The Impact of Susquehanna Sediments on the Chesapeake Bay

Chesapeake Bay Program

Scientific and Technical Advisory Committee

Workshop Report

May 2000

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The Susquehanna River Basin Commission (SRBC), appointed a special Sediment Task Force to assess the potential increase in sediment delivery by the Susquehanna river to the Bay as a result of the filling of the Conowingo and other reservoirs and to evaluate the possible management actions for the reduction or limitation of such increases.

In response to a request from the SRBC, the Scientific and Technical Advisory Committee of the Chesapeake Bay Program (STAC) convened a small group of experts to assess the potential impact of increased sediment delivery from the Susquehanna river on the Bay.

This report presents the conclusions reached at a STAC Workshop to survey these issues, held on March 29th, 2000 at the Belmont Conference Center, Elkridge, MD.

Technical Presentations

The Susquehanna River Basin Commission Sediment Project
Mr. Thomas Beauduy, Chesapeake Bay Commission

Delivery of Sediment and Nutrients in the Susquehanna, History and Patterns
Mr. Michael Langland, USGS, Lemoyne, PA

Deposition and Distribution of Sediment in the northern Chesapeake Bay
Mr. Jeff Halka, Maryland Geological Survey, Baltimore

Physics of the Chesapeake Bay Estuarine Turbidity Maximum
Dr. Larry Sanford, University of Maryland Center for Environmental Science

Chemical Dynamics of Chesapeake Bay Sediments
Dr. Jeffery Cornwell, University of Maryland Center for Environmental Science

Sediment Impacts on Submerged Aquatic Vegetation
Dr.Kenneth Moore, Virginia Institute of Marine Science

Impacts of Sediment Delivery on Benthic Organisms
Dr.Linda Schaffner, Virginia Institute of Marine Science

Estuarine Turbidity Maxima, Water Quality, and Recruitment of Anadromous Fish
Dr. Edward Houde, University of Maryland Center for Environmental Science

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Dr. Richard A. Weismiller, Chairman, Department of Natural Resources Research and Landscape Architecture, University of Maryland, College Park

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Dr. Alan W. Taylor, Chesapeake Research Consortium, Edgewater, Maryland

GENERAL SUMMARY

The Objective of the Workshop was to survey the possible consequences of the increased delivery of sediments from the Susquehanna river to the Chesapeake Bay as a result of the loss of retention of sediment storage in the reservoirs behind the existing dams on the river.

The material presented emphasized **the complexity of the possible effects** of increases in sediment discharge to the Bay and of the increase in severity of scouring events. This is compounded by our inability to forecast the timing or intensity of these scouring events in the river and reservoirs. Detailed predictions are therefore not possible but the consequences that can be predicted with most confidence are:

1) Increased loading of phosphorus in the Middle Bay below the Estuarine Turbidity Maximum zone (the ETM) from sediments that move beyond this zone during large-flow scouring events.

2) Increased needs for dredging the navigation channels in the Upper Bay as the overall load of sediment deposition in the Upper Bay increases. Past information shows that almost all of the sediment delivered by the Susquehanna River is deposited north of the Baltimore area. There is a tendency for high rates of accumulation of finer materials in the deeper channels. These areas are those where the greatest impacts from increased sediment delivery can be expected. If channel dredging continues it will have to be more frequent, and with increased costs.

3) Higher turbidity and faster sedimentation everywhere, but especially in the navigation channels. The range of flow dynamics will be increased, especially during storms. Without channel dredging there will be rapid channel filling, downstream displacement of the salt front, and possible major changes in circulation and sedimentation patterns.

4) Adverse effects on the recovery of Submerged Aquatic Vegetation (SAV) due to decreased light penetration. Most SAV species in the bay have high light requirements. Sediment solids are always a major factor and any increase in the amount present will be a serious hindrance to the recovery and re-establishment of the SAV population and the habitat which this provides for many of the Bay biota.

5) Benthic organisms will be adversely affected by increased sediment loads that increase the energetic costs from burial. Episodic deposition also rapidly increases mortality and recruitment. Young oysters are sensitive to increased sediment deposition and long-term community structures will be changed by the impoverishment of the macrofauna.

