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DENUDATION RATE OF CENTRAL NEW ENGLAND DETERMINED FROM ESTUARINE SEDIMENTATION

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ABSTRACT. Sediment transported by the rivers of central New England is delivered to Long Island Sound, which is a large estuary. Comparison of the sediment yield of the rivers and the present sediment accumulation rate in the estuary shows the trapping efficiency of the Sound to be 100 percent. High trapping efficiency for the entire marine regime of the Sound, which started 8000 yrs b.p., is inferred from oceanographic data. The average sediment yield of central New England rivers over the past 8000 yrs determined from the measured volume of marine sediment in the Sound is 4.2×10^8 kg/yr, the same as the present yield within the accuracy of the available data. The corresponding mean denudation rate is 1.0×10^{-2} kg/(m^{2}yr). The denudation rate is low, because most streams in central New England flow over stabilized surfaces on erosion resistant materials. The principal sediment source is collapse of river banks cut into glacial lake deposits. This bank erosion is insensitive to land use practices and is responsible for the continuous, nearly constant sediment yield of the basin for the past 8000 yrs. The sedimentation rate in glacial Lake Hitchcock between 13700 and 10700 yrs b.p. was three times that in Long Island Sound after 8000 yrs b.p. Streams in the drainage basin are underfit with respect to their valleys because there was a marked reduction in flow between 10700 and 8000 yrs b.p.

Estimates of the rate of loss of solid material from a drainage basin are often made from the sediment yield, the product of the measured sediment concentration, and the discharge of a river. River sediment concentration data are usually available for a few years only and may not be representative of the sediment transported over hundreds or thousands of years (Meade, 1969). If the trapping efficiency of a reservoir is known and its sediment content is measured, the sediment yield of its drainage basin can be determined for a much longer time span than may be possible with available river data (Young, 1969). Trapping efficiencies are usually estimated from Brune's (1953) empirical rule, which appears not to have been tested against the much more extensive reservoir data now available. Sediment yields computed from reservoir surveys are limited by the range of dam ages, and the data usually span the time interval during which drainage basins are most likely to have been disturbed by agriculture and engineering works.

Some estuaries trap nearly all the sediment delivered to them by their rivers. If the volume of sediment above some time horizon in an estuary of high trapping efficiency can be measured, an average erosion rate can be calculated for what may be a much longer time base than is available from reservoir data. It is necessary to make allowance for sediment entering the estuary from other sources, carried in from the sea, or produced in the estuary by biological activity, for example. Trapping of riverine sediment in estuaries is favored while sealevel is rising after glaciation, so the method may be widely applicable. It is illustrated here by an examination of the sediment yield of the drainage basin of Long Island Sound, the estuary that receives the river discharge from much of central New England.

MEASUREMENT OF THE SEDIMENT YIELD

The drainage basins of the principal streams entering Long Island Sound are shown in figure 1; numerical data are given in table 1. The Connecticut River is the dominant source of fresh water and sediment, while the Housatonic and Thames are the only other large rivers entering the Sound. Estuarine circulation in Long Island Sound results from the salinity gradient caused by the inflow of fresh water. More-saline bottom water flows westward, and less-saline surface water, eastward (Riley, 1952,

