 33 meters, the water was sparklingly clear with a m.i.d. of 7,860 mm. The abrupt change in water temperature and correlated change in water viscosity in the thermocline produced this stratification, so that during the warm summer months in several of these deep, power dam lakes the writer has found a warm muddy river, the hyperlimnorrheum, flowing over a cold, clear lake, the hypolimnion, with very little mixing in the thermocline."

From author's summary. Erosion silt: (1) alters aquatic environments, chiefly by screening out light, by changing heat radiation by delaying heating and cooling, by blanketing the stream bottom, and by retaining organic materials and other substances which create unfavorable conditions at the bottom; (2) in river water silt acts chiefly as an opaque screen to all wave lengths of visible light, but in very muddy waters a small differential was found favoring the transmission of scarlet-orange light; (3) it alters the rate of temperature change in river waters. This is particularly significant in deep river lakes [see above]; (4) the amount of organic material carried to the bottom with erosion silt ranged from 8 to 12% of the dry weight of the mud on the bottom of Lake Pepin and Lake Keokuk.

Ellis, M. M.
1937. Some fishery problems in impounded waters.
Trans. Amer. Fish. Soc., 66: 63-75.

Undisturbed natural lakes present a reasonably stable, predictable and aged environment in which adjusted aquatic faunae thrive year after year. Impounded waters are characterized by conditions which often vary abruptly and over wide ranges; no biological adjustment on the part of fishes and other aquatic species is possible to some of these changes; the environment of impounded waters is new and unstable as compared to natural lakes. In fact, changes of catastrophic magnitude as far as the aquatic organisms are concerned occur at irregular intervals and often with effects disastrous to the aquatic fauna. Most natural lakes have a bowl-shaped basin with inlet and outlet. The characteristic feature of the impoundment is the dam, back of which is a body of water roughly in the shape of a right-triangle wedge with its base resting against the dam. This zone of deep, slack water back of the dam accentuates many of the hazards to fish and bottom fauna attendant on stream pollution, organic detritus, oxygen deficiency and other deleterious factors. Fixed nitrogen is necessary for protein formation in living things except certain bacteria. In the case of impounded waters nitrogen is lost to the air as ammonia, and in escaping waters leaving the lake, as well as being removed in the bodies of fish caught. As the supply of leachable materials in submerged detritus is exhausted, impounded waters tend to balance at a lower level of productivity and this aging process is very rapid.

Ellis, M. M.
1940. Water conditions affecting aquatic life in Elephant Butte Reservoir.
U. S. Dept. Int., Bur. Fish., Bull. 49, No. 34: 257-304.

The annual temperature cycle for Elephant Butte Reservoir has a gamut of approximately 20 C for the surface and 12 for the outflow water from the bottom. The maximum surface temperature is 28 C, sometimes 33 C in the 3-foot shallows. The minimum for both surface and bottom waters is about 8 C. Oxygen varies from above 6 ppm at the surface to less than 0.3 ppm at the bottom. The pH varies from 8.6 to 7.4 in summer. Calcium has a range of 126-282 ppm; sulphates, 109-209 ppm; chlorides, 20-33 ppm; fluorides, 0.6-1.2 ppm (this amount may be harmful to some fish); low content of ammonia and low total nitrogen, consequently only a small amount of nitrogen is available for the production of food organisms for fish. Silt is deposited at the rate of 18,260 acre-feet per year. The fish are all warm-water species: catfish, suckers, carp, *Gambusia*, white crappie, largemouth bass, yellow perch. A combination of uncertain water levels and the arid climate almost inhibits natural development of shore vegetation, and this restricts habitats for spawning and young fish. The ammonia content of these waters is almost negligible and the total and non-protein nitrogen are both very low, which condition, together with a low phosphate content, indicates conditions unfavorable to the production of plankton. Chemical tests revealed combinations of electrolytes unfavorable to the growth of plankton. Bottom fauna is very sparse because of pH, turbidity and low dissolved oxygen in summer.

Ellis, M. M.
1942. Fresh-water impoundments.
Trans. Amer. Fish. Soc., 71: 80-93.

Conditions in impoundments that can reduce or limit biological productivity are: stagnation of large masses of water; removal of food materials in the waters drawn out of the reservoir; limited natural lateral areas of shallow water around the margins of the lake; extensive fluctuation of water level; continued and often heavy silting of the bottom.

These limitations of impounded waters for fish production may in part be offset by: controlling the draw-off (where such regulation is compatible with the major interests for which the impoundment has been created) so that a fairly constant water level will be maintained during the nesting season of the desirable species of fish; judicious stocking, not overstocking; construction, where feasible, of lateral areas of shallow water of constant level and tributary to the main impoundment, where adult fish can nest, young fish find refuge, and fish food can be produced; floating nests, floating shelters; artificial enrichment of soil and water with specific substances, such as phosphates.

Ellis, M. M.
1944. Water purity standards for fresh-water fishes.
U. S. Fish Wildl. Serv., Spec. Sci. Rept. No. 2: 1-16.

Extensive field and laboratory studies of the fresh-water streams of the United States show that general water conditions favorable to, not merely sublethal for, mixed faunae of game and food fishes of the "warm-water" types and supporting organisms, present a complex defined by: (1) dissolved oxygen not less than 5 ppm; (2) pH range between 7.0 and 8.5; (3) ionizable salts as indicated by a conductivity between 150 and 500 mho x 10^{-6} at 25 C and in general not exceeding 1,000 mho x 10^{-6} at 25 C; ammonia not exceeding 1.5 ppm; suspensoids of a hardness of 1 or greater, so finely divided that they will pass through a 1,000-mesh (to the inch) screen, and so diluted that the resultant turbidity would not reduce the millionth intensity depth for light penetration to less than 5 meters. If such favorable conditions for fishes are to be maintained, all pollutants not readily oxidizable or removable by the stream should be excluded, including particularly all cellulose pulps, wastes carrying heavy metallic ions and gas factory effluents. Other types of wastes should be diluted to concentrations nontoxic to aquatic life of the particular stream.

Eschmeyer, R. W., and Alden M. Jones
1941. The growth of game fishes in Norris Reservoir during the first five years of impoundment.
N. Amer. Wildl. Conf. Trans., 6: 222-240.

The average rate of growth was determined for six species of game fishes for Norris Reservoir for several years. By the fourth and fifth years of impoundment (1939-1940) the trend in the rate of growth of all six species was still rapid compared with the growth in other waters for which information was available.

Eschmeyer, R. William, and Clarence M. Tarzwell
1941. An analysis of fishing in the TVA impoundments during 1939.
J. Wildl. Mgmt., 5(1): 15-41.

The catch differed decidedly in the waters under consideration. In the storage reservoirs and the tailwaters game fishes predominated, but in the run-of-the-river reservoir pan fishes outnumbered the game fishes. The data suggest that the sauger is the most important species in the tailwater of a relatively new dam, and that in time this fish is replaced by the white bass. Species that are common in the tailwater below a dam are not common in the reservoir proper, and vice versa. The creel census suggests that storage reservoirs should be closed to all fishing during the spawning season, but that on the run-of-the-river reservoirs year-round fishing should be permitted for most of the species.

Note by G. G. H. In 1944 and 1945 the closed season was discontinued for most TVA impoundments as a result of certain findings: (1) Norris Reservoir was well supplied with bass and other game fish. (2) Only a small percentage of these fish was being harvested. (3) Even though the fishing season was open for two consecutive seasons when spawning was at its height, a good crop of young game fish nevertheless resulted.

Eschmeyer, R. W.
1949. The fisheries picture with special reference to the TVA impoundments. Part II.
Wildlife in Carolina, 13(3): 17-20. (Reprinted in Prog. Fish-Cult., 11(4): 267-271)

"Though contrary to all expectation the winter drawdown for flood control appears to be advantageous to game fish. It apparently does not interfere with their reproduction and survival. It does, however, interfere with the well-being of rough fish." This is thought to be so because the carp, buffalo and adult shad are bottom feeders, and the drawdown limited the food available to them.

Finnell, Joe C.
1955. Dissolved oxygen and temperature profiles in Tenkiller Reservoir and tailwaters with consideration of these waters as a possible habitat for rainbow trout.
Oklahoma Acad. Sci, 34: 65-72 (1953)

The building and filling of Tenkiller Reservoir had a marked effect upon the temperatures of the Illinois River below the dam for a distance of 7 miles. Temperatures before impoundment varied from 72-89 F, with an average of 81.5 F. Average temperature at the same station during this study was 73.8 F with a range of 66.8-80.0 F. Adult rainbow were stocked in the winter of 1952-53. Reproduction is unlikely to occur.

Finnell, Joe C.
1956. Comparison of growth-rates of fishes in Stringtown Sub-Prison Lake prior to and three years after draining and restocking.
Oklahoma Acad. Sci., 35(1954): 30-36.

"Sub-Prison Lake is a 60 surface-acre body of water located on the Stringtown state game refuge, Atoka County, Oklahoma. It is formed by the impoundment of a small intermittent tributary of North Boggy Creek and has a drainage area of approximately 1,500 acres. . . Thermostratification is well established during the summer months."

In December, 1950, the lake was partially drained and the remaining 10 acres treated with rotenone to remove the entire population of fish as they were stunted. Restocking was done a year later, largemouth bass, channel catfish, black crappie, redear sunfish. 1954 growth-rate studies showed that the fish population had been converted from an overpopulated, stunted condition to one of accelerated growth commonly associated with new impoundments. Although only four species were replanted the presence of eleven well-established species 3 years later demonstrates the fecundity of the few individuals which either survived poisoning or entered the lake from some unknown source. Of the stocked fish, 1 year old at the time of stocking, only black crappie showed evidence of having spawned in the spring of 1952. Largemouth bass and redear sunfish spawned in 1953. Fishing success has not improved in proportion to the improvement in fish growth. High turbidity has curtailed angling efforts of all types. Unless a greater harvest is realized, reduced growth and a return to the stunted, over-populated condition of 1950 seems inevitable within the next 2 or 3 years.

Goldman, C. R., and R. G. Wetzel
1963. A study of the primary productivity of Clear Lake, Lake County, California.
Ecology, 44(2): 283-294.

Clear Lake is 40,000 acres in area; 19 miles long, formed by lava flow damming Cache Creek, and by a subsequent landslide. It is now markedly eutrophic, with an average depth of only about 6.5 m. Control of huge swarms of midges was attempted by application of DDT resulting in its accumulation in the food chain at higher trophic levels. Many grebes died as a result. This is a study of fertility using the rate of carbon fixation at the level of primary producers as the best available assessment of the actual fertility of a lake.

Findings:

(1) High lake temperature. Thermal stratification is frequent and short-lived. Because of low transparency, primary production is almost entirely limited to the phytoplankton and bacteria.

(2) Primary productivity values are typically bimodal: low in winter and early spring, exhibit a small peak in spring. In summer productivity increased progressively to a large autumn maximum before the rapid winter decline. Seasonal fluctuation in productivity appears to be correlated not only with light and temperature but also with turbidity.

(3) Seasonal fluctuations in alkalinity and pH showed a positive correlation with productivity measurements and an inverse relationship to turbidity and rainfall.
(4) Annual mean primary productivity was 0.44 g C/m^2/day ranging from 0.002 in February to 2.44 g C/m^2/day in October.
(5) In summer and fall most of the carbon fixation in the surface layers was by plankton of a size greater than 5-10 μ. In the deeper strata the ultra plankton contributed a larger proportion of the productivity. During winter and spring the productivity of the smaller forms dominated at all levels.

Hall, Gordon E., and William C. Latta
1952. Pre- and post-impoundment fish population in the stilling basin below Wister Dam.
Proc. Oklahoma Acad. Sci., 32(1951): 14-19.

To reduce erosion, the water flowing from some Oklahoma impoundments is slowed down in concrete stilling basins. Fish were studied in the stilling basin below Wister Dam before and after impoundment. When pre- and post-impoundment populations were compared certain differences were evident. The total number of fish taken was decidedly greater in 1951 than in 1949. But the total weight of the catch was 400 pounds less than in 1949. This was accounted for in part by the much smaller average size of the coarse species (carp and buffalo) and by the appearance of large numbers of small game fish and pan fish in the 1951 sample. Largemouth bass, white and black crappie, and black bullhead were absent in the 1949 collection, but in the post-impoundment sampling these species were numerous. Planting of large numbers of largemouth bass in Wister Reservoir in 1950 would account for their presence in the basin. Periodic sampling of the fishes of the reservoir during the first 2 years of impoundment produced evidence of very successful reproduction of crappies and black bullhead during that time. These findings show that the fish population of these waters is progressing from that native to the river to one more commonly associated with Oklahoma impoundments.

Harris, Benjamin B., and J. K. Gwynn Silvey
1940. Limnological investigation on Texas reservoir lakes.
Ecological Monographs, 10: 111-143.

The authors concluded that biological productivity of an artificial lake seems to be as individually variable as that of a natural lake. It appears that age is only one of the factors governing the productivity of an artificial lake--aging in years is not coincident with "aging geologically." The older lakes appear to be as productive limnologically as those of more recent construction, and in some cases more productive. An artificial lake which may seem to support ample net plankton for the sustenance of fish is often less productive than one that yields very few net plankton.

Lake Worth has the greatest silting of the lakes studied but vegetation does not seem to have been hampered. In deeper lakes silting may be beneficial in cutting out profundal zones and making the entire basin littoral and sublittoral--this has been accomplished in Lake Dallas and Lake Worth. In artificial lakes with a large watershed, much of the silting is not produced by soil but by animal and plant remains which upon decay give up the space they occupy and might contribute to the fertility of the lake if they are not too abundant.

Hartman, George F.
1949. Management of central Wisconsin flowages.
Wisconsin Conservation Bull., 14(4): 19-22.

These flowages varied from 10 to 1,000 acres; were shallow, 18 inches to 5 feet. Wild rice and other plants which provide good waterfowl food were planted. Wild rice showed promise in larger impoundments with better water and soil conditions, but it died out in a few years. It was observed that the best duck ponds were those in which the water level fluctuated most. Ducks fed on smartweed, where a drop of water levels in summer months permitted the growth of these plants.

Hartman, R. T., and J. H. Graffius
1960. Quantitative seasonal changes in the phytoplankton communities of Pymatuning Reservoir.
Ecology, 41(2): 333-340.

This reservoir is highly productive, and composed of three ecologically distinct lakes. Sanctuary Lake which is studied here is the most productive.

The lake has two distinct drainage areas: an extensive swamp which contributes decomposition products from decaying vegetation, and Linesville Creek which drains agricultural and wooded areas and contains silt and also raw sewage from the town of Linesville (pop. 1,246).

Extensive deposits of organic muck, which accumulated when the area was a vast bog and swamp forest, are present. Silting is occurring rapidly; eutrophication is promoted by organic pollution from Linesville Creek.

Summer communities of phytoplankton were dominated by blue-green algae, colonial Cyanophyta. Spring and summer communities were dominated by green algae, Chlorophyta. Winter communities were made up of combinations of Diatomaceae and Chlorophyta.

Hartman, Richard T., and Craig L. Himes
1961. Phytoplankton from Pymatuning Reservoir in down-stream areas of the Shenango River.
Ecology, 42(1): 180-183.

This is a study of the changes in quantity and species composition of phytoplankton from Pymatuning Reservoir as it moved about 10 miles down the Shenango River.

Findings:

1. The phytoplankton of the upper Shenango River is typical of that found in Pymatuning Reservoir.
2. An average decrease of 72.6% in numbers of cells was found between the reservoir and the last collecting station (10.57 miles downstream).
3. The proportion of diatoms in the community generally increased downstream.
4. Rapid current and high silt content of the river were considered important factors in the decrease in numbers of organisms.

The indication is that productive impoundments may greatly affect conditions in rivers for considerable distances below the impoundment. High phytoplankton populations and their accompanying biological, chemical and physical effects create new problems for water plant operators, public health officials, sanitary engineers, and all who are concerned with the use of such waters. There is need for appraisal and consideration of the creation of such conditions when planning for construction of new impoundments.

Hasler, Arthur D.
1947. Eutrophication of lakes by domestic drainage.
Ecology, 28(4): 383-395.