6) Potential effects of increased sediment loading on fish populations in the Upper Bay and the ETM include:
1) direct effects of feeding, clogged gill tissues and smothering of eggs;
2) indirect effects on the abundance of planktonic prey of larval and juvenile fish, and
3) habitat alterations through increased silting and sedimentation with changes in the location and mode of operation of the ETM.

To the extent that increased sediment loading in the Upper Chesapeake Bay will require more dredging and associated activities to maintain channels there may be an increased threat to spawning and nursery habitats for anadromous fishes: this may become an issue in the future.

WORKSHOP PROCEEDINGS

Susquehanna River Basin Commission Sediment Project

Thomas Beauduy, Chesapeake Bay Commission

The Sediment Task Force was established by the Susquehanna River Basin Commission (SRBC) to explore the issues raised by the long-term buildup of sediments behind the Susquehanna dams and to evaluate the problems that are expected to arise as the Conowingo dam is filled to a level where sediment is no longer retained. As a result of this filling, sediments loads delivered annually to the Bay by the river are expected to increase by a factor of 150%.

As part of this assessment the Commission has asked the Scientific and Technical Advisory Committee (STAC) to examine the implications of this increase for the physical conditions and ecology of the Bay.

Delivery of Sediment and Nutrients in the Susquehanna, History and Patterns

Michael Langland, USGS, Lemoyne, PA

Three dams on the river act as sediment retention structures. Safe Harbor and Holtwood are already at saturation. Conowingo, built in 1929, still retains 50 to 70% of the sediment that reaches it. It is estimated that it will reach saturation about 20 to 30 years from now, when the average annual sediment flow to the Bay will increase by 150% or more.

Regression analysis of 100 years of water flows indicates a slight increase in the long-term trend. The most variable flows have occurred in the last 30 years. In contrast there has been a decrease in sediment transport due to both climate variability and the effects of management strategies to reduce sediment delivery to the river and its tributaries.

Large volumes of stored sediment are also released during “scouring flows” when the river flow exceeds about 400,000 cfs. The most recent events were in 1972, 1975 and 1996. In a total period of about three weeks these events released about 33 million tons of sediment, equal to about 10% of the total stored behind the dams. The effect of the dams is therefore to increase the amounts of sediment released during flood events and to decrease the amount discharged during average and low flow years. With the filling of the Conowingo dam the beneficial trapping effects of the dams will be lost and there will be an increase in sediment discharge in average and low flow years, but high flood events will continue to release scoured materials from the deposits behind the dams. This scouring will partly restore the storage of capacity of the dams for a limited time after the flood, but the resulting benefit is not likely to be of long duration.

SUMMARY: There has been a significant decrease in sediment delivery over time. The sediment storage capacity of Conowingo is decreasing, and it is likely to reach its full retention capacity within 30 years. When this happens sediment delivery to the Bay will increase by about 150% with a concomitant increase in phosphorus. As the dam fills there will also be an increase in the amounts of sediment discharged during scouring events that remove sediment retained behind the dams.

Deposition and Distribution of Sediment in the northern Chesapeake Bay[1]

Jeff Halka, Maryland Geological Survey, Baltimore

Predictions of the fate of increased sediment discharges from the Susquehanna can be made on the basis of the distribution of sediment that has entered the Bay in the past. Over the last 21 years the mean annual discharge from the Susquehanna has been 1.31 million metric tons per year (Mt/y), with a median annual discharge of 0.95 Mt/y. The difference between the mean and the median indicates the influence of a few years of high sediment discharge. The effects of very intense episodic events such as the Agnes (1972) and Eloise (1976) storms - which are not included in these years - will increase the discharge for individual years above these values. It is estimated that Agnes discharged about 30 Mt and Eloise 10 Mt to the Bay.

The textural characteristics of the bottom sediments reflect and integrate both long and short-term process operating in the water column. A regional map of the particle size distribution of the existing surficial Bay deposits shows that the marginal shallow areas are characterized by sand sized sediments reflective of an environment with higher mechanical energy. Wind generated waves and rising sea level have combined to form shallow platforms carpeted with the sand-sized materials. Finer grained materials supplied both from the watershed and removed from the shallow water higher energy regions are deposited in deeper areas of the Bay system.