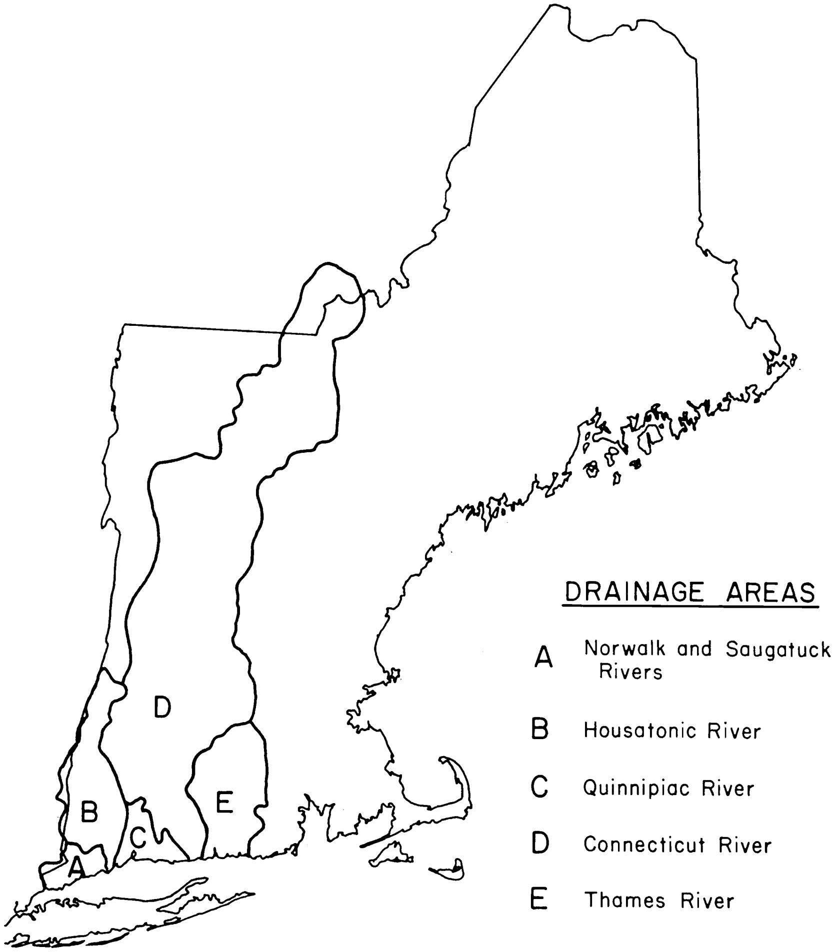

Fig. 1. The principal drainage basins supplying fresh water to Long Island Sound. Small streams not named on the map enter the Sound directly in addition to the named streams in areas A, C, and E.

TABLE 1
Drainage basin areas for Long Island Sound

Connecticut River	29008 km^2
Housatonic River	4999
Thames River	3626
All others	3341
Total	40974

1956; Wilson, 1976). The configuration of the Sound is unusual in that the principal inflow of fresh water, from the Connecticut River, enters near the seaward end (fig. 2). The river discharge is mixed with the bottom water and carried into the central and western Sound before being diluted with additional fresh water and returned to the sea in the outward surface flow (Gordon and Pilbeam, 1975). Silt-clay sediment entering the Sound from the Connecticut River is also carried westward with the bottom water. It passes over the existing muddy bottom of the central Sound and is eventually added to the permanent mud deposits there (Bokuniewicz and Gordon, 1978).

At the maximum of the Wisconsin glaciation, about 18000 yrs b.p., the southern margin of the ice sheet was on Long Island (Flint, 1971). During the subsequent retreat of the ice, much outwash sand and some lacustrine silt and clay deposited in the Long Island Sound basin (Grim, Drake, and Heirtzler, 1970). By 14200 yrs b.p. most, if not all the Sound was clear of ice (Davis, 1969), and its basin was occupied by a large lake separated from the sea by the Mattituck sill (Bokuniewicz, Gebert, and Gordon, 1976). Lacustrine sediments were deposited in the deeper parts of the basin until about 8000 yrs b.p. At that time the sea overflowed the Mattituck sill, the Sound was converted to an estuary, water from the Connecticut River gained access to its central basin, and the present regime of marine sedimentation began.

The total volume of lacustrine and marine sediment inside the Mattituck sill measured from acoustic reflection profiles (Bokuniewicz, Gebert, and Gordon, 1976) is 1.0×10^{10} m^3. Of this, 4.3×10^9 m^3 is sand reworked from the Sound bottom by the tidal stream, and 4.9×10^8 m^3 is thought to be lacustrine. (Positive identification has not been made because no cores penetrating the presumed lacustrine sediment are available.) The mean dry density of Long Island Sound marine mud, measured on core samples, is 0.8 Mg/m^3, and the total mass of silt-clay sediment deposited under marine conditions is 4.2×10^{12} kg. Since the marine regime has lasted ~8000 yrs, the average annual accumulation rate of silt-clay sediment is 5.2×10^8 kg/yr. Error in the determination of this rate may arise from two causes, uncertainty in the sediment volume within the Sound and in the duration of the marine regime. The error in the volume measurement is thought to be relatively small because of the dense network of reflection profile tracks used to map it and the sharpness of the acoustic reflection from the outwash sands on which the marine sediment is deposited throughout most of the Sound. The principal uncertainty in the determination of the date at which the sea reentered the Long Island Sound basin arises from uncertainty in the estimated elevation of the lake spillway on the Mattituck sill. The rise of sealevel as the sea approached the spillway was relatively rapid, and errors in the elevation estimate cause relatively small errors in the date. It is estimated that the uncertainty in the average sediment accumulation rate from all causes is about 10 percent.