Enrichment of water, be it intentional or unintentional, is called eutrophication. Examples in this paper are drawn from lakes in Europe and the United States. The Zürichsee, an alpine, once oligotrophic lake in Switzerland is discussed in detail, showing how it has changed in a relatively short period of time from a whitefish lake to a coarse fish lake as a result of continued pollution by domestic sewage. Another example used is Lake Växjo, Sweden, which is described as follows: "Their waters have lost their color and sparkle; they seem to be filled with a thick green cyanophycean soup." Lundquist (1926, 1927), with the aid of exacting methods of sediment and microfossil analysis, investigated the history of Swedish lakes as recorded by their bottom deposits. In typically oligotrophic regions eutrophication set in as early as the Bronze Age, followed by intensification in those levels which correspond to the Iron Age. However, these may be merely changes due to normal lake development, as the causal connection between eutrophication and these early cultures remains unproved. The extinction of a lake by way of eutrophication is probably hastened to a greater extent by organic sedimentation than by inorganic processes. Where there is a heavy flow of surface drainage from agricultural lands or especially from urban sewage, oligotrophy may change to strong eutrophy in the short period of a few decades. Fertilization of bodies of water by sewage and other materials finding their way into such waters causes an abnormal acceleration of a process (eutrophication) which is regarded as normal. Such acceleration has diverse effects, some of which are not for the best interests of man. The problem is especially serious because there is no way known at present for reversing the process. It may be assumed that most of those having an interest in a body of water desire to prolong its life as a lake over the longest period possible. But conflicts arise among the different groups of lake users, e.g.:

sightseers, anglers, hunters, citizens using the lake water for drinking, boating enthusiasts, bathers, and in the case of reservoir lakes, consumers of electricity and irrigation water. The majority is generally held to be the best judge of its own interest, but majority action should be tempered by the realization that certain policies, including many involved in lake management, are irrevocable, and cannot be withdrawn by legislation.

Hepher, B.
1962. Primary production in fish ponds and its application to fertilization experiments.
Limnol. Oceanogr., 7(2): 131-136.

Primary production was determined in fertilized and unfertilized fish ponds in Israel by the "light and dark bottle" oxygen method. In the unfertilized ponds in summer it was 138-190 $mgC/m^2/hr.$; in the fertilized ponds it was 4 to 5 times higher. There was a sharp decrease in production with depth and in most cases the compensation layer in the fertilized ponds was at a depth of only 40 cm. Chlorophyll a concentration was high reaching a maximum value of 212.3 mg/m^3 in the fertilized ponds. Production per unit of chlorophyll and its variations with season and fertilization is discussed. Fertilization of fish ponds with excessive amounts of fertilizers increases production in the upper layers of water where favorable light conditions exist, but decreases production in lower layers where over-shading by plankton causes decreased light penetration. The effect of excessive doses of fertilizers may thus cause a lowering of production per unit area.

Hoffman, Carl E., and David Causey
1952. Limnological studies in Arkansas. I. Physico-chemical and net plankton studies of Lake Fort Smith in its fourth year of impoundment.
Proc. Arkansas Acad. Sci., 5: 55-72.

Lake Fort Smith, an artificial lake in northwestern Arkansas, constructed by flooding a mountain valley, is subject to the inflow of large quantities of water following rapid heavy rainfall. It has a surface area of 525.5 acres, a volume of 525,598,000 cubic feet and a watershed of approximately 65 square miles. This investigation deals with the period from May 6 through June 12, 1950. In the 6 days prior to May 13, 5.3 inches of rain fell. This rainfall brought about the following physico-chemical changes in Lake Fort Smith: reduced transparency, increased turbidity down through the 12th meter, lowered water temperature, disturbed stratification, increased carbon dioxide content from surface to bottom, lowered pH in the upper 12 meters, lessened bicarbonate content, and reduced dissolved oxygen content in the upper meters. On May 13, after the heavy rainfall, the numbers of phytoplankton were reduced from the surface to the bottom. Zooplankters were concentrated in the 7 to 12 meter depths and reduced in the surface waters. Peritrichia were slightly more numerous than before the rain and in the period after May 13, and as the surface water cleared they reached their highest numbers for the year. In Lake Fort Smith, turbidity, precipitation, and dilution following heavy rainfall, appear to be major factors in the reduction of the phytoplankton.

Hooper, Frank F., Robert C. Ball, and Howard A. Tanner
1952. An experiment in the artificial circulation of a small Michigan lake. Trans. Amer. Fish. Soc., 82: 222-241.

From authors' abstract and discussion:
The water of the hypolimnion of West Lost Lake, a small Michigan trout lake, was pumped to the surface with a centrifugal pump and discharged into the epilimnion during a 10-day period in midsummer. The volume of water displaced was 20.7 percent of the lake volume. As pumping progressed the thermocline lowered steadily and the thickness of the hypolimnion decreased. At the conclusion of pumping, the volume of the epilimnion had increased by 49.9 percent and the water of the hypolimnion had been displaced to the surface. The mean water temperature of the lake remained essentially constant during the experiment. In a 3-week period following pumping, thermal conditions of the lake did not change appreciably. During pumping, conductivity and alkalinity increased in the epilimnion and in the bottom water, and the dissolved oxygen in the bottom water increased rapidly. The addition of bottom water increased the total phosphorus of the epilimnion by 2.8 micrograms per liter during the first 48 hours of pumping. Thereafter, phosphorus decreased to approximately the level encountered before pumping. An eight to tenfold increase in the volume of the phytoplankton of the epilimnion took place during the period of pumping. The volume of the phytoplankton and the weight of the seston remained high for a 3-week period following the experiment. The transitory increase in total phosphorus of the epilimnion, followed by a rapid return to the level encountered at the start of the experiment suggests that sedimentation and perhaps adsorption by bottom materials and littoral vegetation removed phosphorus from the system until it returned to an equilibrium value.

Hooper, F. F., et al.
1964. Status of lake and stream rehabilitation in the United States and Canada with recommendations for Michigan waters. Michigan Dept. Conservation, Inst. Fish. Res., Report 1688.

1. Lake rehabilitation cannot be considered a permanent or even a semi-permanent procedure. Evidence from Michigan and other states indicates that repopulation by undesirable species is relatively rapid. In lakes in which stunted pan fish had been eliminated, after a period of about three years, growth rate is again reduced to pre-treatment level. In Michigan the benefits of such a program have lasted for an average of 3.6 years. Trout lake rehabilitation is a sound management tool where angling pressure is moderate to heavy and where chances of contamination are low.
2. Trout stream rehabilitation should be undertaken only where fishing pressure is heavy and stringent precautions are taken to achieve a good kill and prevent recontamination.
3. Management of warm-water lakes might be attempted on an intensive basis, using all existing management techniques to provide a maximum angler yield. These might include artificial cropping, pike marsh management, fertilization, and maintenance plantings of species not reproducing in the lake.

Hutchinson, G. E.
1941. Limnological studies in Connecticut. IV. The mechanism of intermediary metabolism in stratified lakes.
Ecol. Monogr., 11: 21-60.

The fundamental problem considered in this paper is raised by the work of Juday and Birge (1931), who, unable to find clear evidence in a number of lakes of depletion of phosphate in the epilimnion during the summer stagnation, write "in some of the . . . lakes the quantity of soluble phosphate was maintained or was even increased somewhat during the growing season in spite of the fact that these bodies of water sustain a relatively large growth of phytoplankton." This suggests that our knowledge of the detailed movements of nutrients and other substances dissolved in the water of lakes is inadequate. Phases of stagnation: (1)The oxygen content of the water falls from the high values of the spring turnover to about 1 or 2 mg per liter; alkalinity starts rising as the oxygen falls; total phosphorus remains low, under 0.03 mg per liter; iron has not been determined but is probably low. (2)Oxygen content remains low, usually between 1 and 2 mg per liter; alkalinity continues to rise; phosphorus (under 0.03 mg. per liter) and iron (under 0.50 mg per liter) low, as in Phase 1; manganese may be high. (3)Oxygen content as in Phase 2 or slightly lower; alkalinity rising, but more slowly; phosphorus and iron rising, ultimately reaching values in excess of 0.10 mg per liter and 5.0 mg per liter, respectively. From the results of the study of temperature and turbulence, it is possible to determine what part of the observed rate of increase of bicarbonate is due to vertical mixing and what part to other water movements. The latter are of much greater importance than turbulent vertical mixing. The relationship observed between morphometry and the bicarbonate curve shows that such other water movements are primarily horizontal currents, but a consistent scheme emerges if the supposed density current mechanism is taken into account. Variations in the total phosphorus content of the whole lake are considerable and rapid. In the summer of 1937 the lake (Linsley Pond) gained an average of at least 1.09 kg of phosphorus per week, and lost on an average at least 0.98 kg per week, independent of gain or loss through inlets and outlet. The actual rate of replacement may be 4 to 9 times as great as this minimum estimate. Variations can occur at all depths and can only be interpreted in terms of horizontal water movements that carry phosphorus from the mud-water interface into the free water, and of continual sedimentation of the considerable fraction present as sestonic phosphorus. It is suggested that feces production by the zooplankton constitutes the chief sedimentary agency. Addition of a mixture of potassium phosphate and potassium nitrate to surface water suspended in a bottle leads to a great increase in the zooplankton over that in a control bottle. Addition of one or the other salt alone leads to a smaller increase sometimes greater in the nitrate bottle than in the phosphate and sometimes the reverse.

Hutchinson, G. E.
1944. Limnological studies in Connecticut. VII. A critical examination of the supposed relationship between phytoplankton periodicity and chemical changes in lake waters.
Ecology, 25(1): 3-26.

Considering only the total mass of phytoplankton, it is reasonably certain that the great increase usually observed in spring is due to increasing light intensity and increasing temperature at a time when the water is rich in nutrients. However when individual species comprising this mass of phytoplankton are considered, these are often found to replace one another as dominants with considerable rapidity, and the problem is seen to be more complex than a consideration of the total mass would suggest. The appearance of Dinobryon divergens in the spring in Linsley Pond is correlated with a rise in the ratio of nitrate to phosphate, but is independent of variations in soluble silicate. Pearsall found in the English lakes a further correlation with low silicate. In all cases the Dinobryon population seems to increase after the main components of the spring maximum have declined. Both the supposed chemical determinants of Dinobryon are probably symptoms of nutrient depletion by the dominant species of the main spring maximum. It is suggested that the major factor determining the incidence of Dinobryon maxima is the variation in the total population of other species, but the mechanism of this relation is obscure. There is no evidence that the appearance of Asterionella depends on the inorganic nutrient level. The appearance of Anabaena circinalis confirms Pearsall's contention that blue-green blooms, developing in late summer, arise when the inorganic nutrients are practically exhausted. There is evidence that in small eutrophic lakes all inorganic nutrients, except phosphorus and combined nitrogen are normally present in great excess. The analysis of the observations presented, considered in relation to the known properties of planktonic algae, suggests that in general clear-cut correlations between chemical conditions and qualitative composition of the phytoplankton are not to be expected, and that the physiological condition of the population and the relation to populations of other species are likely to explain many of the apparent inconsistencies observed when different seasons and different lakes are compared. (from the author's summary)

Jenkins, Robert M., and Edgar M. Leonard
1954. Initial effects of impoundment on the growth rate of channel catfish in two Oklahoma reservoirs.
Proc. Oklahoma Acad. Sci., 33(1952): 78-86.

Growth rate studies of fishes taken from several large Oklahoma reservoirs have shown that the most rapid growth occurs in the first 2 or 3 years of impoundment.

Tenkiller Reservoir. Catfish showed remarkably accelerated growth. They grew 1.2 inches more in length in 1951 after partial impoundment than they did in the river channel. On July 1, 1952 the outlet gates closed and the water level rose rapidly. By the first of August water covered many acres and extended upstream about 6 miles. Fish taken during this period had already completed as much growth as had been accomplished during the entire 1951 growing season.

Lake Wagoner. This is a detention reservoir and during 1951 there was a slight acceleration of the growth of catfish.

If the accelerated growth rates found in these two populations could be maintained, the big reservoirs might afford excellent catfish fishing for decades instead of the initial 5 to 6 years. No means have been devised to harvest the enormous numbers of fish which are produced in Oklahoma lakes.

Jenkins, Robert M.
1961. Reservoir fish management--progress and challenge.
Sport Fishing Inst., 1961: 1-22.

In the United States one-third of all inland lake water (or 13,000,000 acres) is in man-made impoundments. They provide 20% of all inland fishing trips. Ellis (1937) said that the high productivity of reservoirs in the early years is due to decay of flooded organic matter--such lakes being great hay-infusions. Bennett et al. (1947) disagreed and argued that the productivity of the impoundment does not decline but that the fish population gets out of hand. The idea that reservoirs are less fertile than natural lakes of the same size has been argued pro and con, as has the contention that reservoirs decline in productivity after a few years. Jenkins maintains that there is no proof that either claim is true, though he does agree that sport fishing does decline and thinks that the decline may be more a matter of population dynamics than a decline in the productivity of the lakes. He says that rough fish in reservoirs perhaps can be controlled by netting, chemicals and planned drawdowns.

Jenkins, Robert M.
1964. Reservoir fishery research strategy and tactics.
U. S. Fish Wildl. Serv., Cir. 196: 1-12.

Industrious beavers have been building dams and altering streams for thousands of years; as a result habitats change, some plants and animals are destroyed, new plants and animals capable of coping with the disrupted environment appear; and the inexorable eutrophication process begins. Obviously man is capable of far greater and more disruptive building feats, but the qualitative effect on the environment is no different."

"Research problems requiring attention include measurements of the effects, on fish production, of primary productivity, rate of water exchange, and water level fluctuations and withdrawal at different depths. Fertile fields of enquiry are the reproduction and early life history of principal fishes, species competition, and analyses of behavior. Intensive study of localized populations, supplemented by extensive examination of the dynamics of total reservoir fish populations, should provide new ecosystem concepts.

Johnson, M. W.
1949. Relation of plankton to hydrographic conditions in Sweetwater Lake. J. Amer. Water Works Assoc., 41: 347-356.

Sweetwater Lake in southern California is a narrow artificial body of water 2 miles long and approximately 10 miles inland, where it is exposed to sea breezes so important to its dynamics. It has marked thermal stratification developed through surface heating and develops the well known summer stagnation common to many deep lakes. This stagnation reaches a maximum during August and in 1944 was confined to depths below approximately 20 feet. Good circulation is maintained in the epilimnion. The vertical position and fluctuations in the heaviest concentrations of plankton are important in determining the level from which water should be drawn from a reservoir for domestic use. The studies made on this lake in the summer of 1944 indicate, as far as the plankton distribution was concerned, the best level from which to draw water would be relatively near the surface, and for depths of 10-15 feet, the clearest water would be obtained in the morning. The observations for July and August show how the maximum depth and abundance of the plankton at the sampling station situated just above the dam--and therefore near the intake--are correlated with the diurnal shift in depth of the thermocline and the direction of flow of the water. In July the vertical shift is clear for the copepods, rotifers and mites. The upward shift of these animals is approximately 2 feet, which corresponds with the upward shift of the top of the thermocline between 9:20 AM and 3:13 PM. There was also an afternoon increase in number of most organisms, and turbidity was likewise somewhat greater in the afternoon. During the summer period of strong thermal stratification there is a continual consumption of the mineral plant nutrients (nitrates and phosphates) by floating plants in the upper water layer. Gradually these nutrients are bound as organic substance in the bodies of plants, or of animals feeding on the plants and hence must be largely precipitated into the deeper water as dead bodies or fecal detritus where they are reduced by bacterial action to the mineral state. The nutrients regenerated at the bottom remain unused. Surface plants may have a supply of nutrients made available by horizontal transport from the shallower parts of the lake. There is also considerable evidence that phosphates and ammonia nitrogen are rapidly liberated from diatom and copepod plankton. As bacterial populations commonly exist together with the main plankton populations in free water above the thermocline some regeneration of nutrients doubtless takes place there. Nitrogen assimilation by some plants, including diatoms has been shown by several workers to be obtained from ammonia (NH_3) or to some extent even from the amino acids. Thus it is not necessary to go through the slower formation of nitrite (NO_2) or nitrate (NO_3) before nitrogen can become available to the phytoplankton.

Juday, Chancey
1940. The annual energy budget of an inland lake. Ecology, 21(3): 438-450.

"The annual energy budget of a lake may be regarded as comprising the energy received from the sun and sky each year and the expenditures or uses which the lake makes of this annual income of radiation. In general the annual income

and outgo. . . balance each other. This is true more particularly of the physical energy budget. Considerable biological material produced in one energy year lives over into the next, but this overlapping crop of organisms is much the same in quantity from year to year . . . so does not require any special consideration. There is a certain amount of organic material contributed to the bottom deposits in the deeper water and to peat formation in the shallow water which lasts for long periods of time, but the annual value of these materials is so small in most cases that they may be neglected."
This was a study made of Lake Mendota and the following findings emerged:

1. The mean annual quantity of radiation delivered to the surface of Lake Mendota over a period of 28 years was 118, 872 gram calories per square centimeter of surface. 2. In the physical energy budget, the melting of ice utilized 3, 500 calories; the annual heat budget of the water was 24, 200 calories and about 31, 000 calories were lost by conduction, convection and radiation. 3. On the basis of a turnover in the organic content of the plankton every two weeks during the year, the energy value of the annual crop of plants and animals was 346 gram calories per square centimeter; of this amount 321 calories were contributed by the plants and 25 calories by the animals. Adding to this the organic matter utilized by the plants and animals in their metabolic processes (232 calories) gives the annual crop an energy value of 578 gram calories. In addition the dissolved organic matter had a value of 71 gram calories. 4. Assuming an average turnover of once a week in the organic matter of the phytoplankton, instead of every two weeks, would raise the energy budget of the annual crop of plants and animals to 977 gram calories, including the metabolized material. Adding the 71 gram calories in the dissolved organic matter gives a total of 1, 048 calories in the biological energy budget. 5. An average turnover of once a week in the phytoplankton would give an annual utilization by these organisms and by large aquatic plants of about one percent of the sub-surface solar energy.

