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The role of lake and reservoir sediments as sinks in the perturbed global carbon cycle

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ABSTRACT

We estimate that recent increases in organic carbon accumulation in the sediments of lakes and reservoirs amount to about $0.02 \cdot 10^{15}$ gC yr^{-1} and $0.2 \cdot 10^{15}$ gC yr^{-1}, respectively. The reservoir accumulation represents a small but significant fraction of the carbon missing in current global budgets.

1. Introduction

Approximately $5 \cdot 10^{15}$ g of carbon are released to the atmosphere annually as CO_2 by the burning of fossil fuel (Keeling, 1973). About 85 to 90% of the fossil fuel carbon released since 1958 is accounted for by increases in concentrations of CO_2 in the atmosphere and oceans (Oeschger et al., 1975; Woodwell et al., 1978; Broecker et al., 1979). Attempts to account for the remaining 10 to 15% have been the subject of considerable speculation and debate. While some have argued that increased terrestrial biomass accounts for the remaining fraction (Broecker et al., 1979), other estimates show a net annual loss from terrestrial biomass to the atmosphere of $1 \cdot 10^{15}$ to $>4 \cdot 10^{15}$ gC as a result of forest clearing, primarily in the tropics (Bolin, 1977; Stuiver, 1978; Woodwell et al., 1978). Thus, of the carbon released annually by fossil fuel combustion and forest clearing, about $0.5 \cdot 10^{15}$ to $4.5 \cdot 10^{15}$ g are not accounted for in current estimates of the annual global carbon budget (Kerr, 1980; Mackenzie, 1981).

Recent efforts to balance the current global carbon budget have involved the search for sizable and increasing fluxes of carbon which have been ignored. For example, organic carbon accumulation in shallow marine sediments, resulting from enhanced phytoplankton production, may account for up to about $1 \cdot 10^{15}$ gC yr^{-1} (Walsh et al., 1981). Increased oceanic CO_2 uptake due to magnesium calcite dissolution (Mackenzie, 1981) and increased carbon transport by rivers (Richey et al., 1980; U.S. Department of Energy, 1981) have also been suggested as helping to balance the global carbon budget.

Because fossil fuel combustion is a relatively recent perturbation of the global carbon system, the carbon released must be accounted for in recent changes in the magnitude of other carbon fluxes which parallel the release from combustion. To date, the focus of attempts to identify and quantify recent changes in carbon fluxes has been on the major carbon sinks (e.g., oceans, atmosphere, terrestrial biomass). The role of inland aquatic sediments as carbon sinks has largely been ignored. In this report, we examine the possibility that, as a result of some of man's activities, the rate of net carbon accumulation in the sediments of inland waters (lakes and reservoirs) has increased in recent years, removing fossil fuel carbon from the atmosphere and accounting for a portion of the "missing" carbon in current global carbon budget estimates.

2 Lake sediments as carbon sinks

Excluding the Black Sea, lakes and inland seas cover about $2 \cdot 10^6$ km^2, about 0.4% of the earth's

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surface (Wetzel, 1975). A few of the world's largest lakes comprise most of this area. The Caspian Sea alone covers 372,000 km^2, about 19% of the world lake surface area, while the 20 largest lakes comprise 51% of global lake area (Todd, 1970).

Lake basins receive inorganic and organic materials from the surrounding terrestrial watershed (allochthonous input) as well as organic material produced *in situ* (autochthonous input). A portion of this organic matter input sinks to the lake bottom, escapes oxidation, and accumulates in lake sediments. As lakes fill in, lake basin sediments act as a sink for carbon that has been removed from the atmosphere and fixed by photosynthesis on land and in the lake.