In order to find the sediment yield from the observed, long term sedimentation rate, the trapping efficiency of the Sound must be determined. The present day rate at which sediment enters the Sound can be estimated with some confidence. The contemporary sedimentation rate has been measured. A comparison of these will be used to show that the trapping efficiency is 100 percent. Examination of the marine history of the Sound shows that this is unlikely to have changed in the past 8000 yrs.

Sediment entered Long Island Sound during the postglacial marine regime from rivers, by inward transport from the sea, and from erosion of the shoreline. Airborn transport and biological production in the estuary also supply sediment, but these sources are probably small compared to the input from the rivers (Benninger, ms). In 1908 Dole and Stabler estimated the sediment yield of the Connecticut River to be 0.8 $\times 10^8$ kg/yr. They also reported delivery of 9 $\times 10^8$ kg/yr of dissolved material, and it seems likely that they have reported as "dissolved" much material that would be reported as "suspended" today. The suspended sediment concentrations at the Enfield Dam (the sampling station closest to the river mouth) have been regularly sampled in recent years. Benninger (ms) used these data to estimate that the suspended sediment passing the Enfield Dam is 3 $\times 10^8$ kg/yr. Combination of data from upstream suspended sediment sampling stations (Anonymous, 1975) yields 5 $\times 10^8$ kg/yr. Benninger has shown that the area of marsh in the Connecticut River estuary is too small to trap a significant fraction of the

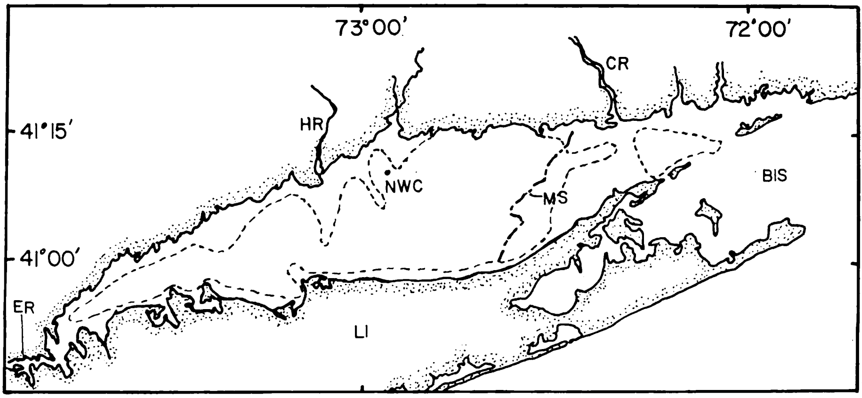

Fig. 2. Long Island Sound, showing the area of the bottom covered with silt-clay sediment (within dashed lines). Features identified are ER, East River; HR, Housatonic River; CR, Connecticut River; BIS, Block Island Sound; LI, Long Island; and MS, the Mattituck sill. The core taken for radiometric determination of the sedimentation rate is from location "NWC".

river sediment. Little sediment is trapped behind dams on the river (Anonymous, 1975), so that essentially all the suspended sediment carried by the river must enter Long Island Sound. (Bed load transport is thought to be relatively small but may contribute to the sand delta at the river mouth; the volume is negligible compared to that of the marine mud deposit in the Sound.) Sediment yield data are not now available for the other rivers and streams entering Long Island Sound. It is assumed that they contribute in proportion to the areas of their watersheds relative to that of the Connecticut River. The present sediment yield of the rivers estimated from all these data (with allowance for their relative reliability) is 4.7×10^8 kg/yr. If all this sediment were to deposit on the existing mud bottom of the Sound, the resulting accumulation rate would be 0.26 kg/(m^2 yr) and the upward growth rate of the Sound bottom due to the present input of riverine sediment would be 0.33 mm/yr.