Kadlec, John A.
1960. The effect of a drawdown on the ecology of a waterfowl impoundment. Michigan Dept. Conservation, Game Div., Report 2276: 1-181.

This is a study made of Backus Lake in Michigan. There were three phases of the study: (1) a 2-year study of pre-drawdown ecology of the impoundment; (2) a study of conditions after the water level was lowered 4 feet exposing most of the submerged soil; (3) a study of productivity during the growing season after the area was re-flooded. The conclusion was reached that drawdown provides a natural, effective method of maintaining the productivity of a marsh. Many of the most productive waterfowl areas are subject to natural drawdowns as a result of droughts. Effects observed were:

1. Temporary abundance of food for waterfowl in the form of wetland seed production.
2. Suitable conditions for the establishment of emergent cover.
3. Soil improvement, physical and chemical.

However, the beneficial effect on vegetation may be of very short duration. Measurements of nutrient levels after one season of reflooding in Backus Lake indicated a return to former levels. Hence poorer growth is to be expected in the second year after reflooding. Invasion of floating-leaf vegetation, water lilies in particular, can probably be used as an indicator of the deterioration of productivity and the need for management.

Kathrein, Joseph W.
1953. An intensive creel census on Clearwater Lake, Missouri, during the first four years of impoundment, 1949-1952.
Trans. 18th N. Amer. Wildl. Conf., 1953: 282-295.

The usual history of fishing in impoundments is one of good fishing for several years after impoundment, followed by a decline. But in Clearwater Lake there was a steady decline for 4 years. The main findings of this study were:

1. The average catch per hour declined from 0.65 fish per hour in 1949 to 0.34 fish per hour in 1952.
2. There were changes in the relative abundance of different species during each of the 4 years. Crappies, bluegills, largemouth bass, and bullheads were the four principal species in the creel. Smallmouth bass have practically disappeared, as have longear sunfish and rock bass. These three species plus suckers are important in the fishery of the upper Black River. Only 8 suckers have been recorded from the reservoir. Fish were taken at the rate of 6.8 pounds per acre in 1949, 10.4 in 1950, 31.3 in 1951, and 15.2 pounds per acre in 1952. In general, the average lengths for all species in the creel increased during the 4 years.

Kimsey, J. B.
1958. Fisheries problems in impounded waters of California and the lower Colorado River.
Trans. Amer. Fish. Soc., 87: 319-332.

Over a period of years, reservoirs experience a typical pattern of high initial fishing success, a sharp decrease, and then a gradual rise to a fishery somewhere near half the magnitude of the initial phase. Fertilization in the pond sense is not practical to restore and perpetuate the initial productivity of impoundments. The establishment of littoral zone cover crops that can survive even though undergoing considerable periods of submersion is suggested. The modification of the use pattern and special construction features are useful but require cooperation of the construction and operating agencies. Population manipulation, principally through the use of rotenone, is a widely used management tool but is a negative approach that usually necessitates the impoundment being removed from the fishery for varying lengths of time. Modification of the population structure by the introduction of threadfin shad into the lower Colorado River as a forage species has met with apparent high success.

La Faunce, Don A., J. B. Kimsey, and Harold K. Chadwick
1964. The fishery at Sutherland Reservoir, San Diego County, California. California Fish and Game, 50(4): 271-291.

Sutherland Reservoir is a warmwater reservoir built on Santa Ysabel Creek, San Diego County, California in 1953, and opened to fishing each year since 1955. The reservoir drainage was chemically treated before impoundment to remove bluegills, green sunfish, and brown bullheads, though some of the last two species survived. Golden shiners and largemouth bass were introduced in 1954. Bluegills and threadfin shad were introduced late in 1956 and early 1957, respectively. The most important results shown by this study are: 1) The fishery continued to improve through the first 6 years rather than reaching an early peak and then declining, as often occurs in reservoirs. 2) The largemouth bass population expanded during the 6 years despite substantial total mortality and exploitation rates, and an expanding bluegill population. 3) After an initial bloom, green sunfish rapidly declined in abundance, possibly because of competition from largemouth bass. This decline and the incomplete kill of bullheads cast doubt on the value of chemically treating the drainage prior to impoundment.

Leopold, Luna B., and Thomas Maddock, Jr.
1954. The flood control controversy. Big dams, little dams, and land management. The Ronald Press, New York. [Sponsored by the Conservation Foundation]

The flood control conflict results from the following situations:

1. Present policy and procedure lead to the construction of a large number of major dams behind which extensive areas of productive land are flooded. People are displaced, towns must be relocated. Many persons believe that upstream programs would reduce the need for a large number of major impoundments. Some advocate that the construction of downstream works should await the installation of upstream measures.
2. Conflict between the Department of Agriculture and the Engineering Corps.

Disadvantages of reservoirs are:

1. Deposition of sediment.
2. Loss of water by evaporation.
3. Cost of spillways. On some dams this is an item comparable in cost to the dam itself. They must be built to pass a flood in excess of that controlled by the reservoir dam because of the potential hazard should there be a failure.
4. A reservoir must flood certain lands to protect others from flood.

Love, S. Kenneth
1961. Relationship of impoundment to water quality. J. Amer. Water Works Assoc., 53: 559-568.

This paper is concerned with the quality of water in impoundments for the purpose of storage for water systems.

Beneficial effects of impoundments:

1. Reduction in turbidity, silica, color and coliform bacteria.
2. Evening out of sharp variations in dissolved minerals, hardness, pH, and alkalinity.
3. Reduction in temperature which is sometimes beneficial to fish.
4. Entrapment of sediment.
5. Storage of water for release in dry periods for the dilution of polluted water.

Detrimental effects of impoundment:

1. Increased growth of algae, resulting in objectionable tastes and odors.
2. Reduction in dissolved oxygen in deeper parts of reservoirs.
3. Increase in CO_2, frequently in iron, manganese, and alkalinity, especially near the bottom.
4. Increase in dissolved solids and hardness as a result of evaporation and dissolution of rock minerals.
5. Reductions in temperatures, which although sometimes beneficial, may be detrimental to fish life.

Lyman, F. Earle
1944. Effects of a flood upon temperature and dissolved oxygen relationships in Cherokee Reservoir, Tennessee.
Ecology, 25(1): 70-84.

In Cherokee Reservoir on May 18-19, 1942 dissolved oxygen was virtually absent below a depth of 25 feet in the upper portion of the reservoir and below 40-60 feet in the lower portion. These conditions may be considered as normal.

A major flood occurred on the Holston River in May. The force and volume of this flood caused a depression of the thermocline at the head of the reservoir and disturbed the isothermal balance. The epilimnion had increased in volume and had at the same time been cooled largely by the influx of colder water, The dissolved oxygen content was temporarily increased.

The data for June 8-10, 1942 demonstrate that when those natural forces which upset the isothermal balance within a large body of water are dissipated, the normal equilibrium is restored by subsurface water movements in order to produce an equal distribution of weight.

McCaig, Robert S., and James W. Mullan
1960. Growth of eight species of fishes in Quabbin Reservoir, Massachusetts, in relation to the age of the reservoir and introduction of smelt.
Trans. Amer. Fish. Soc., 89(1): 27-31.

(Authors' abstract)
"Growth rates of eight species of fish taken by angling from Quabbin Reservoir, a 25,000-acre impoundment in Massachusetts, were determined for all or two of the following three periods of the reservoir's history: A--while the reservoir was filling; B--during the first 7 years after it was filled; and C--after the smelt

had been introduced. Growth of yellow perch showed little change over the three periods; that of white perch declined. Growth of smallmouth bass and chain pickerel increased somewhat after introduction of smelt, but that of black crappie and largemouth bass remained essentially unchanged. There was a marked increase in growth rates of lake trout and brown trout after smelt had become abundant (1954-1958). The proportion of game fishes (black basses, pickerel, and trouts) in the total angling catch increased from 2.1 to 5.4 percent by numbers and 11.0 to 23.0 percent by weight after introduction of smelt. Average angling yield in this deep, soft-water reservoir is 2.5 pounds per acre per year."

McGregor, R. L.
1948. First year invasion of plants on an exposed lake bottom.
Kansas Acad. Sci., 51(3): 324-327.

Tonganoxie Lake was constructed in 1932 when a dam was placed across a valley which forked above the dam to form two arms in the lake. The lake is situated in Leavenworth County; it has an area of 175 acres, a maximum depth of 40 feet. The valley was deep and had rather abrupt banks. Several small creeks supplied the water. Two of these were much more important than the rest; one ran into the west arm of the lake, the other into the eastern arm. The drainage area of these important tributaries consisted of woodlands, fields and some prairie. The less important streams drained the wooded hilly region immediately surrounding the lake. As the lake was within Leavenworth County State Park it was a popular fishing area for several years. Fishing declined steadily and it was decided to drain the lake. This draining was started in December of 1946.

By April of 1947 most of the water had been removed from the lake. The exposed lake bed was rough. Silting had not been severe; in general it was limited to a few inches, though in some areas it measured several feet. During May and June seedlings appeared on the lake bed in great numbers. A smartweed, Polygonum lapathifolium L. was the dominant plant over the entire lake bed. Individuals of this species composed about 90 percent of the flora of the lake bed and formed a dense growth over nearly the entire exposed surface. The greatest number of species was found in the areas just below the entrance of the tributaries into the lake and in the lower more moist areas of the lake bed. There were a few bryophytes; seed plants represented 36 families, 62 genera, 93 species.

McGregor, R. L., and L. D. Volle
1950. First year invasion of plants on the exposed bed of Lake Fegan, Woodson County, Kansas.
Trans. Kansas Acad. Sci., 53(3): 372-377.

Lake Fegan is an artificial lake of 126 acres in Woodson County, Kansas. Construction was completed in 1937. It is situated in bluestem pastures, oak-hickory woods and a limited amount of cultivated land; there is sandy land immediately around the lake. The lake bed is quite rough; the banks are often steep with sudden drops. The lake has an average depth of about 15 feet, except for a considerable area with a depth of a few inches to 3 or 4 feet; maximum depth is 50 feet. Silting is not severe.

It was drained very quickly in contrast to the draining of Lake Tonganoxie where difficulties slowed the procedure. By the latter part of May 1959, seedlings had appeared in great numbers on the lake bed. Smartweeds (Polygonum) and pigweeds (Amaranthus) were the dominant plants. The total number of species was 97. Only 37 species were common to both Lake Fegan and Lake Tonganoxie. Tree seedlings included blackjack oak (Quercus marilandica Munch.) and cottonwood (Populus deltoides).

Manges, D. E., R. W. Eschmeyer, and O. G. Haslbauer
1947. Trends in fishing on TVA storage waters.
J. Tennessee Acad. Sci., 22(1): 45-56.

All available evidence suggests that even with year-round fishing, most fish of desirable size and species die unharvested of natural causes. In Hiawassee Reservoir there was overpopulation of game fish with some starvation.

Martin, N. V.
1955. The effect of drawdowns on lake trout reproduction and the use of artificial spawning beds.
Trans. 20th N. Amer. Wildl. Conf.: 263-271.

Three Ontario lakes which supply water for power were studied. The water is held in the lakes in spring and summer, and drawn off in fall and winter. The time and amount of drawdown varies from year to year in each lake depending upon the amount of precipitation and power demands. Lake trout in small inland lakes usually spawn in the last half of October on open shore lines of broken rock varying from 2-6 inches in diameter and often interspersed with large boulders. Sand, mud and detritus are usually absent. Spawning takes place at a depth of 8 inches to 4 feet in one lake and in another from 3 to 12 feet. Hatching occurs from mid-February to late March. This gives a period of 3 1/2 to 5 months when the eggs are vulnerable to water level fluctuations. In Lake Opeongo drawdown had little harmful effect as spawning occurs in over 3 feet of water. In Hay Lake a drawdown of 6 feet exposed a large proportion of the usual spawning beds and loss was high. Bullheads were observed feeding on eggs. In Shirley Lake in 1950 the drawdown almost completely exposed the spawning beds. Artificial spawning beds might be constructed here if the cost is not too great.

Martin, Robert G., and Robert S. Campbell
1953. The small fishes of Black River and Clearwater Lake, Missouri.
In Black River Studies I: 45-66, Univ. Missouri Studies, 26(2): 1-136.

The species of small fishes found in the new Clearwater Lake in 1948 were similar to those in the river, but there were differences in relative abundance. The brook silversides, bluntnose minnow, bluegill, and longear sunfish together constituted 60% of the small fish population. In 1949 the bluegill constituted 50% of the small fishes collected. By 1950 the fishes that had increased markedly were the fish originally found in small numbers in the backwaters of the river including gizzard shad, golden shiner, largemouth bass and white crappie.

Martin, R.O.R., and Ronald L. Hanson
1966. Reservoirs in the United States.
U. S. Geol. Surv. Water-Supply Paper 1838.

Reservoirs in the United States having usable capacities of 2 million acre-feet or more

Reservoir, (state), river system, and date completed	Area drained (sq. mi.)	Storage (acre-feet) Total	Storage (acre-feet) Usable	Surface area (acres)	Use
	Figures in thousands, add 000				
L. Mead (Ariz., Nev.) Colorado R. (1936)	168	29,827	27,207	158	fimnp
Oahe (S.D.) Missouri R. ↓	244	23,630	23,628	376	finpr
L. Powell (Ariz.) Colorado R. (1963)	108	27,000	20,876	161	fipr
Garrison (N.D.) Missouri R. (1954)	181	24,800	19,900	390	finpr
Ft. Peck (Mont.) Missouri R. (1939)	58	19,410	13,915	245	finpr
Ft. Randall (S.D.) Missouri R. (1956)	264	6,093	6,093	103	finpr
Bull Shoals (Ark.) White R. (1951)	6	5,408	5,400	71	fpr
Roosevelt (Wash.) Columbia R. (1941)	74	9,562	5,232	79	ip
Sam Rayburn (Tex.) Angelina R. ↓	3	4,479	-	114	fmpw
L. Texoma (Okla., Tex.) Red R. (1943)	40	5,530	4,424	144	fmprw
Shasta L. (Calif.) Sacramento R. (1949)	7	4,493	4,377	30	fipr
Cumberland (Ky.) Cumberland R. (1950)	6	6,089	4,236	64	fp
Kentucky (Ky.) Tennessee R. (1944)	40	6,002	4,011	261	fnpr
Oroville (Calif.) Feather R. ↓	4	3,499	3,498	16	fimp
Flaming Gorge (Utah) Green R. ↓	15	3,789	3,516	42	ipr
Table Rock (Mo.) White R. (1956)	4	3,462	3,462	54	fpr
Falcon (Tex.) Rio Grande R. (1953)	164	3,281	3,278	78	fimpw
Hungry Horse (Mont.) Flathead R. (1952)	2	3,468	2,982	24	fip
Eufaula (Okla.) Canadian R. ↓	48	3,848	2,951	48	p
Greers Ferry (Ark.) Little Red R. ↓	1	2,844	2,844	40	fpr
Texarkana (Tex.) Sulphur R. (1957)	3	2,654	2,654	120	cfm
L. Ouachita (Ark.) Ouachita R. (1953)	1	2,768	2,602	40	fpr
Painted Rock (Ariz.) Gila R. (1959)	51	2,492	2,492	53	f
Trinity L. (Calif.) Trinity R. (1960)	1	2,448	2,438	16	fi
Norris L. (Tenn.) Clinch R. (1936)	3	2,567	2,281	40	fnpr
Elephant Butte (N.M.) Rio Grande R. (1916)	29	2,195	2,195	37	fipr
Tuttle Cr. (Kan.) Big Blue R. (1962)	10	2,367	2,134	54	cfr
John H. Kerr (Va.) Roanoke R. (1952)	8	2,808	2,110	96	fnpry
Canyon Ferry (Mont.) Missouri R. (1953)	16	2,051	2,043	35	fimpr
Cherokees (Okla.) Neosho R. (1940)	10	2,197	2,017	60	fpr
Whitney (Tex.) Brazos R. (1951)	26	2,018	2,012	50	fimpw

c = conservation
f = flood control
i = irrigation
m = municipal
n = navigation
p = power
r = recreation
w = industrial
y = low flow augmentation

1 acre-foot = 0.3259 million gal.
1 acre-foot = 0.04356 million cu.ft.
1 acre-foot = 0.5042 cu.ft./sec/day.

↓ Under construction.

Martin, R.O.R., and Ronald L. Hanson
1966. Reservoirs in the United States.
U. S. Geol. Surv. Water-Supply Paper 1838.