The rate at which organic carbon accumulates in lake sediments depends upon the rates of autochthonous and allochthonous input and the rates at which these inputs are oxidized within the lake (respiration rate). These processes are largely controlled by the character of the surrounding terrestrial watershed and by geomorphic and hydrologic characteristics of the lake basin itself, specifically those controlling the mixed layer depth and flushing rate (Hargrave, 1973, 1975). Organic carbon escapes oxidation and accumulates in lake sediments, largely because of the refractory nature of some organic materials or because of a lack of dissolved oxygen in bottom and pore waters. Since many lakes thermally stratify during long periods each year, supplies of dissolved oxygen below the thermocline can be reduced to very low levels if enough readily degradable organic matter settles to the bottom. Also, high rates of total sediment deposition can rapidly bury organic sediments, isolating them from overlying oxygenated waters, and thereby slowing their oxidation. Since the terrestrial system is the source of most fluvial organic carbon inputs and most of the critical nutrients that control aquatic production, the character and size of the watershed, relative to total lake area, are extremely important in determining rates of carbon accumulation in lakes.

Deevey (1955, 1972) has postulated that the rate at which natural lake basins fill depends primarily on their initial size. Currently, cultural activities in lake watersheds also affect, significantly, the rate of organic carbon accumulation in lake sediments. Increased organic carbon accumulation in sediments has been reported for numerous lakes in Europe and North America, as a result of cultural activities (Edmondson, 1974; Kemp et al., 1974; Bloesch, 1977; Pennington, 1978; Birch et al., 1980). Deforestation and soil disturbance accelerate the input of plant nutrients and total sediment from the terrestrial system (Bormann et al., 1974). Runoff from agricultural and urban areas and discharge of domestic wastewater greatly increase the input of nutrients and organic matter to aquatic systems.

Rates of annual organic carbon accumulation in sediments of a variety of lakes are presented by Mulholland (1981) and are summarized in Table 1. These rates vary considerably depending upon lake size and trophic condition (Fig. 1). With the exception of meso-eutrophic Lake Erie and the Caspian Sea, which have accumulation rates of 30 and 19 gC m^{-2} yr^{-1}, respectively, large lakes have accumulation rates ranging from 2 to 10 gC m^{-2} yr^{-1}. Small oligotrophic lakes also have relatively low accumulation rates, mostly <40 gC m^{-2} yr^{-1}, but the upper end of the range is somewhat higher than that for large oligotrophic lakes. The higher accumulation rates of small lakes may be the result of their generally higher ratio of lake watershed area to lake volume. Greater flushing would seem to reduce accumulation of autochthonous production. The rapid filling is a consequence of more allochthonous inputs relative to lake volume in small lakes. Brunskill et al. (1971) have reported an inverse relationship between sediment carbon concentrations and water residence time for sixteen lakes in the Experimental Lakes Area of Canada. Inputs of organic matter to smaller lakes with short mean water residence times are often dominated by more refractory allochthonous organic matter from terrestrial systems rather than *in situ* production, which is more readily decomposed and dominates total inputs to large lakes. However, lakes which are culturally eutrophic (e.g., Lakes Wingra, Sammamish, and Erie in North America) have much higher rates of accumulation than would be predicted by their size alone, usually >30 gC m^{-2} yr^{-1} and some >100 gC m^{-2} yr^{-1}.

Because the rates of accumulation of organic carbon in lake sediments are relatively constant among large lakes (Fig. 1), which dominate global lake area, an estimate of global accumulation weighted by lake size can be made (Table 2). Our weighted estimate of carbon accumulation in lake sediments worldwide is $0.06 \cdot 10^{15}$ gC yr^{-1}. A second estimate can be made by assuming that a

Table 1. *Organic carbon accumulation in lake sediments (from Mulholland, 1981)*

	Mean accumulation rate ($gC\ m^{-2}\ yr^{-1}$)		
	n	Range	Mean
Small lakes (< 100 km^2):			
Oligotrophic*	14	3 to 128	27
Meso-eutrophic†	18	11 to 198	94
Large lakes (> 500 km^2):			
Oligotrophic‡	5	2 to 9	6
Meso-eutrophic§	4	10 to 30	18

* Mirror Lake, New Hampshire, U.S.A.; Lawrence Lake, Michigan, U.S.A.; Castle Lake, California, U.S.A.; Findley Lake, Washington, U.S.A.; Marion Lake, British Columbia, Canada; Char Lake, North-west Territories, Canada; Lakes Ennerdale and Wastewater, England; Lochs Clair, Coulin, and Sionascaig, Scotland; Zugersee, Walensee, and Aegerisee, Switzerland.