A sediment budget published in 1984 estimated that 70% of the Susquehanna input is retained within the ETM, which is usually located between Tolchester and Turkey Point, with only about 4% being deposited south of the Bay Bridge. The sandier fraction of the Susquehanna supplied sediment is generally found in the Susquehanna Flats region, immediately below the river's mouth. Sandy sediments derived from shoreline erosion are also found in the shore adjacent platforms in water depths of less than 3.5 meters. The silt and clay sized components supplied by the river and from shoreline erosion dominate the bottom in the remaining areas. Shoreline erosion contributes about 15% of the total fine grained sediment load to the upper Chesapeake Bay. Combined with input from the Susquehanna River the total fine-grained sediment load averages 1.87 Mt/y.

Throughout much of the entire Bay the average rate of sediment deposition is less than about 1.5 mm/year, and approximates the long-term rate of sea level rise. The deeper channel regions have higher rates of accumulation, which approach 5mm/yr in the middle and lower portions of the estuary. In the upper Bay, however, rates of sediment accumulation are much higher and reflect both the large sediment loads supplied by the Susquehanna River and the effective trapping mechanisms that occur in the ETM region. Fine-grained sediments accumulate away from the shorelines at an average sedimentation rate of 6.2 to 7.8 mm/yr, and the rate in the deeper maintained shipping channels is significantly higher at approximately 170 mm/yr.

The retention of sediment supplied by the Susquehanna in the upper Bay reflects a combination of factors. Rapidly settling particles (eg. sand sized) settle in the Susquehanna Flats area. Across the ETM bottom sediments grade from silty sands and sandy silts close to the Flats

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[1] For a more extensive survey of sediment deposition in the entire Chesapeake Bay, see Appendix A.

area and to clayey silts further from the river. Beyond the normal location of the ETM the bottom sediments consist predominantly of silty clays. This gradation indicates that particle-settling velocities have a dominant effect on the retention of sediments. The finest grained, and thus slowest settling, particles that escape the ETM region in southward flowing surface waters may be swept back by a net return flow at lower depths. During major discharge events the flow structure of the northern Bay is seaward at all depths and under these conditions much of the sediment may be transported beyond the normal ETM zone. The degree to which this sediment may be returned in the northward directed bottom flow under subsequent normal conditions has not be determined at this time.

SUMMARY: These lines of evidence and data suggest that almost all of the sediment delivered by the Susquehanna River is deposited north of the Baltimore area with a tendency for high rates of accumulation of finer materials in the deeper channels. These areas are those where the greatest impacts from increased sediment delivery can be expected. Since this information is based on long-term trends, it should not however be interpreted as showing that the sediment input, particularly from very large events, will be wholly limited to the Upper Bay. During major storm events the flow structure of the Bay is radically altered and sediment delivery can increase far beyond the long-term trends. The ultimate fate of the material from such events will however depend upon its subsequent fractionation and transport under the more persistent flow patterns of the Bay.

Physics Of the Chesapeake Bay Estuarine Turbidity Maximum

Dr Larry Sanford, University of Maryland Center for Environmental Science

Upper Chesapeake Bay is a turbid, light-limited environment with a general background of high concentrations of suspended solids. It is dominated by muddy bottom sediments derived primarily from the Susquehanna River. The ETM, typically about 20 km in length, is usually found in a 40 km reach of the upper Bay between Tolchester and Turkey Point. It is an efficient trap for terrestrial particles of an intermediate range of settling speeds. Larger particles remain in the Susquehanna flats delta. Smaller, slower settling particles are carried seaward. In space and time the ETM contains a limited pool of particles that disappear due to sedimentation and are resupplied from new Susquehanna River inflows. The ETM is maintained by tidally pulsed sediment transport convergence near the intersection of the 1psu isohaline with the bottom.

The ETM is a dynamic feature, responding rapidly to changing physical forcing. Important physical forces for sediment transport include freshwater flow, tides, currents associated with the estuarine circulation and saltwater intrusion, wind-forced currents, and waves in shallower water. Predicting sediment resuspension, transport, and deposition, particularly of scoured sediments, is difficult because the different physical forces can occur in complex, time-varying combinations. At the present time, there is no predictive sediment transport model for the Chesapeake Bay, though models of smaller tributaries have been developed.