Summary of reservoirs showing number, usable storage, and surface area, by State

State	Number of reservoirs	Usable storage (acre-feet)	Surface area (acres)	State	Number of reservoirs	Usable storage (acre-feet)	Surface area (acres)
Ala.	22	4, 905, 100	362, 160	Mont.	60	23, 286, 500	555, 908
Alaska	9	555, 900	9, 912	Nebr.	19	4, 061, 200	113, 257
Ariz.	23	56, 695, 200	483, 374	Nev.	9	655, 500	26, 578
Ark.	15	10, 021, 700	243, 093	N. H.	30	1, 262, 300	112, 600
Calif.	205	28, 368, 500	650, 589	N. J.	12	219, 500	11, 808
Colo.	94	3, 981, 100	129, 334	N. Mex.	23	5, 412, 100	115, 689
Conn.	14	468, 800	20, 779	N. Y.	72	5, 778, 500	371, 185
Del.	1	6, 800	1, 200	N. C.	29	4, 432, 300	142, 488
Fla.	12	3, 718, 200	1, 460, 023	N. Dak.	18	18, 786, 100	456, 671
Ga.	17	6, 582, 900	242, 918	Ohio	43	3, 390, 700	166, 062
Hawaii	3	23, 000	726	Okla.	43	10, 842, 000	428, 067
Idaho	51	10, 560, 100	532, 343	Oreg.	51	4, 785, 100	212, 743
Ill.	15	203, 700	53, 536	Pa.	37	2, 066, 200	69, 499
Ind.	9	395, 000	18, 488	R. I.	2	117, 700	4, 574
Iowa	2	486, 400	53, 960	S. C.	11	4, 148, 600	423, 607
Kans.	19	4, 349, 100	143, 759	S. Dak.	10	30, 620, 600	452, 282
Ky.	6	8, 922, 950	345, 340	Tenn.	20	10, 268, 000	373, 935
La.	23	1, 497, 500	178, 775	Tex.	116	26, 460, 000	1, 013, 395
Maine	76	5, 142, 100	650, 038	Utah	37	5, 721, 400	197, 094
Md.	8	472, 600	22, 052	Vt.	14	532, 900	11, 366
Mass.	24	1, 915, 900	55, 421	Va.	12	2, 506, 800	116, 100
Mich.	29	551, 200	83, 605	Wash.	43	12, 228, 000	350, 248
Minn.	52	12, 589, 600	2, 271, 811	W. Va.	3	1, 169, 900	16, 483
Miss.	5	3, 885, 900	215, 500	Wis.	67	2, 008, 000	516, 819
Mo.	6	6, 138, 200	165, 100	Wyo.	33	5, 993, 200	174, 933
				Puerto Rico	8	169, 300	3, 530
				Total	1, 562	359, 359, 850	14, 830, 757

Martin, R. O. R., and Ronald L. Hanson
1966. Reservoirs in the United States.
U. S. Geol. Surv. Water-Supply Paper 1838.

Michigan reservoirs completed or under construction as of January 1, 1963

Reservoir, river, date	Area drained (sq. mi.)	Storage (acre-feet) Total	Usable	Surface area (acres)	Use
Alcona Pond (AuSable R.) 1924	1,469	5,000	-	1,075	P
Belleville L. (Huron R.) 1925	825	5,000	-	1,280	-
Bond Falls (Middle Br. Ontonagon R.)	190	-	40,000	-	P
Brule (Brule R.) 1919	1,050	18,000	-	774	P
Chalk Hill (Menominee R.) 1927	3,321	8,000	-	765	P
Cleveland Cliffs Basin (AuTrain R.) 1931	80	-	12,300	1,949	P
Cooke Dam Basin (AuSable R.) 1911	1,641	-	5,000	1,800	P
Croton Pond (Muskegon R.) 1907	2,224	-	5,000	1,380	P
Dead R. Storage Basin(Dead R.) 1916	141	-	55,300	4,236	P
Deer L. Basin (Carp R.) 1912	36	-	22,500	1,700	P
Earl L. Holloway (Flint R.) 1953	543	-	17,700	1,973	MW
Fletcher Pond(Upper S. Br. Thunder Bay R.) 1930	171	44,600	40,100	8,500	P
Foote Basin (AuSable R.) 1918	1,664	-	5,000	1,850	P
Ford L. (Huron R.) 1932	812	16,500	-	917	P
Hardy L. (Muskegon R.) 1931	1,851	-	5,000	3,970	P
Hodenpyle Backwater(Manistee R.)1925	1,018	-	5,000	2,025	P
Hubbard L. (Lower S. Br. Thunder Bay R.) 1915	146	34,200	30,000	8,800	PR
L. Allegan(Kalamazoo R.) 1936	1,540	17,200	-	1,600	P
L. Gogebic(W. Br. Ontonagon R.) 1906	162	-	35,200	14,080	PR
Michigamme(Michigamme R.) 1940	642	119,950	119,950	7,000	P
Morrow L. (Kalamazoo R.) 1939	1,000	6,000	-	1,000	W
Norway Pt. (Thunder Bay R.) 1924	1,260	-	6,000	1,700	P
Peavy Pond(Michigamme R.) 1943	710	-	34,000	3,160	P
Sanford L. (Tittabawassee R.) 1925	1,020	5,000	-	1,526	P
Schweitzer(Schweitzer Cr.) 1963	23	-	5,300	360	W
Silver L. (Dead R.) 1912	24	-	26,800	-	P
Tippy Backwater(Manistee R.) 1918	1,451	-	5,000	1,540	P
White Rapids(Menominee R.) 1927	3,325	6,000	-	445	P
Wixom L. (Tittabawassee R.) 1925	985	5,000	-	2,178	P

P = power
W = industrial
R = recreation
M = municipal

Merna, James W.
1964. The effect of raising the water level on the productivity of a marl lake. Pap. Mich. Acad. Sci., 49: 217-227.

In 1957 a dam was installed on Big Portage Lake, Jackson County, Michigan which raised the water level by 3 feet, increasing the area of the lake from 335 to 435 acres. The lake basin now has three depressions with maximum depths of 28, 34, and 43 feet. These are separated by shoal areas where the water is less than 6 feet in depth. By 1959 aquatic vegetation on the shoal areas consisted of Scirpus sp. and scattered beds of Nymphaea odorata. There were few plants at depths greater than 5 feet; in 1946 there had been 20 species of higher plants of which 10 were submergent including: Potamogeton, Ceratophyllum, and Myriophyllum. During the first 2 years after the water level was raised there was an elevation of the phosphorus and a lowering of the alkalinity. During the third year phosphorus and alkalinity had returned nearly to their former concentrations. The bottom fauna did not respond to the increased phosphorus content of the water. There was a significant decrease in the average standing crop of the benthos between 1953 and 1959. Chaoborus exhibited the greatest decrease in numbers. The growth rate of bluegills, largemouth bass, and black crappie increased after the water level was raised. As the bottom fauna was not increased after the water level was raised it is possible that this increased growth of fish resulted from a greater production of zooplankton. The increase in phosphorus and the reduction in numbers of higher plants may have resulted in a greater production of phytoplankton, periphyton, and zooplankton.

Meskova, T. M.
1960. Izmenenie fauny ozera Arpilich v svazi s prevrashcheniem ego v vodokhranilishche. [Changes in the fauna of Lake Arpilich in connection with its transformation into a reservoir]
Zool. Zhur. 39(11): 1597-1606.

Summary (translation) from Biol. Abstr. 1961-70933.

The Arpilich Reservoir (in the northwestern part of the Armenian SSR), created for the purpose of irrigation, appeared in 1952 as a result of damming of the Akhuryan River flowing out of Lake Arpilich. Before this the lake had been a shallow eutrophic body of water, overgrown with higher aqueous vegetation. The biomass of zooplankton was approximately 8 g/m^3. The zoobenthos was qualitatively varied, but quantitatively poor (average biomass of 3.6 g/m^2). Commercially the most significant fish were carp, bullhead, and "khramulya". After the water level rose, all the higher aqueous vegetation died, and due to the great turbidity of the water the quantity of phytoplankton decreased and "blooming" stopped. The previously predominant facultative planktonic types disappeared from the zooplankton, but the amount of zooplankton was still quite large (biomass of approximately 1 g/m^3). As a result of the slow silting up of the reservoir and the constant agitation, the zoobenthos became qualitatively poorer, dominated by oligochaetes and Tendipedidae larvae, and the biomass of the benthos decreased sharply to 0.1 g/m^2, The only commercially important fish, the carp, began to feed primarily on plankton. In view of the slow accumulation of organic substances the food base of the carp will henceforth be very limited.

Moen, Tom
1956. Stratification of Iowa artificial lakes.
Proc. Iowa Acad. Sci., 63: 714-720.

Thirty-six impoundments were studied. The lakes ranged from 16 to about 400 acres in surface area, and from 7 to 55 feet in depth; averaging about 100 acres and 22 feet respectively.

These lakes were placed in three groups: Those that do not stratify, those that have a temporary or very limited stratification, and those that have a strong stratification each year. Epilimnions extended from 5 to 21 feet, averaging about 9 feet. Thermoclines usually extended to the bottom except in the deeper lakes. Temperature declines within the thermocline varied from a minimum to over 20 degrees. Transparency was usually over 2 feet except in group one where the turbidity was always high. Alkalinity of the surface waters of 25 lakes varied from 65 to 155 ppm. Epilimnions of three lakes of group three encompassed 31 to 71% of the total lake volumes.

Moore, Emmeline
1931. A follow-up program on the impounded waters of the Sacandaga Reservoir.
Trans. Amer. Fish. Soc., 61: 139-142.

The flooded basin of the Sacandaga Reservoir is situated in the foothills of the Adirondacks about 60 miles north of Albany. At high level it has an area of 26,700 acres or 41 square miles, and at low level, 35 square miles. It has an irregular shoreline of 125 miles. When the reservoir is full, the depth of the water is from 30 to over 45 feet over a large part of the basin and a considerable area is permanently over 40 feet deep. The maximum depth near the dam is 70 feet.

During the first year after impoundment the pike fishing was excellent. In the basin which was flooded were several hundred acres of swamp land traversed by 20 miles or so of streams where there had always been good pike fishing in accessible portions. Fish in the order of abundance were: pike, bullheads, perch, and smallmouth bass. Carp were abundant and rock bass, sunfish, chain pickerel and common suckers were taken. A speckled trout and a pike perch were taken from the reservoir and a brown trout from one of the tributaries. The reservoir is a warmwater lake except where the depth exceeds 26 feet. At a depth of 39 feet in the lower channel where the level will remain most constant, the readings of oxygen were zero. It was in this area that it was hoped lake trout might find a suitable habitat but the lack of oxygen precludes the stocking of this species. At present none of the well known water weeds is represented. Plankton is sparse. Nearly all the streams entering the reservoir are trout streams with natural barriers few or non-existent. One of the tributary streams, the West Branch, is a notably fine trout water. At present no barrier exists to stop a run of the predaceous species up this stream. How sharply the barrier of temperature and other conditions incident to annual changes in level of the reservoir water may distinguish the habitats of the trout and pike, for example, is problematical at this stage.

Moore, Emmeline
1932. Certain minnows showing adaptability to conditions in impounded waters. Trans. Amer. Fish. Soc., 62: 290-291.

Follow-up studies on the Sacandaga Reservoir show that after the drowning of a valley the bottom layers at once become stagnant due to the decomposition of flooded vegetation and its incident animal life. In consequence there is an abnormally low oxygen supply, a condition that is likely to persist indefinitely. Weed beds, if established at all, will always be meager. Fluctuations in level cause an indefinite but persistent loss. On the credit side there is an enormous volume of good water in the upper levels and in marginal shallows. There is a continuous and enormous yield of plankton which bulks large as a basic food resource. A suitable minnow should be stocked which is a plankton feeder, such as golden shiner, blunt-nosed and fathead minnows. These fish can tolerate the vicissitudes of reservoir life.

Morgan, Paul V., and Charles Gainor
1960. A survey of the heterotrophic bacteria in Sanctuary Lake of the Pymatuning Reservoir.
Ecology, 41: 715-721.

Sanctuary Lake is a shallow eutrophic lake which receives water from two drainages. Linesville Creek contains raw sewage and agricultural drainage. Pymatuning Swamp also contains drainage from agricultural lands. The water from these two drainages is separated in the lake by an area of emergent vegetation except at the western end of the lake. Sanctuary Lake supports an abundance of aquatic life.

The high concentration of coliform bacteria in Linesville Creek was greatly reduced as its waters entered Sanctuary Lake. The reduction continued as these organisms were horizontally distributed across the lake until they almost or entirely disappeared. The vertical distribution of these coliform organisms indicated that sedimentation occurs.

The Pymatuning Swamp drainage contains large numbers of another bacterium.

Average temperature and the amount of sunlight had no apparent effect on the distribution of bacterial populations.

Mortimer, C. H.
1941. The exchange of dissolved substances between mud and water in lakes. J. Ecology, 29: 280-329.

The fact that vertical chemical stratification is maintained in the water column of a body of water suggests that the main agents of production or depletion of dissolved substances are located at the lower boundary of the column, at the mud surface.

Most, Charles E.
1965. A fisherman looks at reservoirs.
U. S. Fish Wildl. Serv., Bur. Sport Fish. Wildl., Cir. 227: 14 p.

This is a booklet for popular consumption. There are speculations as to the reasons for the decline of fishing quality in impoundments. Listed are: competition for food supply, spawning areas, living space, and the effect of fluctuating water levels on fish. Drawdowns made just after a fish has spawned will have a bad effect on fishing if the spawners are valuable game fish, but a good effect if the species is too numerous or undesirable. Mention is made of preparation of reservoir sites before flooding. The recommendation here is to leave trees standing so that the slow rotting process will promote the growth of plankton.
[Note by G.G.H. This recommendation is contrary to the one given by Sylvester and Seabloom that all standing timber, logs and other debris be removed from a site before flooding. Their primary concern, however, was quality of water for domestic use. See Sylvester and Seabloom, 1965. "Influence of site characteristics on quality of impounded water," J. Amer. Water Works Assoc., 57(12): 1528-1646.]

Moyle, John B.
1949. Some indices of lake productivity.
Trans. Amer. Fish. Soc., 76: 322-334.

In an attempt to evaluate lake-survey procedures some of the chemical, physical, and biological measurements that have been considered possible indices of lake productivity have been examined in the light of 11 years of lake surveys and 6 years of pond rearing of yellow pikeperch. In Minnesota waters total alkalinity and total phosphorus appear to be the most valuable indices. Nitrogen is usually present in excess; sulphates are of most value in considering waterfowl areas; and chlorides, pH, and dissolved carbon dioxide are of little value in comparing waters and judging potential productivity. Potassium, manganese, and iron concentrations are discussed; all are necessary for plant growth and may be limiting factors. In Minnesota, present knowledge of these elements is too incomplete to warrant any definite conclusions. Quantitative plankton and bottom-fauna samples have been found unsatisfactory as productivity indices for ordinary lake surveys, and the distribution and abundance of larger aquatic plants are of greatest value when related to waterfowl management. In estimating the potential productivity and formulating fish-management plans for lakes the structure of the fish population and the nature of the lake basin should be considered. Moyle finds Minnesota lakes do not fit Rounsefell's (1946) conclusion that fish production usually has a straight-line logarithmic relationship to the size of the body of water, due to the relatively larger area of fertile shallow water in the smaller lakes. In Minnesota hard-water lakes, the catch rate of gill nets shows no decline as the size of the lake increases. Length of growing season and water temperature are also important where lakes in different latitudes and altitudes are compared.

Muenscher, W. C.
1933. Aquatic vegetation of the upper Hudson watershed.
New York Conserv. Dept., Biol. Surv., 7(1932): 216-238.

". . . The establishment of a reservoir or the enlargement of an existing pond involves the shifting of several major factors of the environment such as are brought about in nature through slow and gradual changes over a long period of time. The probable effect of such changes upon the plant and animal life should be considered before, and not after, the water is impounded. Normally the land vegetation dies within the first year after it is flooded. This will produce a large amount of decaying organic material."

Among the waters of the Upper Hudson Watershed the impounded lakes or reservoirs present some of the most difficult problems. Most of the reservoirs were made, and some are still being made, by damming the outlet of small natural lakes or ponds, large streams, or even a whole valley. Regardless of the purpose for which the impounded water is used, the fact that it is impounded means that its flow is controlled. The extreme fluctuation to which the water level is subjected presents great problems which involve not only its scenic, recreational, sanitary and administrative aspects but what, perhaps, is of even greater importance, its biological aspects. Considerable interest has centered about the Sacandaga Reservoir, the largest and most recently established reservoir in the Adirondacks. The permanently rooted aquatic plants of the reservoir will probably always be limited to such forms as can adjust to a water depth which is greater than the fluctuation of the water level, about 31 feet, or to those plants which can grow part of their life in the water and part of it out of the water. Judging from the depths at which the larger aquatic plants occur in most lakes of the Adirondacks, it is not likely that many attached plants will grow in the Sacandaga Reservoir at depths over 9 meters below the high water line. Some species of *Nitella* and possibly a few mosses may establish themselves below this line. Several beds of the water smartweed, *Polygonum amphibium* have appeared in water about 5 meters (15 feet) deep in the Sacandaga Reservoir.