† Lake Wingra, Wisconsin, U.S.A.; Lakes Washington and Sammamish, Washington, U.S.A.; Bob Lake, Ontario, Canada; Linsley Pond and Rogers Lake, Conn., U.S..; Lakes Esthwaite, Loweswater, Blelham Tarn, Windermere, and Grasmere, England; Lakes Lucerne, Rotsee, Zurichsee, Griefensee, Zellersee, and Pfaffikersee, Switzerland; Lake Mikelajskie, Poland.

‡ Lakes Huron, Michigan, and Superior, U.S.A.; Lake Victoria, Africa; Lake Baikal, U.S.S.R.

§ Lakes Ontario and Erie, U.S.A.; Lake Biwa, Japan; Caspian Sea, U.S.S.R.

constant fraction of lake net primary production accumulates in the sediments. Likens (1975) estimated that an average of 200 $gC\ m^{-2}\ yr^{-1}$ are produced in world lakes. If sediment accumulation amounts to 10 to 15% of net primary production, then $0.04 \cdot 10^{15}$ to $0.06 \cdot 10^{15}$ $gC\ yr^{-1}$ are sequestered globally in natural inland lakes.

A relatively large portion of current organic

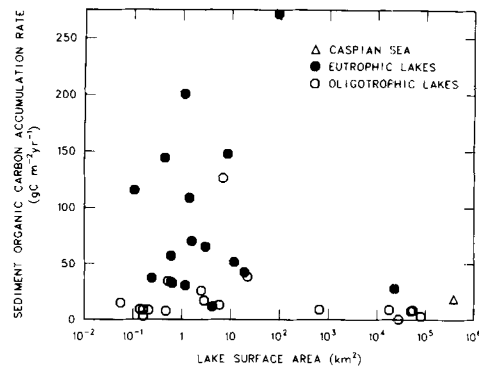

Fig. 1. Organic carbon accumulation in lake sediments as a function of lake size for oligotrophic (○) and eutrophic (●) lakes.

carbon accumulation in lake sediments is a recent increase resulting from cultural eutrophication and increased erosion in watersheds of lakes throughout the world. Rates of total sedimentation (both inorganic and organic) have increased from two- to six-fold in three lakes in western Washington since the mid-1800s (Birch et al., 1980), and about three-fold in Lake Erie and portions of Lake Ontario since 1930 (Kemp et al., 1974). Deevey (1972) reports that rates of organic carbon accumulation in the sediments of some Swiss lakes have increased by about 0.5 to 5 times since 1900. Greatly increased nutrient loadings with resulting increases in biomass and production have been reported for lakes throughout the world (Stewart and Rohlich, 1967; Ahl, 1975; Pennington, 1978). Even in Lakes Huron and Superior, which remain oligotrophic (Vollenweider et al., 1974), about one-fourth of the current organic carbon accumulation in sediments is attributed to increases resulting from anthropogenic activities (Kemp et al., 1978). Thus, perhaps as much as $0.015 \cdot 10^{15}$ to $0.03 \cdot 10^{15}$ $gC\ yr^{-1}$ (one-fourth to one-half of the