Resuspension of sediments temporarily deposited on the shoals adjacent to the main channel occurs during storms, largely due to wind-waves and currents. This results in preferential deposition in the channel, which are isolated from waves by their depth. Thus, even though the shoals account for almost all of the sediment surface area of the upper Bay, deposition rates on the shoals are many times lower than in the channel.

A key factor for the efficiency of sediment trapping in the ETM is how fast particles settle, which is controlled by the rate of aggregation of fines. This is due to their “stickiness”, which is only partly related to electrochemical flocculation. Settling rates may be seasonally dependent with more rapid aggregation in the warmer months when organic matter increases and the “stickiness “ of the particle increases. As an example, in October 1996 there was a pulse of fresh water carrying a large amount of sediment that was rapidly trapped in the ETM. In contrast, during the February 1996 flood a large amount of sediment bypassed the ETM and entered the mid-Bay. Though some of the sediment carried into the mid-Bay in such situations may be carried back in the deep return flow of the estuarine circulation, major events such as the February 1996 flood may represent an increased phosphorus input to the mid-Bay.

SUMMARY: Increased sediment loading will result in higher turbidity and faster sedimentation everywhere, but especially in the dredged channels. The range of dynamics will be increased, especially during storms. Without channel dredging there will be rapid channel filling, downstream displacement of the salt front, and possible major changes in circulation and sedimentation patterns. Future channel dredging will have to be more frequent, and more costly. Circulation and deposition patterns will then probably remain unchanged.

Chemical Dynamics of Chesapeake Bay Sediments

Dr Jeffery Cornwell, University of Maryland Center for Environmental Science

Below the ETM close to the Bay Bridge, the Bay has moderate salinity, high turbidity and high primary productivity. There is a strong gradient of organic matter, decreasing southwards. Metabolism in the Upper Bay is driven more by land inputs than its own reserve resources.

Most phosphorus from the rivers tends to be deposited close to the river mouths. The sediments in the Upper Bay have high iron contents with a ferric oxide cap which buries and seals phosphorus deposited there. Much of the phosphorus input ends up in these iron rich shallow sediments. The Middle Bay has a higher phosphorus deposition but also has the lowest retainment and there is high productivity in the mesohaline zone due to phosphorus release. The most important effect of increased delivery of sediments during large flows and scouring events may be the increased delivery of phosphorus to the Middle Bay in the sediment that over-runs the ETM zone. It is possible that this aggravation of the effects of increased phosphorus entering the Middle Bay during scouring events may be the most serious effect of increased sediment loads on the Bay. The severity of the consequences will depend a great deal on the time of year at which this occurs.

Channel sediments have a high iron and iron oxide content and the high rates of deposition with rapid burial, which keeps their phosphorus buried in the sediments. Even when they are anaerobic these sediments often lack the organic matter necessary for reduction of the ferric oxide.

Channel sediments contain significant amounts of ammonium in the pore waters of the sediments, but little is released under quiescent conditions. If the channels are dredged this will be released to the water column. The sediments above the dams are also likely to have a large store of nitrogen, including ammonia, which will be released if they are dredged.

Bay sediments contain moderately high concentrations of sulfur, of which 90% can be re-oxidized with significant acid production. The possible effects of dredging on acid production by this reaction are currently unclear. This is also an issue for upland disposal of sediments dredged from behind the dams.

SUMMARY: The result of increased sediment delivery from the Susquehanna River that can be forecast with most certainty is the adverse effect of increased delivery of phosphorus to the Middle Bay in sediments which move beyond the ETM zone during large flow scouring events. The effects of dredging both behind the dam and within the Bay are unclear.