Murphy, Garth I.
1962. Effect of mixing depth and turbidity on the productivity of fresh-water impoundments.
Trans. Amer. Fish. Soc., 91(1): 69-76.

The productivity of many fresh waters appears to be controlled by the effectiveness of the energy regime which is a direct function of the incoming radiation, non-productive sources of turbidity, and mixing depths. A drawdown regime designed to maximize reservoir productivity might well be the opposite of the usual practice of drawing water from the bottom, which tends to remove the lake's store of un-utilized nutrients, and tends to lower the thermocline. In contrast, withdrawal from the epilimnion would permit the photosynthesizers to function more efficiently, and would increase stirring into the nutrient-rich deeper layers of the lake. Although it is not now possible to document the hypothesis with respect to reservoirs, a number of observations indicate that it has merit. It should be relatively easy to develop a research program to explore the possibilities by providing a reservoir with a completely flexible outlet.

Neel, Joe Kendall
1963. Impact of reservoirs.
In Limnology of North America, p. 575-593, David G. Frey, editor. Univ. Wisconsin Press, Madison.

"Two American rivers that have been brought under control of large multipurpose reservoirs are the Tennessee and the Missouri. The relative size of these two developments is strikingly illustrated by the fact that the total storage capacity of the Tennessee system--somewhat in excess of 11,000,000 acre-feet--is approximately one-half the volume of any one of the three largest Missouri River impoundments."

"In the now predictable course of events reservoir utility will decline with capacity losses occasioned by silting and aquatic vegetation. However, it is possible that filling processes may be brought under control. If river regulation as now practiced is replaced by a system offering greater conservation of water, reservoirs will in all likelihood be retained for some purposes, possibly flood control, recreation, etc. Storage may be de-emphasized."

Natural lakes usually have a bowl-shaped form; reservoirs are typically wedge shaped bodies of water, the deepest portion of which rests against the dam.

Phenomena occurring in reservoirs: 1. Filling and retention; 2. Erosion of basin. In 1955, as Garrison Reservoir was filling, bed-element solutes added 10 ppm to the annual average alkalinity of the inflowing water and 14 ppm to the annual average hardness. In Lake Mead about 20 million tons of materials have been dissolved from the banks and bed over the period of 1935-1948. 3. Sedimentation and mineral precipitation. 4. Density currents. 5. Evaporation of water from the surface.

Effects of reservoirs on streams: 1. Native discharge patterns are altered. 2. Reservoirs delay rise and fall of temperatures in streams. 3. The chemistry of the impounded stream is changed. For example reservoirs often increase a stream's oxygen resources, and frequently promote photosynthesis to the level of supersaturation in the upper layers, hence hypolimnion releases generally stimulate phytoplankton or other algal growth, and may in this manner be responsible for high oxygen content levels further downstream. 4. Turbidity.

Neess, John C.
1946. Development and status of pond fertilization in Central Europe.
Trans. Amer. Fish. Soc., 76: 335-358.

This paper contains an historical review of fish culture in central Europe. European carp ponds in early times were dry-fallowed and planted with vetch, barley or beans which were harvested.

Neess points out that there are two regions in bottom soils: (1) an upper, well aerated, often highly colloidal layer of decomposed organic material, and plant debris, (2) a lower anaerobic zone, differing widely in composition from place to place and often containing a large proportion of mineral matter.

The ability of these soil layers to direct certain processes in the pond is the result of the special properties listed below:

1. The mineral composition of pond water is to a large extent a reflection of the mineral composition of the soils of the pond bottom and the surrounding basin.
2. The often predominant colloidal fraction, consisting of humic substances, ferric gels, and clay is a powerful adsorbant of certain soluble nutrient elements and a governor of their distribution among pond organisms.
3. The bottom is the medium with microorganisms responsible for the decomposition of organic debris and chemical transformations such as the conversion of organic phosphorus and nitrogen to soluble compounds, oxidation of ammonia, production of carbon dioxide, and possibly the fixation of free nitrogen. These microorganisms are chiefly bacteria and some fungi. Where the bottom is not well aerated, decomposition is slow and its products are only partially oxidized tending to produce strongly acid soils.

Management of soil bottoms in ponds must produce soil neither so adsorptive as to impoverish the soil of nutrients nor so inactive as to permit excessive loss of nutrients by seepage and outflow. The soil should be loose and sufficiently aerated to permit rapid oxidative decay. These aims can be achieved in two general ways: (1) application of lime and (2) direct treatment of bottom soils after draining the pond.

Nursall, J. R.
1952. The early development of bottom fauna in a new power reservoir in the Rocky Mountains of Alberta.
Canadian J. Zool., 30: 387-409.

<u>Author's abstract</u>

"The Barrier Reservoir, on the Kananaskis River, Alberta, was examined periodically from May, 1947, shortly after water impoundment began, until June 1949. The reservoir is fundamentally oligotrophic; rapid replacement of water, periodic fluctuation of water level, and a marked annual deposition of sediment contribute to this condition. The bottom fauna consisting chiefly of immature Chironomidae, was much influenced by these factors during the period of the investigation. A <u>Pentapedilium</u>-<u>Chironomous</u>-<u>Tanytarsus</u> succession is interpreted as indicating a change from original eutrophic conditions on the bottom to oligotrophic, as the rich leaf litter of the original bottom was lost under sediments."

O'Connell, Timothy R., and Robert S. Campbell
1953. The benthos of Black River and Clearwater Lake, Missouri.
<u>In</u> The Black River Studies I, p. 25-41, Univ. Missouri Studies, <u>26</u>(2): 1-136.

Black River supported a standing crop of 82 organisms with a volume of 3.5 cubic centimeters per square foot. Striking changes in the bottom population occurred with the inundation of Black River by Clearwater Lake. The most obvious changes were: (1) a marked decrease in the kinds of organisms; (2) a shift in the groups that were dominant; and (3) a quantitative difference in the standing crop. The total number of taxonomic groups present in the river was 33; this was reduced to 20 in the new reservoir and to 13 two years later. Lost with impoundment were the riffle-inhabiting families, Simulidae and Sialidae, and 14 families belonging to the orders Plecoptera, Trichoptera, and Diptera. Taxonomic groups which were dominant by number and dry weight in the river decreased from at least seven to three in the lake. The reservoir supported more benthic organisms per unit area than did the river, but the change in numbers of organisms reflects the replacement of larger insects such as mayflies in the river by the smaller, more numerous mosquito larvae and oligochaetes in the reservoir. River samples averaged 455 milligrams dry weight per square meter as against 373 milligrams average for all lake samples. The standing crop of bottom fauna was poor compared to natural lakes.

Orr, H. D.
1954. Quantitative studies of protozoan populations from two areas of Pymatuning Lake, Pennsylvania.
Ecology, 35: 332-334.

Pymatuning Lake is a large artificial lake on the Pennsylvania-Ohio boundary, resulting from a dam built on the Shenango River at Jamestown, Pennsylvania in 1933. Its uppermost section, Sanctuary Lake, covers 2, 000 acres, has a mean depth of 9 feet. This section is of interest not only because of its high plankton productivity (Tryon and Jackson, 1952) but because the northern portion of it receives raw sewage from the town of Linesville by way of Linesville Creek. The southern portion, which is somewhat larger, drains a 5-mile swamp. Mixing of two types of drainages is prevented by an area of emergent vegetation except in the lowermost part of the lake.

It is difficult to explain the difference between the populations of protozoa in the two areas. Of the six predominant species, only two were higher in numbers of individuals in the sewage area, while three were more abundant in the swamp area. The environmental factors which were measured do not seem to offer an explanation because their ranges are not beyond the optima of the species. If pollution is effective, it is probably an indirect factor. In most cases of pollution the number of species decreases, while the numbers of individuals increases. (Lacky 1938) In Sanctuary Lake more species were observed in the area subjected to pollution. It is possible that raw sewage may increase the food in the form of bacteria and thus favor the holozoic types. Quantitative sampling in Linesville Creek revealed that better than 80% of the species were ciliates.

Parsons, John David, and Robert S. Campbell
1961. Metabolism of an eutrophic reservoir.
Verh. Internat. Verein Limnol., 14: 613-618.

<u>Authors' summary</u>

1. The effective net primary production, i.e., the biomass that remained in the water mass, was determined for an eutrophic reservoir [Ashland Lake, constructed in 1937] as 40.1 gm $C/m^2/mo$.

2. The utilization of potential carbon amounted to 82.5% or 33.1 gm C/m^2/mo., and the bioactivity amounted to 73.2 gm C/m^2/mo.
3. The carbon dioxide accumulation-oxygen deficit method can be profitably used to estimate net primary production in eutrophic reservoirs if: (1) the outflow of water is restricted to the epilimnion, and (2) the amount of oxidation during the winter is sufficient to break down all but the more reduced carbohydrates.
4. On the basis of the carbon released during the winter and the loss of biomass with the outflow of epilimnic water, it is suggested that reservoirs, and possibly lakes be classified on the basis of bioactivity per year, i.e. gm/m^2/year.

Parsons, John W.
1958. Fishery management problems and possibilities on large southeastern reservoirs.
Trans. Amer. Fish. Soc., 87: 333-355.

Principal problems concerning fisheries of large reservoirs in the Southeast are: Inefficient and highly selective exploitation of fish stocks, and protection and reclamation of damaged or threatened fisheries in tailwaters and tributary streams.

Tailwaters and Tributaries

The drawing of waters from the cold depths of reservoirs and discharging them directly into rivers or reservoirs below probably is the biggest threat to the fishery potential of the Southeast. Usually waters discharged below mainstream and flood-control reservoirs are warm. Below storage reservoirs, and to a lesser extent on power reservoirs, most water discharges are cold (less than 70 F).

All storage and power reservoirs in the Southeast are located on warmwater streams and the discharge of cold water below the dams accordingly has profound effects on the fish populations. Where reservoirs such as Bull Shoals Dam in Arkansas and Lake Cumberland in Kentucky, are on large streams, warm-water fisheries may be eliminated for distances up to 200 miles. Many miles of streams and upper embayments of some reservoirs support adequately neither a warm- nor a cold-water fishery.

Fish populations of streams tributary to reservoirs likewise have been affected adversely by impoundment. For example, one formerly excellent 35-mile sport fishing stream in Tennessee was found to contain a fish population consisting of 75% large non-sport fish by weight, that had migrated from a downstream reservoir. These fish were principally carp, smallmouth buffalo, freshwater drum, and gizzard shad. Except for the extreme lower regions of the stream, there was little evidence that sport fish had migrated upstream from the reservoir.

Patriarche, Mercer H., and Robert S. Campbell
1958. The development of the fish population in a new flood-control reservoir in Missouri, 1948 to 1954.
Trans. Amer. Fish. Soc., 87(1957): 240-258.

Clearwater Reservoir on the Black River was completed in 1948. Its surface area is 1,650 acres.

All species numerically important by 1954 had spawned at least once by 1952. The population was fairly well stabilized by 1954. White crappie was the most abundant species after 1951. Black crappie did not succeed; smallmouth bass recruitment was poor; largemouth bass and rock bass declined; bluegills spawned and were important in the sport fishery.

All fish grew rapidly in 1948; growth increments declined noticeably thereafter except for smallmouth bass of which, however, few were caught after 1949.

Peterson, Elmer T.
1954. Big dam foolishness. The problem of modern flood control and water storage. (with introduction by Paul B. Sears)
The Devin-Adair Co., New York, 1954, 224 p.

This book reviews the points of indictment against the big dam program in prairie plowlands and gives examples supporting the thesis that big dams are uneconomical, wasteful of good agricultural land, and ineffective in conserving water, particularly ineffective in promoting the recharge of ground water supplies.

Kentucky dam flooded 300,000 acres of rich bottom land which had been producing foodstuffs at a rate of $21,000,000 annually--yet its power house generates electric energy worth only $3,000,000 annually. Most of the river tonnage consists of government traffic--25% represents broken rock used for riprapping lake banks, and 35% is coal for a steam plant.

Average reservoirs have a life of about 50 years. Prairie rivers like the Washita receive vast amounts of eroded soil. For the Washita this is 2 acre-feet of solids per square mile per year. This is a pile 1,000 feet long, 700 feet high and 1,000 feet wide deposited each year. Such sediments form a delta in the reservoir and are deposited upstream into the tributaries.

Evaporation from reservoirs is tremendous. Oklahoma City often has a consumption of 25,000,000 gallons of water a day. The superintendent of the water department of the city said, "When the weather is hot and windy, our two reservoirs lose 25,000,000 gallons a day by evaporation."

As alternatives to big dams Peterson urges: 1. Construction of dry dam systems, small, empty pools situated to take care of floods at their sources; 2. Ground water replacement by "insoak" combined with flood control structures on the smaller tributaries of large streams. Insoak involves terracing, contour plowing, regrassing and reforestation where these practices are needed to stop the rain where it falls. The potential ground water storage is 8 times the annual rainfall of the nation. Open-tilled crops show 10-11% runoff; sweet clover 3 1/4%, Bermuda grass 1 1/2%.

Soil conservation is an important factor in water conservation. It has been estimated that the average depth of the original topsoil over what is now the United States was 9 inches, and that one-third of this has been lost since our forefathers' plows first turned the virgin soil.

Pfitzer, Donald W.
1954. Investigations of waters below storage reservoirs in Tennessee.
Trans. 19th N. Amer. Wildl. Conf., 19: 271-280.

The construction of large dams in the Tennessee Valley has caused major changes in the ecology of the waters below them. A lower average temperature, 50-55 F, a reduction of the extreme temperatures, 39-65 F., and an erratic seasonal dissolved oxygen content pattern have resulted. Also great daily fluctuations in water velocity and volume take place. Many minnow species have disappeared and only a few species of those remaining are successfully reproducing. The bottom faunal pattern has changed from large warm-water species to small cold-water species. The most abundant groups are members of the insect families Tendipedidae, Simulidae and Hydropsychidae along with the scud, Gammarus and snails. The plant populations are dominated entirely by algae of several species. There are tremendous growths of these plants in some areas. Experimental planting of rainbow trout fingerlings has shown that this species is very well suited for continued management. Brook trout have not survived tailwater conditions.

Purcell, L. T.
1939. The aging of reservoir waters.
J. Amer. Water Works Assoc., 31: 1775-1806.

The Wanaque Reservoir, the largest in New Jersey at the time the paper was written, was studied over a period of years. Construction was begun in 1920; filling started in 1928; completed in March 1929. Water was used for domestic consumption.

Tests of conditions in reservoir

April 1930

1. Water in a state of vertical circulation.
2. Temperature constant throughout its entire depth, and below the point of maximum density (4 C).
3. Dissolved oxygen was practically at 100% saturation from surface to bottom.

July 18, 1930

1. Definite stratification.
2. Dissolved O_2 approaching zero in the bottom samples.
3. Concentration of micro-organisms in upper 20 feet with the maximum number at the 20-foot level.
4. Carbon dioxide increased gradually to 25 ppm at the bottom.

August 18, 1930

1. Narrowing of the transition zone between the 25-and 30-foot levels.
2. Below the 25-foot level there was practically no oxygen.

September 17, 1930

1. Dissolved O_2 had increased at 25-foot depth. Indicates thermal circulation and circulation due to wind action. Not due to microscopic growths.
2. Number of microorganisms maximum at 10-foot depth.
3. CO_2 content increased between the 20-foot depth and bottom of the transition zone which was in 30-40 foot depth.
4. Maximum hydrogen sulfide and little O_2 below the 25-foot level. The hydrogen sulfide was produced by anaerobic bacteria acting on the sulfates in the lower regions.

After 9 years of aging

April 25, 1938

1. Beginning of summer stratification, carbon dioxide and dissolved oxygen not yet affected.
2. Thermocline at 30-40 feet.
3. Microorganisms fairly evenly distributed throughout the depth of the reservoir.

July 6, 1938

1. Transition zone (thermocline) between 20- and 40-foot depth.
2. Above thermocline dissolved oxygen at saturation point; below thermocline oxygen content constant at about 75%. Below thermocline the carbon dioxide showed evidence of increasing.
3. Color of bottom water decreased as the reservoir aged.

Interesting comment

Dismal swamp water has a color rated as high as 1,000. (Most of the color is derived from breakdown of chlorophyll which contains iron.) "The whaling ships used to prefer Dismal Swamp water on their voyages because it 'worked' and left a limpid, agreeable water above a stable ooze, or, as a physical chemist would say, the protective colloidal organic matter decomposed in the presence of oxygen while agitated by the movement of the vessel, thus permitting the iron to form flocs with the altered organic matter and clarify the water . . . without the production of bad taste."

Rawson, D. S.

1939. Some physical and chemical factors in the metabolism of lakes. In Problems of lake biology. Publ. of Amer. Assoc. Adv. Sci., 10: 9-26.

"The shape or contour of the bottom appears to affect the life in a lake in a way to some extent independent . . . of the effects of depth and area. It is clear that a lake with gradually sloping sides will be somewhat richer than one with a steep decline into deep water . . . It appears that the rich flora and fauna of this area [littoral zone] are important factors in the production of a lake."