Table 2. *Global accumulation of organic carbon in sediments of natural lakes*

Lake category	Total area ($10^3\ km^2$)	Organic carbon accumulation rate ($gC\ m^{-2}\ yr^{-1}$)	Total organic carbon accumulation ($10^{15}\ gC\ yr^{-1}$)
Caspian sea	372	19	0.007
Lakes >4000 km^2	770	10	0.008
Lakes <4000 km^2	858	50	0.043
Total	2000		0.058

current global accumulation in lake sediments) is a recent increase resulting from cultural eutrophication of lakes throughout the world. Finally, Deevey (1972) has reported that total sediment accumulation over the past 10,000 years in a large number of European and North American lakes is relatively uniform, between 6 and 12 m. Assuming an average sediment accumulation of 9 m, an average specific density of 1 g cm^{-3}, and an average organic carbon content of 2% (typical of most large and oligotrophic lakes, Thomas et al., 1972; Brunskill et al., 1971), organic carbon accumulation has historically amounted to $0.04 \cdot 10^{15}$ gC yr^{-1}, globally, or about $0.02 \cdot 10^{15}$ gC yr^{-1} less than the current accumulation rate.

3. River impoundments as carbon sinks

Recently some have argued that organic carbon transport in rivers to the oceans may have increased in recent decades (Richey et al., 1980; U.S. Department of Energy 1981). However, construction of impoundments on many rivers throughout the world has increased the retentiveness of these river basins for particulate materials, including organic carbon. Thus, reservoir sediments may be important additional sinks for organic carbon if (1) the accumulated organic carbon represents part of an increased input to streams and rivers, or (2) if, in the previously unimpounded system, the organic carbon would have been oxidized in transport or on floodplains following its deposition.

The organic carbon accumulation in reservoir sediments consists partly of organic carbon transported into the reservoir by rivers and streams. Allochthonous inputs are greater in reservoirs than in natural lakes due to the generally greater watershed area:water surface area ratio for reservoirs. River impoundments generally trap >80% of the sediments transported into them by rivers (Roehl and Holeman, 1973). Trapping efficiencies of particulate organic matter, however, are somewhat lower because of its lower specific gravity compared to inorganic particles. Accumulation of organic carbon results, also, from primary production within the reservoir. Reservoirs usually support higher rates of net primary production than do unimpounded rivers (Wetzel, 1975), due to their unique combination of river and lake characteristics-particularly, high nutrient inputs, due to the high ratio of watershed area to reservoir surface area, and relatively long residence time of water compared to that in free-flowing rivers. High rates of total sedimentation in reservoirs cause rapid burial of organic carbon deposited on the bottom, inhibiting its oxidation. However, the typical variation in water levels in reservoir management may permit increased oxidation of organic deposits during some periods of the year.

Construction of river impoundments has likely altered the organic carbon dynamics of river systems. Because the reduced transport of allochthonous carbon in impounded rivers may be offset by an increase in the export of the products of autochthonous primary production from reservoirs, the question arises as to the net effect of impoundments on carbon transport in rivers. In their organic carbon budget for the Ivankovo Reservoir in the U.S.S.R., Kadukin et al. (1980) report that total annual output via downstream transport approximately balanced annual allochthonous inputs to the reservoir (via river transport), but amounted to only about 40% of total annual input (allochthonous plus autochthonous). Although a portion of the allochthonous input was retained within the reservoir, a similar amount of autochthonous production was exported, and the net change in total river transport after impoundment was small. Lind (1971) reported similar results for a reservoir in Texas. Thus, although there may be no appreciable reduction in river carbon load upon passage through reservoirs, the lack of reduction does not indicate that there is little carbon accumulation in reservoir sediments. This is because flushing from reservoirs of autochthonous production, which can be very large, compensates for the sedimentation of allochthonous and autochthonous production in the reservoir.

Water retention time appears to be an important determinant of organic matter retention in reservoirs. Summarizing budget data for readily degradable organic matter (BOD_5) in European reservoirs, Straskrabova (1975) reported that organic matter outputs were only 25 to 40% of total inputs for reservoirs having retention times >10 d, but the percentages were higher for reservoirs with retention times <10 d. In addition, oxidation of the incoming, terrestrially derived organic material is less in impounded rivers, because the organic matter is no longer maintained in transport in the well-oxygenated water column or deposited on floodplains which eventually dry out. The net effect of river impoundment on the global carbon cycle thus is (1) to reduce the transport and oxidation rate of allochthonous river organic carbon and (2) to increase the removal of atmospheric CO_2 by autochthonous primary producers (algae, macrophytes), both of which contribute to a carbon sink in reservoir sediments.