Sediment Impacts on Submerged Aquatic Vegetation

Dr. Kenneth Moore, Virginia Institute of Marine Science

There are about 20 species of submerged aquatic vegetation (SAV) in the Chesapeake Bay, with more diversity in the less saline areas. Most species have high light requirements, and both quantity and quality of the light are important. Sediment effects on the SAV are due to both surface deposits of sediment on the leaves and by light attenuation in the turbid water. Increased nutrients also encourage the growth of epiphytes and phytoplankton, which have the same effects, but as sediment levels are increased the light attenuation in the water from them becomes more important than either epiphytes or phytoplankton. The greatest effect on SAV photosynthesis is the attenuation of the blue light fraction which can be caused by both particulates and dissolved organics. In fresher water, suspended solid materials are the main cause of attenuation as opposed to epiphytes or phytoplankton. Sediment has different impacts on different SAV species due to differences in leaf architecture. Sediments tend to stick on the leaf surface of SAV species living in low salinity areas because of their spreading canopies, but not to the surface of high salinity species such as eelgrass that produce meadows of strap-like leaves.

There is not much impact of sediment on SAV growth during the colder part of the year. During this period the light requirements of the high salinity species are low due to the low metabolic rates, while freshwater and low salinity species have no standing crop. Freshwater species grow between March and November, drawing nutrients and carbohydrates from the belowground rhizome reserve, where they are stored in the winter. Sediment deposition in winter will have little effect unless it is very excessive and persistent, but even short periods (2 to 4 weeks) of high turbidity in late spring and summer can have large effects because these are the times of high growth and light demand. Resuspension at these times is also highly significant.

Resuspension of bottom sediments is less serious where there are SAV beds of sufficient size to give self-protection. Because existing SAV beds have the capacity to reduce resuspension and promote particle settling, light levels within SAV beds are typically greater than adjacent unvegetated areas. Typically this effect becomes significant as the bottom cover of the SAV bed exceeds 25-50%. Because of this self-protection, background levels of suspended sediments must generally be lower to permit growth or regrowth of SAV than levels necessary for survival of existing vegetated areas.

There were Bay-wide precipitous losses of SAV within the 2 years after Agnes in 1972, but in the upper regions of the James and Potomac rivers and some other regions large scale losses have been reported as early as the early 1900's. In the James, for example, SAV in freshwater regions declined by the 1940's, in low salinity regions by the 1960's and in high salinity regions in the 1970's. SAV beds have generally moved back from the 2 m or greater to the 1 m depth in most areas today. There has been most recovery in the higher salinity regions which are vegetated with eelgrass, with much less in the Upper Bay and low salinity areas, although the introduction of *Hydrilla* in the upper Potomac in the 1980's initiated SAV re-growth in that region.

SUMMARY: The general pattern of SAV loss across the Bay suggests a widespread decrease in the amount and quality of available light over time. The general situation is complex, depending on the ecosystem, but sediment solids are always a major factor and any increase in the amount present will be a serious hindrance to the recovery and re-establishment of the SAV population and the habitat which this provides for many of the Bay biota.

Impacts of Sediment Delivery on Benthic Organisms

Dr. Linda Schaffner, Virginia Institute of Marine Science

Increased sediment delivery may not have acute effects on benthic ecosystems, but there may be chronic effects on macro-invertebrates (clams and worms) due to bioenergetic effects, particularly where the biota have to dig themselves out of fresh sediment deposits. Organisms that live in muddy environments can withstand high concentrations of suspended sediments for short periods of time, but there are still energetic costs (e.g. on the pumping capacity of oysters), which tend to have more chronic rather than acute effects. Those living in sand tend to be more sensitive.

Burial can have effects on benthic microfauna recruitment because its effects are more severe on juveniles than on older members. Recruitment can be impaired even for the more mobile species. A 10 cm increase in sediment depth translates into a 75% rate of mortality, and 30 mm translates into 100%. Burial and the effects of physical disturbance of looser newly deposited sediments are harder than anoxia on burrowing biota.

Sediment deposition is also a problem for first year oysters. In oyster reefs, mortality and growth respond to physical conditions: there is a clear association of higher mortality with sedimentation, which has probably contributed to the loss of reefs. Again, the physical effects of increased sediment are having a greater effect than anoxia. Due to their sedentary nature, oyster populations, which have their northern limit close to the southern limit of the ETM, are expected to be among the most susceptible fauna.