Rawson, D. S.
1958. Indices to lake productivity and their significance in predicting conditions in reservoirs and lakes with disturbed water levels.
In The investigation of fish-power problems, H. R. MacMillan Lectures in Fisheries, Univ. British Columbia 1958: 27-42.

Factors affecting lake productivity

Morphometric factors: mean depth; maximum depth; area depth zones; volume of depth strata; altitude; latitude; shore length and development; littoral slope and development; number, area and shore length of islands; drainage area; rate of run-off; average inflow and outflow; time of "flushing"; water levels; area.

Physical and chemical factors: variations in temperature from weekly readings; highest mean temperature; highest bottom temperature; mean temperature 0-10 m; degree and duration of stratification; summer heat income; duration of ice cover; average bottom O_2; lowest percent saturation O_2; average pH surface and bottom; colour; secchi disk average and range; total dissolved solids; total alkalinity; calcium; magnesium; bicarbonates; sulphates; chlorides.

Lake Minnewanka in Banff National Park was studied by Rawson in 1936 and in 1938 before impoundment (Rawson 1942); in 1941 while the dam was being constructed; and in 1943 and 1944 after the new high level had been reached. It was studied by Solman in 1947, and by Cuerrier in 1952 (Cuerrier 1954). The power dam raised the lake level by 65 feet, increased the area of the lake 40% (to 8.5 sq. mi.); the lake has a drawdown of 35 feet which exposes more than 1 square mile of its bottom.

Changes after impoundment (some expected, some were not)

1. Physico-chemical conditions changed very little--already a deep lake, an additional 20 meters did not alter the temperature structure. With cold water and a great volume in the hypolimnion, the dissolved O_2 showed no reduction from decomposition of woody debris.
2. Plankton population retained its quality and quantity--perhaps increasing a little.
3. Bottom fauna decreased in weight by 50% in the first 3 years, then gradually increased until at 10 years it was 75% of original weight.
4. Bottom fauna changed in composition: chironomid larvae were 52%, now 93%; sphaeriids have been reduced from 39% to 5%; oligochaetes and gastropods also declined.
5. Water level fluctuations have practically obliterated littoral fauna except for a few chironomid larvae, thus destroying a very important supply of fish food.
6. Changes in fish population were remarkable and not of a kind expected. Lake trout adapted to spawning at depths below the maximum drawdown. The number of larger lake trout diminished; trout 15-20 inches in length were 39% of the catch in 1941, only 7% in 1947, and since then of negligible numbers. A stunted population is developing, and examination of stomach contents shows these trout have practically ceased eating fish, subsisting almost entirely on chironomid larvae. This is difficult to explain as ciscoes and other former fish foods are abundant.

Rawson, D. S.
1960. A limnological comparison of twelve large lakes in northern Saskatchewan. Limnol. Oceanogr., 5: 195-211.

Author's summary

1. Twelve large lakes in northern Saskatchewan show a wide range in their standing crops of living organisms. Five eutrophic lakes on the glacial drift have standing crops of plankton, bottom organisms and fish, several times as great as those of five oligotrophic lakes on the Precambrian Shield. Lakes lying across the margin of the shield are intermediate, or mesotrophic.
2. It is suggested that the underlying reason for low crops on those to the south is edaphic, i. e., dependent on the availability of chemical nutrients derived from the watersheds. Since most of the northern lakes are deep and most of those south of the Shield are shallow, this morphometric difference accentuates the primary or edaphic influence. The four farthest north lakes are subject to a slightly colder climate and shorter growing season, thus climate also may contribute a little to the difference in biological production.
3. Comparisons between individual lakes of the Precambrian group, and especially the unique features of Frobisher Lake [see note below], tend to suggest that in this group, morphometric conditions may be somewhat less effective than edaphic. Comparison of conditions in the five lakes on the glacial drift suggests that in one instance, Big Peter Pond, continuous mixing of essentially eutrophic lake greatly increases its productivity while in another, Ile a la Crosse, a rapid flushing results in a marked lowering of production.
4. From a wide range of observational data it has been possible to select eight values (three biological and five physical) which appear to be most useful in classifying these twelve lakes. The device of ranking each lake with respect to these values and comparing their sums as physical and biological scores also gives promise of utility, especially where a primary purpose of the limnological investigation is to understand and manage the fish production in a group of lakes.

Note: Frobisher Lake is different from other lakes on the Shield because of high turbidity and high temperature. It has the highest indulosity (27.5%) of all of the lakes. It is composed of 313 km^2 of water broken into narrow channels and bays by 190 km^2 of islands. While conditions in Frobisher Lake may stand in strong contrast to the four deep northern lakes, there are undoubtedly many others like it on the Precambrian Shield.

Ricker, W. E.
1946. Production and utilization of fish populations. Ecol. Monogr., 16: 373-391.

Fish caught from a body of water differ from those fish which die there. The body substance of the catch is taken away from the basin and will return only indirectly, if at all. This loss is not to be measured in terms of the basin's yield of fish, because in a year's total primary production, as measured by the energy fixed, the same actual atoms (carbon, nitrogen, etc.) may be represented several times over.

Note by G. G. Hubbell (Not a new idea!)

"Imperious Caesar, dead and turned to clay,
Might stop a hole to keep the wind away."
William Shakespeare (Hamlet)

Rounsefell, George A.
1946. Fish production in lakes as a guide for estimating production in proposed reservoirs.
Copeia, 1946(1): 29-40.

" . . . there is a tremendous difference in the potential yield of various bodies of water, from the 200-pounds (or better) per-acre yield of the fertilized, properly-stocked farm pond to the one-pound-per-acre yield of Lake Superior." "In the range of lakes for which total populations are available, i.e., 1 to 200 acres, the annual yield of sport fish varies from 74.0 to 94.6 pounds per acre, or 27.6 to 29.3 per cent of the total population estimate. As the total populations include fish of all sizes, as well as forage and rough fishes . . . it is obvious that the sportsmen annually harvest a very appreciable proportion of the available gamefish of legal size."

Rounsefell concluded that fish production usually has a straight-line logarithmic relationship to the size of the body of water, due to the relatively larger area of fertile shallow water in the smaller lakes. He states that there are various reasons for variation in the yield of lakes of similar size. Some of these differences are related to the physical and chemical conditions of the lake itself, such as depth, temperature, heat budget, and the quantities of various nutrient materials present. Even in lakes which are comparable both physically and chemically, the yield may differ because of a difference in the species of fish and other organisms present.

Curves of production in natural lakes are only a guide for predicting the fish production of reservoirs. Reservoirs differ in important features from natural lakes: they are more subject to frequent and severe fluctuations in water level; they are more apt to have silt-covered bottoms; the deep water of reservoirs usually is confined to one end, causing unnatural temperature stratifications. All of these features tend to make reservoirs less productive than natural lakes.

Ruhr, C. E.
1957. Effect of stream impoundment in Tennessee on the fish populations of tributary streams.
Trans. Amer. Fish. Soc., 86: 144-157.

Data from a statewide survey of warm-water streams in Tennessee were used to determine the extent to which gizzard shad, carp, smallmouth buffalo, and drum inhabit smallmouth bass-rock bass streams. Reproduction of these species in tributary streams was minor or absent. By comparing samples from streams that were accessible from an impoundment and streams that were in an unimpounded watershed, it was shown that large populations of the above-mentioned fish in streams originate in impoundments. In streams without migration barriers there was no decrease in the concentration of lake fish with an increase in distance from the impoundment. Population pressure among fish of various species in the impoundment is advanced as the reason for the movement of these fish into streams. It is suggested that mill dams be preserved as barriers to movement of lake fish and the pre-impoundment surveys include consideration of the effect not only on the inundated stream but on the streams above the full-pool level of the proposed reservoir.

Senning, W. C.
1939. The chemistry of impounded waters as a factor in game fish production. Trans. Amer. Fish. Soc., 68: 303-308.

The author made a survey of small lakes and ponds of New York state from 1931 until this paper was written, and had an opportunity to study a large number of the smaller artificial lakes of the state.

Minerva Lake (Essex County)
The Minerva Lake dam was completed and the lake basin filled with water in the fall of 1931. The land flooded was carefully cleared and all precautions taken to insure a clean lake. At the time of the first survey the lake was less than a year old.

It was assumed that since Jones Creek, the stream dammed, was a trout stream, the new lake would be a trout lake. Trout were stocked in September 1932, a few days before the first survey was made. Many of the stocked fish were found dead along the shore. Chemical analysis of the water explained their death. Nowhere in the lake where temperatures were satisfactory for trout was there sufficient oxygen for their respiration. Even the surface water was low in dissolved oxygen (2.5 ppm). Some areas of surface water lacked oxygen entirely. The cold bottom waters were devoid of oxygen and contained 102.0 ppm of free carbon dioxide. The only fish observed were a few dace near the inlet from Jones Creek.

The question arises as to whether adverse chemical conditions are characteristic of newly impounded waters, and if so, whether the conditions later improved. To answer this question, surveys of Minerva Lake were made again in 1933 and 1934. The second year's analysis showed only slight improvement, and in 1934 conditions were still generally unfit for trout. Bottom waters were still deficient in oxygen. The surface water had changed from a slightly acid condition accompanied by a deficiency of oxygen and a high concentration of carbon dioxide to an alkaline condition where the oxygen concentration was high even to the point of super-saturation and free carbon dioxide scarce or absent. But high surface temperatures made these waters unsuitable for trout, but suitable for warm-water species. A large proportion of Minerva Lake is shallow, and very dense weed beds have become established; this accounts for the super-saturation of oxygen in certain areas, and the decaying vegetation causes oxygen depletion in greater depths.

The study of Minerva Lake emphasizes the fact that when a trout stream is dammed with the intention of creating a trout pond, the size and depth of the pond in relation to the volume of inflow must be considered. The volume of inflow from Jones Creek is so small in comparison with the size of Minerva Lake that conditions in the lake are only slightly affected by the stream, if at all.

Shetter, David S., and Marvin J. Whalls
1955. Effect of impoundment on water temperatures of Fuller Creek, Montmorency County, Michigan.
J. Wildl. Mgmt., 19(1): 47-54.

This paper describes observations made in connection with the changes resulting from re-establishment of an old beaver dam on subsequent stream temperatures below the dam. It was concluded that the re-establishment of the Fuller Creek dam, with the resultant spreading of the water over several times the normal stream channel area, raised midsummer water temperatures from 6.5 to 10.1 F. The effect of the dam on mid-winter average daily water temperatures was obscured partially by significantly higher average air temperatures in January and February of the 3-year period, combined with what is inferred to have been a significantly lower average discharge rate during this post-impoundment period. The increase in midsummer water temperatures apparently did not change the quality of angling for brook trout in this stream. The probable reason that the angling quality showed little change lies in the fact that the stream temperature increase was well within the limits of physiological tolerance by brook trout.

Shields, James T.
1958. Fish management problems of large impoundments on the Missouri River.
Trans. Amer. Fish. Soc., 87: 356-362.

"Problems of reservoir management of the . . . Missouri River impoundments are many and varied. Each impoundment has its own combination of physical and chemical characteristics and must be managed as a separate and distinct entity. . . Probably the primary problem is, and will be for some years, inadequate harvest and incomplete use of the fisheries resource. . . The impoundments are situated in areas of low population density. Access to the reservoirs is poor and facilities for fishermen are poor or non-existent. . . Undesirably large populations of certain species of fish, especially rough fish, are likely to become established in certain impoundments. If this occurs, the acreages of water and tremendous numbers of fish involved will pose a major problem of control."

"Along with these major problems are those which arise from time to time in most bodies of water; the problems of pollution, parasites, diseases, and habitat deterioration are serious in small lakes, but may be magnified in large impoundments."

Tools of Management:

1. Planned water drawdowns. Drawdowns of 1 1/2 to 2 feet in Fort Randall Reservoir were effected immediately following periods of major carp spawning in 1955, 1956, and 1957. Eggs thus exposed were killed and there was relatively little carp reproduction in these years.
2. Improvement of spawning conditions for desirable species.

3. Increasing food production by inundating natural or artificially vegetated areas.
4. Improved design of tailwater areas below dams to allow maximum harvest of fish that concentrate there.

Shull, David Lear
1963. Limnological characteristics of two Michigan marl-forming lakes. PhD thesis, Michigan State University.

Marl-forming water is unique in its physical, chemical and limnological characteristics. Marl-forming lakes have scant growth of phytoplankton and poor fishing quality. This is a study of North Lake and Pintail Pond, Ogemaw County. Both lie in a glacial outwash plain whose surrounding moraines have abundant limestone fragments. Both are hypermarl lakes, both are spring fed. Ground water contains large quantities of calcium-magnesium bicarbonate. North Lake has an outlet active the entire year.

Low trophic levels result from the high alkalinity, and particularly from the carbonate alkalinity which forms a direct relationship to summer temperatures and the physiological activities of plants. Effects of the alkalinity are threefold: (1) the aquatic vegetation, including Chara, was rigidly suppressed in growth by heavy incrustations of carbonate, (2) 90% of the carbonate deposition occurred on the lake basin above the hypolimnion producing unusually steep slopes, reducing the productive zone of the macrohydrophytes, and (3) the high alkalinity of the water and the homogeneous marl soils adsorb and fix the soluble phosphorus of the water.

Hydrogen sulfide emanating from basin muds may have restricted plant growth since toxic quantities of sulfide accumulated in the waters of the hypolimnion. Light penetration of marl-forming water did not limit plant growth although high winds increased light extinction coefficients.

The ratio of calcium:magnesium in the water was about 10:1. The rate of decalcification ranged from 9.2-66.5 mg hr^{-1} $meter^{-2}$ and was inversely correlated with phytoplankton volumes. The maxima of calcium occurred with the development of aggressive carbon dioxide in the hypolimnion when marl was transformed to calcium bicarbonate.

The trophic level of Pintail Pond increased significantly with six applications of inorganic fertilizer. Plankton increased after each application, macrohydrophytes increased 4-6 fold, and bottom fauna 1-2 fold. The addition of organic matter increased production. Peat and sod substrates placed within the marl lake increased plant production 25-138 fold and bottom fauna production 3 1/3-12 1/2 fold, respectively. Burlap bags filled with peat or sewage sludge, planted with aquatic root stocks and placed in the lake basin, increased the plant production 400 fold on a ft^{-2} basis.

The fish population of North Lake was composed of eight families, 20 species, and hybrids of two sunfishes. The fishing quality of North Lake is poor in comparison to non-marl lakes in the locality having the same species of fish but supporting abundant stands of aquatic vegetation.

Smith, W. O., et al.
1960. Comprehensive survey of sedimentation in Lake Mead.
U. S. Geol. Surv., Prof. Paper 295.

It was found in Lake Mead that density flows control patterns of water circulation and salinity distribution. There were three types of density flows noted:

1. Overflow--when inflowing stream water spreads over the surface of the water of the reservoir;
2. Interflow--when the density of the inflowing water is greater than that of the surface water, but less than that of the deep water, inflowing water sinks to its own level of density and spreads out laterally downstream;
3. Underflow--when the density of inflowing water is so great that it sinks to the reservoir bottom and travels downstream at or near the bottom, usually along the old river channel.

Spencer, J. L.
1950. The net phytoplankton of Quabbin Reservoir, Massachusetts, in relation to certain environmental factors.
Ecology, 31(3): 405-425.

Periodicity of the net phytoplankton is influenced by many factors and many genera are specific as to their requirements. The population increases seem to be limited or enhanced by competition among the forms of organisms and by the prevailing physical-chemical conditions. Throughout the survey each genus displayed its own pulses. Population peaks of the total free floating algae were normally the results of considerable increases in only one or two genera.

Sprayberry, James A.
1964. Summary of reservoir sediment deposition surveys made in the United States through 1960.
U. S. Dept. Agr., Misc. Publ. 964: 1-66.

Reservoir	Stream	Total drainage (square miles)	Storage capacity (acre-feet)	Years between surveys	Average annual sediment accumulation per sq. mile over period	
					Acre-feet	Tons
Wheeler	Tennessee	29,590	1,061,005	3	0.027	32.0
Wilson	Tennessee	30,750	674,000	3	0.479	552.9
Kentucky	Tennessee	40,200	2,814,338	5.2	1.107	1,278.0
Norris	Clinch	2,912	2,051,418	10.3	0.317	379.7

Many other reservoirs were included in this summary.

Stockinger, Niles F., and Horace A. Hayes
1960. Plankton, benthos and fish in three strip-mine lakes with varying pH values. Kansas Acad. Sci., 63(1): 1-11.

Lake	Area (acres)	Depth (feet)	Acidity	Thermocline	Plants and animals except fish	Fish
1	2	12	3.2-3.6	None	Plankton restricted to rotifers and micro-crustaceans (90% of volume). Few insects.	No fish
2	1.2	10	6.2-7.4	Partial and temporary	Slightly greater plankton crop than Lake 1. Poorest in benthos production. Some insects.	Varied fish population. Stunted bluegills.
3	6	18	7.0-7.8	-	Larger, more diversity in plankton than Lakes 1 or 2 but ranked second to #1 in quantity and volume of organisms per sq. ft. of bottom.	Bass slightly stunted but compared favorably with fish from natural lakes.