The sediment accumulation rate at one location in Long Island Sound has been measured by Benoit, Turekian, and Benninger (1979). They used the radiocarbon method to date sediment as a function of depth over the past 1400 yrs and found accumulation at a constant rate of 0.7 ± 0.1 mm/yr at the location designated "NWC" (see fig. 2). The sediment accumulation rate on the bottom of the Sound is not uniform, and the spatial variation of the long term mean rate has been mapped (Bokuniewicz and Gordon, 1978). We will assume that this spatial variation holds for the sedimentation rate over the past 1400 yrs. The ratio of the long term rate at site "NWC" to the long term mean rate is 1.4. Benoit, Turekian, and Benninger's data, therefore, imply that the mean sedimentation rate in the Sound over the past 1400 yrs is 0.5 mm/yr. This exceeds the 0.33 mm/yr rate due to riverine sediment, so it is concluded that all sediment delivered to Long Island Sound by rivers is trapped on the existing mud bottom of the Sound and that additional sediment sufficient to contribute 0.1 to 0.2 mm/yr to the bottom growth rate may be entering the Sound from erosion of the north shore of Long Island or from the sea, carried in by the estuarine circulation. Evidence of inward sediment transport from the sea has been presented by Hathaway (1972) and Wakeland (1978) from studies of the clay mineralogy of the mud in Long Island Sound. The erosion rate of the north shore of Long Island over the past 90 yrs has been determined by Davies, Axelrod, and O'Connor (undated rept., Marine Sci. Research Center, State Univ. of New York, Stony Brook), but composition data for the eroded material that would permit an estimate of its contribution to the marine mud deposit in the Sound are not available.

When the sea entered Long Island Sound, the central and western Sound basin was occupied by a large lake. The size and configuration of the lake were such that when it was connected to the sea, the resonant semi-diurnal tidal oscillation characteristic of the Sound today would have been initiated early on. Thus, it is likely that the present hydraulic regime of the Sound — a large resonant co-oscillating tide with superimposed estuarine circulation — has been in existence for the major part of the 8000 yr duration of the present marine period. The tidal stream is too strong to permit deposition of silt-clay sediment on the sandy bottom of the Sound, but nuclei for deposition of muddy sediment were present in the form of lake deposits. Thus, it is likely that Long Island Sound has been a trap for all riverine sediment delivered to it for the past 8000 yrs.

It was shown above that sediment has been accumulating in the Sound at the average rate of 5.2×10^8 kg/yr for the past 8000 yrs. If we suppose that 20 percent of this has entered the Sound from the sea or from shoreline erosion (as demonstrated for the present sedimentary regime), then the average sediment yield of the rivers entering the Sound has been 4.2×10^8 kg/yr for the past 8000 yrs. This is the same, within the accuracy of the data, as the present yield of 4.7×10^8 kg/yr. Thus, the sediment yield has remained constant over 8000 yrs, or, if there have been intervals of increased yield, these have been compensated by periods of decreased yield. Since there is no significant sediment storage in the larger reservoirs on the river system, the sediment yield is a measure of the rate at which earth materials are being removed from the drainage basin. This may be expressed as an average denudation rate of 1.0×10^{-2} kg/(m^{2}yr) to facilitate comparison with rates reported for other regions. (Normalizing the sediment yield to drainage basin area may not be the best method of comparison, since different mechanisms of denudation may be active in different basins. It is used here because of a lack of data that identify the denudation processes in other areas.) Computed mean denudation rates for comparison with the central New England data are listed in table 2. The reservoirs listed were selected because of the long time base of the data published for them and because they receive drainage from glaciated terrain. The Unadilla and Tioga rivers have the smallest and largest yields reported by Williams and Reed (1972) for the Susquehanna River basin. They illustrate the great vari-

TABLE 2

Denudation rate computed from sediment yield

Locality	Reference	Time interval	Denudation rate
Estuary			
Long Island Sound	—	8000 yrs	1.0×10^{-2} kg/(m^{2}yr)
Reservoirs*			
North Esk	Lovell and others (1973)	121	2.5
Cropston	Cummins and Potter (1967)	95	2.9
Strines	Young (1958)	87	5.4
River			
Unadilla	Williams and Reed (1972)	2	1.3
Tioga	Williams and Reed (1972)	3	11.4
Susquehanna	Williams and Reed (1972)	**	3.6
Driftwood	Williams and Reed (1972)	1	2.3

* Computed for dry sediment having 18 percent of volume of wet sediment.
** Composite of data spanning up to about a decade.

ability of the sediment yield in the glaciated part of this basin. Driftwood Branch was selected by Lewis (ms) as representing the denudation rate of unglaciated, undisturbed, forested land. The sediment yield of the Long Island Sound drainage basin is the smallest of all those listed in table 2. Since it has been nearly constant for the past 8000 yrs, it is unlikely that the low denudation rate of central New England is due to the relatively long averaging time used. The area of the drainage basin is smaller than that of the Susquehanna, so a basin size effect is not probable. Alternative reasons for the low rate are discussed below.