There are no suspension feeders in the ETM zone itself, which is impoverished in macrofauna. Increased sediment means further loss of macrofauna and an increase in the bacterial feeders in the zone. Bivalves that burrow do well in the presence of sediment, but all other biomass declines as we move northward into the ETM and beyond. In general these organisms are coping with the highly dynamic system of sediment resuspension and movement. More sediment entering will give more to be moved around and redistributed with a concomitant increase in stress on the organisms. Older and more consolidated sediments are (or were) a better environment.

SUMMARY: There are adverse impacts on benthic organisms susceptible to increased sediment loads, which increase the energetic costs from burial. Episodic deposition also rapidly increases mortality and recruitment. Young oysters are sensitive to increased sediment deposition and long-term community structures will be changed by the impoverishment of the macrofauna.

Estuarine Turbidity Maxima, Water Quality, and Recruitment of Anadromous Fish

Dr. Edward Houde, University of Maryland Center for Environmental Science

Suspended sediments potentially can adversely affect eggs, larvae and juveniles of fishes. Anadromous fish spawn and nurse their young in the upper reaches of estuaries near the ETM. These highly turbid areas support abundant planktonic food resources and have circulation features that promote retention of plankton organisms and young fish as well as suspended sediments. The enhanced trophic interactions and the retention feature are hypothesized to assure successful recruitment of anadromous fishes.

The high suspended loads in the Chesapeake Bay ETM zone do not apparently have deleterious effects on eggs and larvae of striped bass, white perch, and the anadromous river herrings and shads (*Alosa* spp.). Experiments on eggs and larvae of these species have shown few harmful effects of sediment loads <500 mg/l. Higher loads can cause hatching failures of eggs, impede feeding by young fish and can clog gills or other respiratory surfaces, sometimes causing mortalities. High suspended sediment loads impede feeding more as a consequence of the lower light levels and lower visibility of food particles in the more turbid environment than as a consequence of interference by sediment particles. Low suspended sediment loads may actually increase the feeding efficiency of larval fish by improving the visual contrast between the larva and its planktonic prey.

Larval and juvenile stages of anadromous fishes are abundant in the ETM zone, which is a region of importance for recruitment of anadromous fish. It is a region for aggregation and retention of planktonic organisms (including earliest life stages of fish) and is therefore the place where sediment may affect young spawn and young fish. The present levels do not appear to impair hatching, but increased loads could be problematical. The most important direct effect of increased sediments could be the silting and filling of the breeding areas and concomitant movement of the entrapment feature in the ETM zone, which is essential habitat for both larvae and juvenile fish. Some adverse effects also may occur if increased sediments cause a change in the volume of the water in the Bay above the ETM zone. There could also be adverse effects if increased sediment delivery requires increased dredging of the Bay itself.

It is also possible that increased loads up to some point may impair predation on young fish, which would be beneficial, up to a certain point, in promoting survival of the young fish but perhaps detrimental to the predators. The nature of the effects is complex and difficult to predict at this time.

SUMMARY: Effects of increased sediment loading in the Upper Bay and the ETM zone cannot be predicted at this time, but some potential effects include;
1) direct effects on feeding, clogged gill tissues and smothering of eggs,
2) indirect effects on the abundance of planktonic prey of larval and juvenile fish,
3) a reduction in the ability of predators on young fish to feed successfully (a potential benefit to the survival of young anadromous fish but a detriment to predators,
4) water quality changes and especially increases in contaminant loads that may be associated with suspended sediments, and
5) habitat alterations through increased silting and sedimentation with changes in the location and mode of operation of the ETM retention mechanism.

To the extent that increased sediment loading in the Upper Chesapeake Bay will require more dredging and associated activities to maintain channels there may be an increased threat to spawning and nursery habitats for anadromous fishes.

APPENDIX A

DEPOSITION AND DISTRIBUTION OF BOTTOM SEDIMENT
IN THE CHESAPEAKE BAY

Jeffrey Halka
Maryland Department of Natural Resources
Maryland Geological Survey

Sediment delivery via the Susquehanna River is known to contribute a significant amount of particulates to the Chesapeake Bay ecosystem. In order to gain an understanding of the potential impacts from these sediments and impacts associated with any increase that may occur it is necessary to review what is known about the overall processes of sediment accumulation in the system, both on a spatial and a temporal basis.