Widespread impoundment of rivers is a modern phenomenon, roughly paralleling the increase in fossil fuel use (Fig. 2). Prior to 1920, only one large reservoir (>1000 km^2), the Gauin Reservoir in Quebec, Canada, had been built. Since 1940, more than 40 large reservoirs covering more than 115,000 km^2 have been built worldwide (Fels and Keller, 1973). Ploskey and Jenkins (1980 reported that, in the United States, reservoirs >2 km^2 in

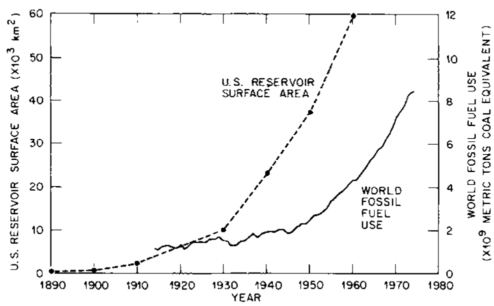

Fig. 2. Time course of reservoir construction and fossil fuel use.

surface area now cover about 40,000 km^2. Earlier, Martin and Hanson (1966) reported that there were about 60,000 km^2 of reservoirs of all sizes in the United States as of 1963. Estimates of total reservoir area in other parts of the world are much less certain. Avakyan and Sharapov (1968) estimated that reservoirs built for hydroelectric power production in the Soviet Union covered about 120,000 km^2. Worldwide, Fels and Keller (1973) estimated that by 1973 there were 315 reservoirs, each $\geqslant$100 km^2 and together covering an area >200,000 km^2. Using data of these authors, we estimate that the current total surface area of reservoirs $\geqslant$100 km^2 is about 260,000 km^2 (Table 3). The total surface area of reservoirs <100 km^2 is unknown, but in the United States they cover about as much surface area as the large reservoirs (Martin and Hanson 1966). Fels and Keller (1973) estimated global reservoir surface area to be >300,000 km^2 as of about 1970. Using these figures, we estimate total global reservoir area to currently be about 400,000 km^2.

Reservoir sedimentation rates are typically nonuniform. Sediment deposition rates are generally highest in the upper reaches of reservoirs, where suspended sediment concentrations are maximum and where river water velocities decline sharply, and in coves and embayments, where tributary streams empty into quiescent waters. Resuspension and redeposition of fine sediments may also "focus" sediment in the deeper portions of the basin, usually in the middle and lower portions of

Table 3. *Worldwide distribution of man-made reservoirs with a water surface area >100 km^2 each*

Location	Number	Approximate surface area (km^2)	Average surface area per unit storage capacity (km^2 km^{-3})	Percent of world total
U.S.S.R.	51	117,000	88.2	45
Canada	51	45,000	71.9	17
U.S.A.	112	32,000	79.1	12
Africa	17	28,000	44.4	11
Latin America	31	17,000	54.9	6
Asia (except India and U.S.S.R.)	18	10,000	41.4	4
India	25	7000	59.3	3
Europe	9	2000	43.4	1
Australia	12	2000	41.3	1
World	326	260,600	66.9	100

Source: Avakyan and Sharapov (1968), Fels and Keller (1973).

reservoirs. Sedimentation rates also vary greatly from reservoir to reservoir, ranging from <1 cm yr^{-1} to 22 cm yr^{-1} for those tabulated here (Table 4). Variations in sediment accumulation rates can be attributed largely to differences among drainage basins in climate, soil characteristics, land use, and upstream reservoir development.