DISCUSSION

The denudation rate.—The small denudation rate in the Long Island Sound drainage basin over the past 8000 yrs is most likely due to the erosion-resistant mechanical properties of the earth materials over which water flows in the basin. Sediment may enter a stream in several ways. It may be removed from the land surface by overland flow (Horton, 1945). Temporary rills (rills that are destroyed by soil creep in the interval between rains) may be formed. New streams may develop where none were before, as by the extension of gullies (Ireland, 1939). Sediment may also enter existing streams directly by excavation of the stream bed or by bank erosion or collapse.

In the Long Island Sound drainage basin, streams flow over bed rock, glacial till, and unconsolidated materials such as glacial outwash, ice contact stratified drift, or alluvium (including former lake deposits). The contribution of bed rock to the particulate matter in streams is negligible for the time span of interest here. It is believed that the same is true of till for both overland flow and for stream bed and bank erosion. The distribution of particle sizes in much of the till in the drainage basin is similar to that that makes excellent stabilized road surfaces. The silt-clay component of the till has sufficient cohesion to hold the stones and cobbles of the till in place. Inspection shows that overland flow removes exposed fine-grain components and leaves an armored surface on the till that is resistant to further erosion. Fines available for further erosion are only released by subsequent mechanical disturbance of the surface. River beds and banks in till-covered areas are observed to become similarly armored once the bank slopes become sufficiently low. The small amount of material removed from these banks may be made up by soil creep so that the channel cross section may remain stable.

Unconsolidated materials in the Long Island Sound drainage basin are subject to erosion by overland flow where a bare land surface is exposed. These materials are also eroded, where they make up the banks and bottoms of established streams. In the southeastern United States almost all the land surface is on unconsolidated or deeply weathered material, and about 90 percent of the sediment entering streams is introduced by sheet erosion (Roehl, 1962). Much of the sediment eroded from the land surface is held in storage in the upper reaches of the drainage basins (Trimble, 1977), but anthropogenic effects have increased the suspended sediment load of streams in the southeastern United States by a factor of four (Meade, 1969). It is estimated from examination of published geological maps that unconsolidated materials cover only about 10 percent of the surface area of the Long Island Sound drainage basin; much of this material is concentrated in the valleys of the larger streams. In this basin the present stream load of suspended sediment is the same as the long term average load even though much of the land in the Connecticut Valley is still used for agriculture. Thus, it seems likely that little of the sediment delivered by the rivers of the basin enters the streams by overland flow or by the creation of new streams or gullies. Most of it must be obtained from the beds and banks of established streams. Inspection suggests that the most important of these sources on the larger streams is the collapse of banks due to seepage pressure resulting from rapidly falling water level, as during the recession stages of a flood. (Under flood conditions water velocities are great enough to scour banks at only a few locations on the Connecticut River, for example Anonymous, 1976.) Since bank collapse is little influenced by land use patterns, no marked changes in the sediment delivery rates over the past 8000 yrs are expected.

The stream density in the Long Island Sound drainage basin is about 1 km^{-1}, and the total length of stream bank is about 8×10^4 km. If all the sediment delivered by the rivers to the Sound is supplied by bank collapse and erosion, the density of the bank material averages 2 Mg/m^3, and the average bank height is 0.5 m, then the average rate of bank retreat would be 5 mm/yr; the total retreat for the past 8000 yrs would be 42 m. (Where a stream is eroding one bank and depositing sediment on the opposite bank, as described by Leopold, Wolman, and Miller (1964, p. 325), a 0.5 m height difference between the opposite banks is assumed.) For reasons discussed above, the rate of retreat of banks composed of till will be substantially less than that of banks of unconsolidated materials (quantitative data are not available). Smaller streams are more likely to be flowing directly on till, and larger ones, on unconsolidated material. Observation shows that erosion of stream banks composed of unconsolidated material is often quite localized. Hence, local bank erosion rates may be very much greater than the mean. Some quantitative data are available for the Connecticut River (Anonymous, 1974). They show that the present sediment yield of the river can be accounted for in terms of the observed bank retreat at places of active erosion along the river. At most of these places the river banks are cut into sediments deposited in former glacial lakes. These glacial lake deposits are thus the principal source of sediment in the Long Island Sound drainage basin. Williams and George (1968) have suggested that the same is true for the glaciated portion of the Susquehanna River basin.