Gauge data available from the U.S. Geological Survey-Water Resources Division indicates that over the past 21 years a mean of $1,310\text{x}10^6$ kilograms ($1.31\ \text{x}10^{12}$ grams) are delivered to the upper Chesapeake Bay each year (Figure 1). The median value over this time period is $953\ \text{x}10^6$ kilograms/year ($0.953\ \text{x}10^{12}$ grams/year). The separation of the mean value from the median is a result of what is obvious from the graph: that relatively few years with high sediment yields have a strong influence on the overall mean value. Over the 21 year record twice as many years (14) delivered below the mean value of sediment as those that were above the mean (7). This period of record does not incorporate the yields and potential effects of extreme events such as Hurricanes Agnes and Eloise. Agnes (1972) is estimated to have input $30,000\text{x}10^6$ kilograms ($30\ \text{x}10^{12}$ grams) to the Chesapeake Bay in a few days while Eloise (1976) input $10,000\text{x}10^6$ kilograms ($10\ \text{x}10^{12}$ grams).

In order to place this information into the context of the Bay as a whole we need to first step back and take a look at some overall characteristics of the Bay system. The bathymetric map produced by the Virginia Institute of Marine Sciences (Figure 2) is illustrative of the fact that the Chesapeake Bay formed by drowning the lower reaches of the Susquehanna River during the last post-glacial rise in sea level. The axial channel and surrounding shallower platforms combined with the complex shoreline is often cited as evidence for this formation mechanism. But a closer look at the bathymetry reveals some interesting features that relate to the long term evolution of the Chesapeake. First, the continuous axial channel essentially disappears north of the Annapolis-Kent Island bridge, as well as south of the Rappahannock River in Virginia. The first of these characteristics suggests that the northern most portion of the Chesapeake, north of Annapolis, is functioning as the pro-delta of the Susquehanna River and has been rapidly filling with sediments that are derived from that watershed. Similarly the southern portion of the Bay is also rapidly filling with sediments that have obliterated the continuous channel in that region. The most likely source of sediments for the southern portion of the Bay input through the Bay mouth from the Atlantic Ocean and longshore transport along the adjacent shorelines. Budget calculations for the Bay as a whole support this source for much of the sediment in the southernmost Chesapeake ((Hobbs, Halka, and others, 1992).

An examination of the distribution of sediment types in the Bay provides further information useful for interpreting sedimentation processes in the estuary. Surficial grab samples (upper 5 cm) were collected throughout the Bay during the initial Chesapeake Bay Program in the mid-1980's. In Maryland over 4,000 samples were collected and analyzed for the proportions of sand (>63 microns diameter), silt (2-63 microns), and clay (<2 microns) sized particles (Figure 3). A companion study was completed in Virginia. The full data set for the Maryland data as well as the accompanying maps are available on the Maryland Geological Survey web site (http://www.mgs.md.gov/coastal/cegmaps2.html).

A plot of these data on a ternary diagram with sand, silt and clay end members reveals two major end member populations (Figure 4), sands and silty-clays. Relatively few samples plot across the center of the diagram. This suggests that there are two distinct populations related to the energy available in the system to move sediment particles: a low energy region in which relatively fine grained sediments accumulate, and an area of higher energy wherein mostly sands occur. There are relatively few areas where intermediate energy conditions exist and where sediment mixing occurs.

The regional map of surficial sediment types confirms this observation and provides additional insight into sediment accumulation characteristics of the Bay (Figure 5). The marginal shallow platforms apparent on the bathymetric map are characterized by sand sized sediments indicative of a higher energy environment. Wind generated waves and rising sea level have combined to facilitate shoreline erosion producing planar erosional platforms at the wave base. These platforms are carpeted with a lag deposit of sand sized materials. They tend to be wider and extend further from shore on the eastern verses the western shore due to the prevailing westerly winds that occur in the mid-Atlantic region. The finer grained particles that were once present in the underlying geology and soil are effectively removed by the high energy conditions that prevail in the shallows and are deposited in deeper portions of the Bay system.