There have been very few studies in which organic carbon accumulation in reservoir sediments was measured directly. However, estimates can be made from measurements of total sediment accumulation rates and percent organic carbon content of accumulated sediments. Approximately $1.2 \cdot 10^9$ m^3 of storage capacity is lost in the United States each year as a result of sedimentation (Dendy et al., 1973). Specific dry weights of reservoir sediments are generally 0.7 to 1.3 g cm^{-3} (Dendy and Champion, 1978); thus, about $1.2 \cdot 10^{15}$ g of sediment accumulate annually in U.S. reservoirs. The organic carbon content of these sediments, measured in various regions of the United States, is relatively constant at 1.5 to 2.0% (Ritchie et al., 1975; Ritchie and McHenry, 1977). Hence, about $18 \cdot 10^{12}$ to $24 \cdot 10^{12}$ g of organic carbon accumulate in U.S. reservoirs each year. Taking total U.S. reservoir surface area as 60,000 km^2 (Martin and Hanson, 1966), the annual accumulation rate per unit surface area is about 350 gC m^{-2}. Organic carbon accumulation rates computed for individual reservoirs throughout the world vary by as much as an order of magnitude on both sides of this figure (Table 4).

If the global reservoir surface area is 400,000 km^2 and the mean annual organic carbon accumulation

Table 4. *Annual rates of sediment and organic carbon accumulation in reservoirs*

		Sediment accumulation rate (cm yr^{-1})		Organic carbon accumulation rate* (gC m^{-2} yr^{-1})	
Region	Number	Range	Mean	Range	Mean
United States†	24	0.4–13.7	2.3	52–2000	350
Central Europe‡	10	0.1–11.1	3.1	14–1700	465
Asia§	16	0.8–22		20–3300	980
Africa‖	1		1.7		260

* Where only sediment accumulation rates are presented by the author, sediment specific weight was assumed to be 1 g cm^{-3} and sediment organic carbon content to be 1.5%.

† John H. Kerr, Virginia; Sardis and Grenada, Miss.; Guntersville and Wheeler, Alabama; Kentucky, Kentucky; Pickwick Landing, Cherokee, Douglas, Norris, and Watts Bar, Tennessee; Fontana, N. Carolina; Eufaula, Oklahoma; Texoma, Garza-Little, Whitney, and Belton, Texas; Elephant Butte, New Mexico; Roosevelt, Arizona; Mead, Nevada; Pathfinder and Seminoe, Wyoming; Fort Peck, Montana; Pine Flat, California (from Martin and Hanson, 1966; Dendy and Champion, 1978).

‡ Forggensee and Sylvensteinsee, F.R. Germany; Lesna, Pilchowice, Lubachow, Otmuchow, Turawa, Porabka, Roznow and Myczkowce, Poland (from Cyberski, 1973).

§ Rybinsk, Syzranskoe, Borschenskoe, Uspenskoe, and Nelidorskoe, U.S.S.R. (from Lopatin, 1965; Sorokin, 1972); Bahkra, Amaravathi, Standley, Panchet, Maithon, Mayurakshi, Tungabhadra, Matatila, Nizamsager, and Shivaji Sagar, India (from Rao and Palta, 1973; Ganapati and Sreenivasan, 1972; Murthy, 1980); Bhumibol, Thailand (from Chitchob and Cowley, 1973).

‖ Lake Nasser-Nubin, Egypt–Sudan, based upon reservoir volume of 157 km^3 and expected lifetime of 1700 years (from Entz, 1978).

rate 500 gC m^{-2} (roughly the mean of those presented in Table 4), about $0.2 \cdot 10^{15}$ g of carbon accumulate annually in reservoir sediments worldwide. While this amount is small compared to the amount of carbon released to the atmosphere by human activities, it does account for a portion of the "missing" carbon. Further, the annual accumulation of organic carbon in reservoir sediments is undoubtedly increasing, since new construction is continuing worldwide. Frey (1967) reported that reservoir surface area in the United States was increasing at a rate of about 3.5% per year, although it has slowed in recent years. Planned construction in the Soviet Union will eventually bring its reservoir area to about 250,000 km^2, a fourfold increase over the area reported in 1961 (Frey 1967). In less developed regions of the world, new reservoirs are being constructed for hydroelectric power, drinking water supply, and irrigation. Furthermore, as climates change in response to CO_2-induced global warming and as the price of fossil fuels increases, more reservoirs will be built for water supply, flood control, and hydro-electric power generation. Thus, the role of reservoir sediments as organic carbon sinks will increase in importance in the future.