Stroud, Richard H.
1949. Growth of Norris Reservoir walleye during the first twelve years of impoundment.
J. Wildl. Mgmt., 13(2): 157-177.

Although the growth rates of walleye were expected to decline as the impoundment became older, age of impoundment appears to have little influence on rate of growth so far. Growth rates of walleye increased through the first 7 to 9 years of impoundment and were probably correlated with generally increasing food supply. Growth was somewhat less rapid through the 12th year of impoundment due to significant increases in population density. Growth rate at the time of writing was fully as rapid as during the first 5 years of impoundment. Intra-seasonal growth is irregular among the first four age groups, with relatively rapid growth occurring in spring and early summer following the hatch of all species. Growth virtually ceases at times in midsummer but becomes rapid again in late summer. Fall growth is slow. No length increases occur between the end of November and the time of annulus formation in the spring. This irregularity is probably due to the tendency of walleye to remain in deep water in July and the proclivity of young fish for shallow water until late summer. Increased fishing pressure, following the institution of year-round fishing in 1944 had an unknown, but probably beneficial effect.

Stroud, Richard H.
1952. Management of warm-water fish populations in Massachusetts' lakes, ponds, and reservoirs.
Trans. 17th N. Amer. Wildl. Conf., 1952: 214-220.

This is a study of 450 separate water units having an average of 85 acres. It has shown that the fish populations in many of these waters are out of balance. There is a preponderance of small pan, weed, and forage species, together with a scarcity of predatory game fishes. "There are exceptions but the condition of unbalance is widespread. For example, in 45-acre Heard Pond, Wayland (Middlesex County), 371 pounds of fish were collected during a standard 1-day survey (1951). Of these fish less than 4 percent by weight were predators (chain pickerel, largemouth black bass); 55 percent were pan fish and 41 percent were weed species. Stunted white perch predominated."

"A study of angling pressures suggests a high degree of selectivity for predators. Tagging studies initiated in 1950 show that the annual harvests of adult predators (pickerel and bass) may exceed 60 percent of the available supply; the adult pan fish catch does not appear to exceed 12 percent."

Suggested control measures:
1. Direct population control--netting, spawn destruction, poisoning, draining.
2. Indirect population control--bass shelters installed, etc. However excessive shelter may prevent predation.
3. Concentrated stocking of predators.
4. Liberalization of regulations.
5. Education of the angling public--political pressure for stocking may be reduced.

Sublette, James E.
1955. The physicochemical and biological features of Lake Texoma (Denison Reservoir), Oklahoma and Texas: A preliminary study.
Texas J. Sci., 7(2): 164-182.

Lake Texoma was constructed for flood control and hydroelectric power on the Washita River and the Red River. It was first filled to top of power pool in March 1942. At spillway crest, it has a surface area of 144,000 acres, total capacity of 5,718,900 acre-feet. To date it has never reached this level--but has a surface area of 94,874 acres, capacity of 3,005,000 acre-feet, and a shoreline of 580 miles. Lake Texoma rates 9th among reservoirs of the United States in capacity, and 6th in area (including reservoirs under construction at the time of this writing). It is shallow in comparison with many large reservoirs, having a maximum depth of 29 meters at the main pool just above the dam, and with deeper portions (18 meters in most places) extending up the old drowned river channels. Most of the lake is less than 13 meters deep.

Deltas are forming near the points of inflow of the two major streams. [Note by G. G. Hubbell: Somewhere, either in this paper or elsewhere a prediction was made that the useful life of Lake Texoma would be somewhat under 100 years.]

Water circulates almost continuously throughout the year. Normally, oxygen, carbon dioxide, carbonates, and pH values are fairly uniform in distribution; however, there is some tendency for stratification to occur, at least in areas protected from the prevailing winds.

There is only one species of higher aquatic plant, Potamogeton americanus, present in the lake proper. Forty-five net plankters were listed. Species composition and relative abundance indicate eutrophy.

Sublette, James E.
1957. The ecology of the macroscopic bottom fauna in Lake Texoma (Denison Reservoir), Oklahoma and Texas.
Amer. Midland Nat., 57(2): 371-402.

Notes from Summary

The waters circulate almost continuously throughout the year, with some tendency for stratification to occur, at least in areas that have some protection from the prevailing winds. This tendency is reflected to some extent in the composition and distribution of the bottom fauna, at least in the profundal area. In this region of the lake floor, the benthos is of a limited quality (indicative of lessened amounts of oxygen--only a few species are tolerant to lowered oxygen content) and compared to other cenoses of the lake, of relatively large quantity throughout the year (showing the absence of complete stagnation). In addition, this profundal community does not develop a concentration zone, again showing a lack of complete stagnation.

A total of 87 species or groups of macroscopic invertebrates was collected. Insects predominate with 70 species.

The annual standing crop of bottom fauna from two cenoses [littoral and profundal] is given. The minimum standing crop was found in late summer and the maximum in late winter and early spring. It is suggested that although this figure is low, the lake is probably more productive on the next trophic level (fish) due to certain of the modifying factors that would be expected from the amount of benthos produced.

Sylvester, Robert C., and Robert W. Seabloom
1965. Influence of site characteristics on quality of impounded water.
J. Amer. Water Works Assoc., 57(12): 1528-1546.

"Generally natural lakes begin as oligotrophic bodies of water . . . with eutrophication requiring a great number of years. Reservoirs on the other hand begin with high initial algal productivity potential owing to the leaching of nutrients from the rich underlying soil." This study was made, both in the field and under laboratory conditions of the Howard A. Hanson multipurpose reservoir three miles above Tacoma, Washington on the Grand River.

Conclusions:
1. Water quality changes at soil-water interface were more of a biochemical nature than they were of a purely physical or chemical nature. Nitrogen was more limiting for microbial action than was phosphorus.
2. Heavy algal blooms could produce more changes in water quality than any other factor.
3. Undesirable effects from soil organic content may include an increase in water color, decrease in dissolved oxygen, release of algal nutrients, decrease in pH and alkalinity, and an increase in dissolved mineral matter. Wood, bark, grasses, leaves and ferns have a high BOD and produce many changes in water quality, bark produces more undesirable effects than wood.

Recommendations:
1. Reservoir soils should be subjected to water-soil studies to predetermine their expected effect per unit of soil surface on overlying water and if leaching and exchange studies indicate that a soil will impart undesirable properties to the overlying water, then it is possible that the site should not be used, or a mineral soil, if available, should be used to cover the undesirable soil to a depth of 6 inches.
2. All standing timber, brush, stumps, logs, and man-made debris should be removed from the reservoir site.
3. Grass and herbage on river bottoms should be removed just prior to inundation.
4. Impoundment areas should be flushed several times before use, if possible, to remove debris, soluble soil constituents and fine soil particles.

Taube, Clarence M.
1965. Final Report Dingell-Johnson Project No. F-27-R-2.

Abstract: After a dam was constructed on the outlet of Big Portage Lake in 1957, the effects of increased water level on fish and conditions for fish were investigated. This is a low-productive, marl-bottomed lake. The higher level had no apparent effect on the density of the fish population; significant increase in growth rates occurred only among black crappies and bluegills.

Thompson, William H.
1955. Problems of reservoir management.
Trans. Amer. Fish. Soc., 84: 39-46.

Reservoirs in the southwest are not biological deserts. In fact the reproductive potential of these stable bodies of water is so great that they become so crowded with fish that problems of overpopulation and associated retarded growth rate are sooner or later felt. Because of high reproductive potential of channel catfish in reservoirs, it is not unusual to observe the species growing so slowly that it takes 5 to 6 years to reach Oklahoma's 10-inch legal length. The problem of interspecific and intraspecific competition needs clarification. Black bass, channel catfish and other species will "stunt" in waters teeming with gizzard shad which is available as a food item. It is generally accepted that rough fishes compete and exert a population pressure which has an important effect on species composition within a reservoir. Commercial fishing and public education to encourage a maximum harvest of all fishes is suggested.

Tryon, Clarence A., and D. F. Jackson
1952. Summer plankton and productivity of Pymatuning Lake, Pennsylvania.
Ecology, 33(3): 342-350.

In general the plankton shows great numbers of individual organisms which belong to relatively few species. The organic material present in the water, as determined by samples, roughly paralleled the plankton counts.

Tucker, Allan
1957. The relation of phytoplankton periodicity to the nature of the physico-chemical environment with special reference to phosphorus.
I. Morphometrical, physical and chemical conditions.
Amer. Mid. Nat., 57: 301-333.

Several lakes were studied but only Douglas Lake, Cheboygan County, Michigan will be considered in this review. The work described in this paper was done in South Fishtail Depression, one of several such holes which behave as separate lakes. This depression has a maximum depth of 24 meters; the area of the basin below the 9-meter level (at which depth it is isolated from the other depressions of the lake) is 0.14 square mile.

During periods of thermal stratification, oxygen is distributed uniformly throughout the epilimnion; in the hypolimnion it decreases as summer progresses and disappears from the bottom several months before the autumnal overturn. In winter the bottom waters again become depleted of oxygen. There was chemical stratification; the pH varied between 8.0 and 8.4 in the epilimnion and between 7.0 and 8.0 in the hypolimnion, decreasing from surface to bottom. Phosphorus: during the 16 months of investigation the amounts of total phosphorus at the surface fluctuated between 7 and 14 micrograms per liter; at the 20-meter depth, however, a different phenomenon occurred. On August 31, about 4 or 5 weeks after oxygen had disappeared from this depth, the amount of total phosphorus was 50 micrograms per liter (three times the highest value found between July 3 and August 4), and by September 16 it had reached the enormous value of 641 micrograms per liter. On October 2, during the fall overturn it was down again to 22 micrograms per liter; after the ice cover formed it gradually increased to 46 micrograms on February 26, 1951.

Tucker, Allan
1957. The relation of phytoplankton periodicity to the nature of the physico-chemical environment with special reference to phosphorus. II. Seasonal and vertical distribution of the phytoplankton in relation to the environment.
Amer. Mid. Nat., 57: 334-370.

Douglas Lake is considered a diatom lake. The average percentage of diatoms occurring in the standing crop (arbitrarily defined as containing at least 50,000 units per liter) varied between 54.3 and 95.4. The fall phytoplankton pulses of 1950 and 1951 each contained over 85% of diatoms.

In Douglas Lake the soluble organic phosphorus fluctuated irregularly in the epilimnial waters during the 16-month investigation, but these fluctuations seemed to have no relationship with the occurrence of spring and fall phytoplankton pulses, each of which, however, occurred almost immediately after the beginning of the overturns.

Tucker found that before the fall overturn a concentration of 641 micrograms of total phosphorus (460 micrograms of soluble phosphorus) was contained in a layer of water one meter thick at the bottom of the hypolimnion.

The author was able to make no clear cut correlations between the plankton pulses and changes in chemical factors in the water, but discussed the sequence of events preceding each pulse in Douglas Lake. Dead organisms on the bottom are being decomposed by bacterial action until toward the end of summer such activity has exhausted the oxygen of the lake bottom water. However, phosphorus which was supposedly being released by the decomposition of dead organisms could not be detected even at the bottom of the lake until about 8 weeks after the oxygen disappeared. Furthermore no increase was found in the concentration of phosphorus in the epilimnion following the overturn. Einsele (1938) found that divalent iron and phosphate can exist side by side in solution in hypolimnetic waters only when oxygen is absent; but if oxygen is introduced, as at the fall overturn, the iron and phosphorus will combine to form an insoluble ferric phosphate precipitate which will sink to the bottom mud and become a part of it. Conversely when oxygen is removed from the water, the iron will be reduced to ferrous phosphate which is soluble. Mortimer showed that another reaction can take place (1941). Phosphorus is strongly adsorbed on ferric hydroxide or ferric hydroxide organic complexes in the oxidized bottom mud when oxygen is present in the overlying water. When oxygen is depleted these ferric compounds are reduced and phosphorus is liberated into the water.

Tucker proposed the hypothesis that the magnitude and duration of each of the phytoplankton pulses which occurs after an overturn may depend upon the magnitude and duration of nutrient liberation from the mud, which in turn depends upon how soon before the overturn the bottom becomes depleted of oxygen.

Uhler, Francis
1963. Testimony in Michigan Supreme Court Case 49859. [Appeal from Circuit Court of Mecosta County re Martiny Lake drawdown.]

Results of drawdown on Cash Lake. "The drawdown was as complete as we could make it, leaving a residual pool of possibly two acres. . . subsequent drawdowns on a biennial basis exposed from one-third to one-half of the bed of the impoundment. After the second year of reflooding. . . the rate of growth of fish stepped up amazingly, bass up to 8-9 pounds. . . and we have continued this biennial drawdown and have continued to have excellent fish production as a result." Exposure of the bed of the pond to an extent of one-third to one-half of the full pool aerated the bottom soil and undecayed and partially decayed organic matter. After the first drawdowns it might not be necessary to repeat oftener than every ten years.

U. S. Bureau of Sport Fisheries and Wildlife
1961. Reservoirs. A prospectus for sport fishery research.
U. S. Fish Wildl. Serv., Bur. Sport Fish. Wildl., 1961: 1-30.

"The purpose of this prospectus is to review some of the present circumstances about fish in reservoirs and to explore research possibilities for the future. . . It outlines a long-range, broad-scale and basic program of reservoir research . . ."

Among the topics treated are: some reservoir statistics; characteristics of some Federal reservoirs; a brief account of federal fishery research on reservoirs; current fishery research and management; the state of our knowledge about reservoir fishes; recognized reservoir game fish problems; outline of a sport fishery research program for reservoirs.

U. S. Soil Conservation Service
1953. Summary of reservoir sedimentation surveys for the United States through 1950.
U. S. Dept. Agr., Soil Cons. Serv., Sedimentation Bull. No. 5: 1-31.

Wheeler Reservoir, Tennessee River has 175 ppm by weight of sediments in its water.

	Average annual sediment accumulation per square mile	
	Acre-feet	Tons
Cherokee Reservoir	0.248	297.0
Norris Reservoir	0.376	450.4

Wiebe, A. H.
1938. Limnological observations on Norris Reservoir with special reference to dissolved oxygen and temperatures.
Trans. 3rd N. Amer. Wildl. Conf.: 440-457.

Distribution of temperature, dissolved oxygen, free carbon dioxide, pH, and total alkalinity in Norris Reservoir has been investigated and the following conclusions seem warranted:

1. Change in dissolved O_2 follow changes in temperature to within the region of the thermocline. From here on changes in each of these factors pursue an independent course.
2. In the late summer the dissolved O_2 reaches a minimum--approaching zero--at a depth of from 35' to 45'.
3. Below the depth of 45' the dissolved O_2 increases again reaching a second maximum at 90'. Below that it decreases again.
4. There is no upswing of temperature between the depth of 45' to 90' to correspond to the increase in dissolved oxygen in this stratum.
5. The vertical distribution of free carbon dioxide and hydrogen-ion concentration follow that for dissolved oxygen.
6. A thermocline is present.
7. The region of low dissolved oxygen at about 40' is caused by the subsurface movements of stagnant water from the head of the reservoir. These subsurface movements are accelerated by the drawdown of the dam.
8. As the season advances and the drawdown continues, the thermocline and the region of low oxygen both descend to greater depth. This descent is caused by influx of fresh water from the tributaries.
9. Finally the region of low oxygen referred to above merges with the low oxygen zone near the bottom and the thermocline disappears.
10. Summer stagnation in the hypolimnion is terminated by displacement caused by the drawdown and the influx of fresh water before the onset of the fall turnover.

Wiebe, A. H.
1940. What are the prospects for the continuation of sport fishing in Tennessee Valley Authority waters?
Trans. 5th N. Amer. Wildl. Conf.: 131-136.

Norris Reservoir is an extreme situation from the standpoint of fluctuating water level.

1. Maximum depth 200 ft.; situated in a relatively narrow gorge.
2. Thermal stratification.
3. Hypolimnion subject to oxygen depression; bottom fauna restricted to a few species that can exist in stagnant conditions.
4. Drawdown makes littoral zone of vegetation impossible.

Norris Reservoir in each successive year is virtually a new body of water.

1. The 60 ft. annual drawdown represents two-thirds of the volume of the reservoir below spillway level.

2. If the incoming water, the quality of which does not vary greatly from year to year, produced fish food and a suitable environment for game fish in 1937, why should it not do the same in 1945 or 1950?
3. Gizzard shad the dominant fish in Norris--it feeds on algae.

Guntersville Reservoir is an extreme situation with a low drawdown.
1. Normal fluctuation is 2 feet, maximum drawdown in advance of flood is 4 feet.
2. Fair crop of aquatic vegetation, and areas of relatively shallow water.

Other TVA reservoirs are between these two extremes.