None of the stream-flow erosion-rate data, short term or long term, yield useful information about the rate of change of relief of the central

New England land surface. Larger amounts of debris were produced during glaciation than could be cleared from the land surface by ice flow and the subsequent flushing by melt water. (A similar conclusion for other glaciated areas has been advanced by Church and Ryder, 1972.) The dominant activity of the river system of the Long Island Sound drainage basin continues to be the rearrangement of the debris produced during glaciation. The streams in the basin have not attained steady state in the sense that the rate of sediment production by erosion balances its rate of removal by the drainage system. The time required to attain such a steady state is estimated to be at least 10^5 yrs, the time required to remove accumulated glacial debris at the present denudation rate. The rate-limiting step in the denudation process for the past 8000 yrs has been the insertion of debris into the streams, principally by stream-bank erosion. Thus, denudation rate data for this drainage basin are a measure of the rate of insertion of sediment into the streams. They do not yield an erosion rate.

Time variation of the denudation rate.—The available data show that the sediment yield in the Long Island Sound drainage basin has been constant over the past 1400 yrs and is the same as the average yield over the past 8000 yrs. Short term fluctuations in this rate may have occurred, but they may not be recorded in the estuary sediment because bioturbation mixes the surficial sediment layer to a depth of at least 10 mm (Rhoads, 1974), equivalent to 30 yrs of sediment accumulation. Evidence of large changes in the denudation rate since the end of the last glaciation is found in the Connecticut Valley, however. For a period of about 3000 yrs ending at 10700 yrs b.p. the Connecticut Valley between Rocky Hill and the ice margin was occupied by Lake Hitchcock (Flint, 1956). Two estimates of the denudation rate during the existence of Lake Hitchcock can be made. Deltas of outwash sand were formed around the lake margin, but deposits of varved clays accumulated over most of the lake bottom. The rate of delivery of sand to the Chicopee delta in Lake Hitchcock has been estimated to be 2.2×10^6 m^3/yr (Ashley, 1975). The minimum denudation rate in the Chicopee drainage basin was then 1 mm/yr while the delta was being formed. The bottom area of Lake Hitchcock was 1640 km^2, about the same as the area of mud bottom in Long Island Sound, 1680 km^2. Volumetric measurements of the Lake Hitchcock sediments have not yet been made, but since the varved clays range up to 30 m thick (Jahns, 1947), the quantity of lake bottom sediment can hardly be less than the volume of mud in Long Island Sound. Since the lake lasted for only about 3000 yrs, the mean rate of deposition of silt and clay in it must then have been at least three times greater than the rate in the Sound from 8000 yrs b.p. onward. Dury has described many of the rivers and streams in the Long Island Sound drainage basin as being "underfit" today and ascribed this to a large diminution of stream flow due to climatic change. Limits can be placed on the time at which this change took place. The change in stream flow in underfit streams, which cross sediments that were deposited in glacial Lake Hitchcock, must have occurred after the draining of the lake, that is, after 10700 yrs b.p. It could not have occurred much after 8000 yrs b.p. or a larger amount of sediment would be present in Long Island Sound today.

Application to other estuaries.—If sedimentation in an estuary is to be used to determine the erosion rate of a drainage basin, the estuary must be an efficient trap for riverine sediment. Several conditions must be met. The first is that the estuary have sufficient volumetric capacity to retain the sediment delivered by its rivers. If the estuary has sufficient initial area, this condition will continue to obtain if the rate of rise of sealevel is greater than the upward growth rate of estuarine sediment deposit. (In Long Island Sound it is 10 times greater.) Since sealevel is rising on coasts not subject to subsidence from tectonic activity or removal of ground water (Hicks, 1978), it is expected that this condition will be satisfied in many localities. The second requirement is that the rate of dissipation of tidal and storm energy in the estuary must be low enough to allow retention of the sediment delivered under all runoff conditions. The acceptable dissipation level is raised substantially when benthic animal communities capable of processing the delivered sediment into more easily deposited forms are present, as they are in Long Island Sound (Rhoads, 1974). Finally, the estuary must be of sufficient volume relative to the river flow that the main salinity gradient is confined within the estuary. (This is not true for the mouth of the Connecticut River, for example, Garvine, 1974. The sediment load of the river is deposited in the Sound rather than in the River estuary.)

An additional requirement is that identifiable time horizons be present in the marine sediment of the estuary. Glacial outwash sand provides such a horizon in Long Island Sound and probably can be so used in many estuaries in glaciated areas. Examples of other estuaries that seem to be suitable sites for determination of drainage basin denudation rates are Narraganssett Bay and Penobscot Bay on the northeast coast of the United States.

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