4. Summary and conclusions

The role of inland aquatic sediments as sinks in the global carbon cycle is significant although small compared to that of terrestrial systems and the oceans. Annual carbon fixation by plants in inland waters amounts to only about $0.5 \cdot 10^{15}$ g worldwide, small compared to the $26 \cdot 10^{15}$ g of carbon fixation in the oceans (Woodwell et al., 1978). Compared to the oceans, a larger fraction of the carbon fixed in inland aquatic ecosystems is preserved in organic form in their sediments. This is the result of shallower water columns (resulting in a shorter time for oxidation of suspended particulate organic carbon), lower dissolved oxygen levels in bottom waters, higher production rates, and higher rates of total sedimentation in many inland waters. In addition, inland aquatic ecosystems receive large inputs of organic carbon from terrestrial ecosystems. These inputs are often less readily decomposable than organic carbon produced *in situ*.

Rates of organic carbon accumulation in the sediments of inland aquatic ecosystems appear to be related to the flushing rates of these systems (Fig. 3). The highest accumulation rates are found in systems which have relatively large inputs of terrestrial organic matter. These systems usually have high watershed area:water surface area ratios, which are usually inversely related to water residence time, but at the same time have sufficient water residence times for substantial sedimentation of allochthonous inputs and medium to high autochthonous production. Reservoirs, with water residence times intermediate between those of rivers and large lakes, have particularly high rates of sediment carbon accumulation.

Estimates of the contribution of inland aquatic ecosystems to the budget of the perturbed global carbon cycle are summarized in Table 5. Annual organic carbon accumulation in lake sediments amounts to about $0.06 \cdot 10^{15}$ g globally, one-fourth to one-half of which may be a recent increase in response to eutrophication. Reservoir develop-

Table 5. *Lake and reservoir sediments as sinks in the perturbed global carbon cycle*

System	Present organic carbon accumulation (10^{15} gC yr^{-1})	Recent increases in accumulation* (10^{15} gC yr^{-1})
Lake sediments	0.06	0.02
Reservoir sediments	0.2	0.2

* Increases occurring over the past 5 to 6 decades.

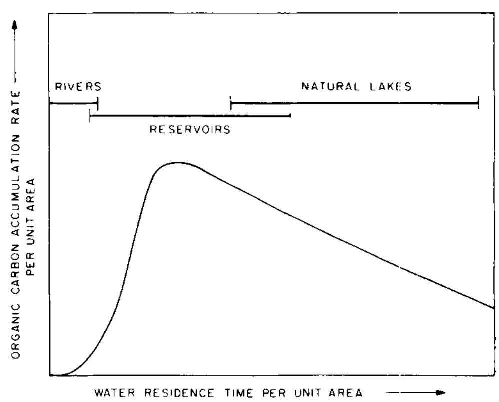

Fig. 3. Hypothesized relationship between organic carbon accumulation rates in sediments and water residence time in aquatic ecosystems.

ment, primarily an activity of the past five or six decades, has resulted in an increased organic carbon accumulation in freshwater sediments amounting to about $0.2 \cdot 10^{15}$ gC yr^{-1}. This estimate is probably conservative and will certainly increase as reservoir development continues worldwide. However, reservoir sediment accumulation may be temporary, in a geologic sense, if reservoirs are dredged or rivers are permitted to erode sediments after reservoir basins fill up.

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