Wiebe believes that stabilization of water levels can be accomplished without interfering with power production. The matter of exhausting the fertility of the bottom would be to some extent compensated for by the nutrient matter mixed with silt content of the incoming water. He thinks that the character of the run-off from the watershed will to a large extent determine the fertility of a reservoir.

Wiebe, A. H.
1941. Density currents in impounded waters--their significance from the standpoint of fisheries management.
Trans. 6th N. Amer. Wildl. Conf.: 256-265.

Natural lakes present three well defined vertical strata:
1. Epilimnion--high dissolved O_2 content, decrease in temperature and dissolved oxygen with increase in depth is gradual.
2. Thermocline--rapid decrease in temperature with decrease in depth, the dissolved oxygen may or may not decrease rapidly as the depth increases.
3. Hypolimnion--the bottom layer in which temperature and dissolved oxygen both decrease gradually with increased depth and dissolved oxygen may be completely used up. The hypolimnion of a eutrophic lake may be stagnant; the corresponding region of an oligotrophic lake still shows a relatively high concentration of dissolved oxygen.

In Norris:
1. A zone of stagnant water, generally in thermocline, below which is a second layer rich in dissolved oxygen.
2. Presence of sub-surface or density currents would explain how stagnant water could be transported to a point 40 miles from its place of origin as in Norris.
3. In Norris density currents are due to differences in the density of the water in the reservoir and of the inflow from the tributaries. They are due to differences in temperature, concentration of electrolytes, especially carbonates, and silt content.
4. Sub-surface strata of stagnant water formed by density currents exert an effect upon the vertical distribution of fishes and contribute to fish mortality.

Wickliff, E. L., and Lee S. Roach
1937. Management of impounded waters in Ohio.
Trans. 2nd N. Amer. Wildl. Conf.: 428-437.

O'Shaughnessy Reservoir in the Scioto River above Columbus, and containing 1,120 acres, silted in 6% of its volume in 9 years. Griggs Reservoir of 364 acres, approximately 5 miles below O'Shaughnessy, silted in 25.6% of its volume in 30 years.

Limnological data of Meander Reservoir (flooding of 2,000 acres of land with 100 billion gallons of water, February, 1932). In August 1932, oxygen content was 0.8 ppm at 10 meters; August 1933, oxygen content was 0.3 ppm at 8 meters and 0.00 ppm below 27 feet. At age 2 1/2 years water for treatment and use was taken from the bottom. In October 1936, oxygen content was 4.9 ppm at a depth of 12 meters. The number of fish increased with flooding but the number of species decreased.

Absence of gross aquatic vegetation may be a problem; but if too prolific it manufactures oxygen in abundance on bright sunny days, but night followed by dark days may cause a drain on oxygen until none is left and fish die. Excess of vegetation in early spring is ideal for spawning and rearing, but thicker growths in late season do not remain favorable to young fish.

Wohlschlag, Donald E.
1952. Estimation of fish population in a fluctuating reservoir.
California Fish and Game, 38(1): 63-72.

Searsville Lake (98 acres) was first impounded in 1891; later alterations raised the height of the dam to 90 feet. During the past few years there have been severe fluctuations in water level. It was completely drained following the 1923-24 drought, and then stocked with bass, bluegills and black crappie. The abundant carp disappeared but it is possible that a few brown bullheads survived. Silting is very heavy during the rainy season. There is a prodigious growth of rooted vegetation in the shallow waters of the entire lake, and all species follow the receding shoreline as the water level drops in summer. In population estimates it was found that an expression of the standing crops on a per-acre basis for this weed-choked reservoir were much more realistic when the acreage at low water level was used. On the low water basis the total standing crops for bullheads, bluegills and crappies were approximately equal to 162 pounds per acre, while on the high water basis the standing crop in the shallower water was disproportionately low. Brown bullhead was the dominant species in numbers and weight.

Wood, Roy
1951. The significance of managed water levels in developing the fisheries of large impoundments.
Tenn. Acad. Sci., 26(3): 214-235.

Management of water levels is perhaps the most promising tool useful in controlling fish populations in large impoundments. Stroud (1948) found that fish grew more rapidly in Norris Reservoir immediately following a period of dry years when low water levels of water permitted the invasion of vegetation. Eschmeyer, Stroud, and Jones (1944) believed one drawdown might control buffalofishes, and another limited drawdown might expose the eggs of carp without interfering with the nests of bass or crappies which nest in deeper water at different seasons. Holloway (1949) reported that a drawdown of up to 75% of the volume of water in ponds and lakes is effective in restoring a balanced population of fish.

Conclusions:
1. The productivity of an impoundment is dependent upon the fertility of the watershed and the availability of essential plant nutrients in its bottom soils.
2. The availability of plant nutrients in the bottom soils can be increased by management of water levels.
3. Fishing success is related to the type of fish population supported by an impoundment as well as to its productivity. Good fishing is usually afforded by expanding populations and balanced populations consisting principally of game fish; poor fishing is a result of overcrowded populations and balanced populations of rough fish.
4. The expanding population probably affords the best opportunity for management to provide good fishing in large impoundments.
5. The type of fish population supported by an impoundment is dependent not only upon the kinds and numbers of fish present or introduced at the time of initial filling, but also upon habitat conditions and rates of harvest.
6. Habitat conditions favorable to desired fish populations may be provided, and removal of undesired fish populations may be facilitated by management of water levels.

Wright, John C.
1954. The hydrobiology of Atwood Lake, a flood control reservoir. Ecology, 35(3): 305-316.

Atwood Lake, on Indian Fork Creek, Muskingum watershed, was impounded in 1937, and has failed to produce good fish crops. Because a large carp population was present and the water "murky", the hypothesis was advanced that carp, by virtue of their feeding habits, were making the lake turbid, thus creating an unfavorable biotic situation for game fish. In the fall of 1946 the lake was drained, and after refilling it was stocked with desirable fish. The author's problem was to evaluate the effect of draining.

Carp and other undesirable fish gained entrance after drainage. Findings:
1. Poor light penetration in parts of the lake was due to the presence of iron-humus colloids, turbidity was important only during the spring and was due to surface runoff.

2. Compared to more productive lakes, phytoplankton crops were extremely low, and correlated with this low phytoplankton population bottom fauna was very low.
3. The fish population consisted mainly of black and white crappie in very poor condition and stunted bluegills, with such rough fish as carp, gizzard shad and a small population of largemouth bass. Bass was the only game fish that showed a good growth rate. Crappies and bluegills showed good growth rates the first year following drainage but grew at very low rates the second year. This satisfactory first year's growth correlated with high zooplankton population resulting from submergence of vegetation following drainage. The growth rate of bass was attributed to the abundance of small fish upon which the bass could prey.
4. No evidence was found that carp were affecting the productivity of the lake either by making the water turbid, eliminating weed beds, or by interference with spawning activities of game fish.
5. It was concluded that the natural level of productivity of the lake was too low to maintain satisfactory growth rates of fish.

Wright, John C.
1958. The limnology of Canyon Ferry Reservoir. I. The phytoplankton-zooplankton relationships in the euphotic zone during September and October, 1956. Limnol. Oceanogr., 3(2): 150-159.

Canyon Ferry Reservoir is an artificial impoundment located on the Missouri River near Helena, Montana. It was filled during 1955; extends upstream 25 miles; its surface is 35,180 acres and its maximum depth is 165 feet.

<u>Author's abstract</u>

Phytoplankton and zooplankton standing crop, gross and net primary production were measured. From these data the daily loss of phytoplankton from the euphotic zone was calculated. The phytoplankton loss correlated well with zooplankton during September and with vertical water movement during October. A grazing coefficient was calculated (G = 1.064 L water/mg dry wt. zooplankton/day). By use of this coefficient the loss of phytoplankton by zooplankton grazing was calculated for the period of study and averaged 0.255 mg glucose/L/day, Zooplankton assimilation averaged 0.216 mg glucose/L/day, indicating a digestive efficiency of 85%. Gross and net primary production from September 6 to October 17 amounted to 137.2 and 114.0 g glucose/m^2, respectively. Zooplankton assimilation was estimated to be 85% of net primary production. The ratio of zooplankton net production to zooplankton assimilation was 10.5%.

Wright, John C.
1959. Limnology of Canyon Ferry Reservoir. II. Phytoplankton standing crop and primary production.
Limnol. Oceanogr., 4(3): 235-245.

<u>Author's abstract</u>

In general, one μg chlorophyll was equivalent to 0.5 mm^3 cell volume and 0.12 mg ash-free dry weight. The average seston content consisted of 34.5%

phytoplankton, 9.8% zooplankton, and 55.7% detritus. Optimal photosynthesis per unit chlorophyll and cell volume averaged 0.39 μmole $O_2/\mu g$ chl/hr and 0.86 μ mole O_2/mm^3/hr, respectively. The average euphotic zone photosynthetic rate was 52% of the optimal rate. Chlorophyll content per unit volume of cells and photosynthesis per unit chlorophyll or cell volume decreased with increase in population size. Evidence was found of an interacting effect of temperature, light intensity, and phosphates on photosynthesis. An empirical method was described for estimating photosynthesis on the basis of chlorophyll content, optimal rate of photosynthesis per unit chlorophyll, extinction coefficient, and the ratio of euphotic zone photosynthesis to optimal photosynthesis. Determinations of phytoplankton respiration were made, and net euphotic zone photosynthesis was computed for various sizes of chlorophyll standing crop. It was concluded that the most frequently occurring values of chlorophyll standing crop were most likely to produce a maximum net production and to be at a steady state level.

Wright, John C.
1960. The limnology of Canyon Ferry Reservoir. III. Some observations on the density dependence of photosynthesis and its cause. Limnol. Oceanogr., 5(4): 356-361.

Author's abstract

"A series of 24-hour determinations of net photosynthesis confirmed conclusions derived from previous 6-hour experiments that the relationship between photosynthesis and standing crop is not linear. The optimal rate of net photosynthesis per unit chlorophyll varied inversely with chlorophyll concentration. As a result net euphotic zone photosynthesis was maximal at intermediate values of chlorophyll concentration and was less at chlorophyll concentrations above or below the intermediate range. From previously derived relationships between chlorophyll, gross photosynthesis, and respiration, values of net euphotic zone photosynthesis were computed for each chlorophyll concentration. The computed values agreed well with the observed values. The decline of CO_2 concentration as standing crop increased was suggested as the most probable cause of the observed photosynthesis standing crop relationship."

Wright, John C.
1961. The limnology of Canyon Ferry Reservoir. IV. The estimation of primary production from physical limnological data. Limnol. Oceanogr., 6(3): 330-337.

"In previous papers (Wright 1958, 1959, 1960) estimates were made of gross and net primary production in Canyon Ferry Reservoir by means of oxygen changes in black and clear bottles. This paper is concerned with an attempt to estimate primary production from physical data collected during the summer of 1958."

Abstract

"Biological rates of oxygen production and consumption were computed by adding the rates of turbulent transport of oxygen to the observed rates of change in concentration at successive depths. This involved using coefficients of vertical eddy diffusivity which were assumed to be equivalent to coefficients of vertical eddy conductivity, computed on the basis of a heat transport equation utilizing Birgean heat budgets. An attempt was made to assess the validity of the coefficients as follows. In the clinolimnion, the average values of the coefficients were similar when computed either on the basis of temperature change with depth and time or on the basis of the heat transport equation. A satisfactory correlation was obtained between the coefficients and a function of shearing stress (velocity gradient) and resistance to mixing (stability). The coefficients decreased with increasing depth in the epilimnion, became minimal and constant in the metalimnion, and increased in the hypolimnion. Oxygen consumption exceeded oxygen production below 5.5 m and was maximal just below the euphotic zone (9-12 m). Oxygen consumption was minimal in the metalimnion and increased in the hypolimnion. An oxygen consumption maximum was correlated with the metalimnetic oxygen consumption minimum. Euphotic zone oxygen production equivalent to dysphotic zone oxygen consumption amounted to 1.01 g O_2/m^2/day. Euphotic zone respiration would have been 1.21 g O_2/m^2/day if it proceeded at the same rate as in the 9- to 12-m stratum. On the basis of ratios, oxygen consumption/chlorophyll and oxygen consumption/seston euphotic zone respiration amounted to 1.44 g/O_2/m^2/day, and 2.01 g O_2/m^2/day, respectively. Gross production values then would range between 2.22 g O_2/m^2/day and 3.02 g O_2/m^2/day. The latter value was extremely close to the black and clear bottle estimates of 3.00 g O_2/m^2/day.

Yeatman, Harry C.
1956. Plankton studies of Woods Reservoir, Tennessee.
J. Tennessee Acad. Sci., 31(1): 32-53.

"Generally speaking, ten pounds of food are required to build one pound of the animal that eats it."

1,000 pounds of unicellular algae, bacteria, and protozoa
100 pounds of animal plankton (chiefly crustacea)
10 pounds of minnows and small fish
1 pound of bass, trout, perch, etc.
1/10 pound of man (for replacement of worn-out tissues or actual growth)

In 1953 the Arnold Engineering Development Center completed a dam on the Elk River, Franklin County, Tennessee, to impound water for use in cooling wind tunnels, called Woods Reservoir. It covers about 5,000 acres.

Upon finding a great abundance of phytoplankton during daylight at a certain depth which is characterized by abundance of oxygen, little carbon dioxide, alkaline in reaction, and with a larger amount of calcium than at other depths, one might wrongly conclude that such phytoplankton were present at that depth because such conditions were ideal for their existence and reproduction. Actually the phytoplankton was not seeking out these conditions but was rather the cause of them. During daylight most zooplankton is seeking and utilizing oxygen for respiration and avoiding ultraviolet light rays penetrating into the water; hence zooplankton will be found at a depth below that of phytoplankton. At such a depth, there will be much carbon dioxide being given off by the respiring organisms, and calcium bicarbonate being formed when the carbon dioxide combines with calcium carbonate in the water. Also the water at that depth will be less alkaline, neutral, or acid because carbon dioxide plus water will form carbonic acid.

Conclusion

Woods Reservoir shows most of the characteristics of a eutrophic lake. It has an excellent supply of nutrients and hence is high in productivity of plankton. Except during the fall and spring turnovers, the circulating topwater or epilimnion exceeds the hypolimnion in volume, also there is a low transparency and high calcium content. The deep water is usually about neutral and the upper, slightly alkaline. There are many individual plankters, but few species. Temperature seems to be a major factor in influencing seasonal succession. Organisms pass through unfavorable seasons in cysts, spores, or dormant in the bottom mud. Maximum growths of diatoms occur after periods of stagnation and stratification and during turnover periods.

Zeller, Howard D.
1952. Nitrogen and phosphorus concentrations in fertilized and unfertilized farm ponds in central Missouri.
Trans. Amer. Fish. Soc., 82: 281-288.

It was suggested that the limiting factor in productivity is soluble phosphorus. Yearly mean concentrations of phosphate at the surface ranged from 0.016 to 0.028 ppm in the fertilized ponds and from 0.010 to 0.016 ppm in the unfertilized ponds. Daily phosphorus analyses showed good correlation between concentrations of phosphate and plankton production. Each addition of fertilizer was followed by a rapid settling out which resulted in bottom phosphate concentrations which, in one pond, were as much as 10 times as great as the surface concentrations. Phosphorus added as fertilizer was found to be utilized within one week and on occasion within 24 hours depending on the degree of biological activity. Nitrogen was not limiting for algal growth in these ponds.

ZoBell, C. E., F. D. Sisler, and C. H. Oppenheimer
1953. Evidence of biochemical heating in Lake Mead mud.
J. Sedimentation and Petrology, 23: 13-17.

"Lake Mead, formed by the Hoover Dam across the Colorado River on the Arizona-Nevada border, is rapidly filling with sediment. Bathythermograph tracings have revealed anomalous temperature gradients in the sediment. At the bottom of the lake as the bathythermograph entered the mud, there appeared to be a sharp temperature increase, which at certain stations was as much as 9° F within the first five feet of penetration."

"On December 22, 1948, a test was made a short distance upstream from Hoover Dam. During the descent of the bathythermograph, especially designed to penetrate the soft mud to a depth of nearly 100 feet, it registered temperatures increasing from 52.6° F at the water surface to 53.8° F at the mud-water interface. As the instrument entered the mud the temperature increased sharply within the topmost few feet. After reaching a maximum of 58.8° F at a mud depth of about 30 feet, the temperature decreased with further penetration."

"Bacterial thermogenesis appears to be responsible, at least in part, for the higher temperatures found in the sediment. Millions of living bacteria per gram were found in Lake Mead mud, the largest populations occurring in the topmost layers where the thermocline is steepest. Assuming that the bacteria generate heat, at an average rate of 30×10^{-12} calories per cell per hour, ten million might generate 2.6 calories in a gram of mud a year."

"Biochemical oxygen demand (BOD) tests on samples of Lake Mead mud collected at various depths showed little variation in the vertical distribution of biologically oxidizable organic matter thereby indicating that most of the organic matter reaching the lake bottom must be oxidized in the topmost layers of mud."