The relatively deeper platforms as well as the deep axial channel are characterized by the fine grained silty clays that extend from north of Baltimore southward through Maryland and into Virginia as far as the Rappahannock River (not shown on this figure). North of Baltimore, the fine grained sediments located in the relatively deeper waters are slightly coarser in nature, with silt sized particles dominating over clay sized. This difference from sediments in the deep waters to the south suggests that some hydraulic fractionation is occurring proximal to the Susquehanna River. These coarser sediments define the approximate average southern limit of the estuarine turbidity maximum, the zone of relatively high suspended sediment concentrations in the water column. This again suggests that the bottom sediment textural characteristics are reflecting and integrating the relatively long term processes operating in the water column of the system.

As a final piece of the bottom sediment puzzle we need to estimate the long term rates of sediment accumulation within the estuary and determine what this may reveal about the sources of sediment and the long term sinks. Only then can we begin to judge the potential impacts of the Susquehanna River sediment load relative to other sources such as shoreline erosion and input through the Bay mouth. I’ll take two approaches to this estimate: 1) averaged long term (~10,000 years) rates of accumulation determined from geophysical methods, and 2) thickness accumulations estimated from comparing bathymetric data spanning 50 to 100 year periods. What these data lack in terms of site specific accuracy, compared to radionuclide or pollen dating of specific core sites, they make up for in spatial robustness.

Geophysically we have measured the thickness of sediment that accumulated since the formation of the estuary approximately 10,000 years ago(Colman, Halka, and Hobbs, 1991). These data cover the area from Annapolis south to the Bay mouth, and were derived from 2,600 km of acoustic sub-bottom surveying lines. Unfortunately this technique is not effective north of Annapolis because the presence of widespread methane gas filled voids in the bottom sediment precludes its use. The sediment thickness can then be divided by the time since inundation based on the local sea level curve for the late Pleistocene to determine an average rate of accumulation. The results represent a long term average and smooths out shorter period variability. We anticipate, however, that these rates will be low relative to more modern rates because in the early stages of inundation while the estuary was still narrowly confined in the incised river valleys, sediment accumulation was probably much lower in a system with much greater tidal excursions than at present. In addition, flood events would have a relatively larger impact on an estuary with a significantly lower overall volume.

A plot of the rates of sediment accumulation against distance from the Susquehanna River mouth for approximately 6,000 points (Figure 6) shows that most average less than 1.5 mm/yr accumulation. This rate approximates the long term rate of sea level rise indicating that the system is attempting to achieve equilibrium over much of its area. Both the rates and the variability increase to the south, toward the Bay mouth. These data again suggest that the mouth may be a significant long-term avenue for sediment input to the estuary, and that there are strong loci of deposition in the southern Bay. As seen in the bathymetric map of the Bay the axial channel has been eliminated in Virginia due to these high sedimentation rates. The narrow form of the channel relative to the overall width of the Bay system reduces the overall number of data points with high sedimentation rates on Figure 6. The Susquehanna River channel that was cut 18,000 years ago actually passes partially under Fisherman’s Island at the southern tip of the Delmarva peninsula. Sedimentation rates within the southern most portion of the channel have been so high that it has been completely filled in a relatively short (geologically speaking) 10,000 years. Additional evidence indicates that the Delmarva peninsula is still actively migrating to the south continuing to cover this portion of the old Susquehanna River channel.

The combination of existing bathymetry, the surficial sediment characteristics and these long term sedimentation rates suggest that two broad scale processes are operating to move sediment within the system. The relatively shallow shoal areas are formed from sea level rise and the accompanying wave induced erosion of fastland. These platforms are cut to the level of wave base as the sea continues to rise and become covered with a relatively thin lag deposit of sandy sediments. The accumulation rates approximate the rate of sea level rise. In the axial channel, relatively finer grained sediments accumulate under more quiescent conditions that exist below the zone of significant wave action. The axial channel has relatively higher rates of sediment accumulation with sources that include shoreline erosion, the upland watersheds and the Bay mouth.

Plotting sedimentation rates verses distance along the Bay and depth (Figure 7) confirms those suggestions. In the shallow waters sedimentation rates are relatively low and remain constant along the axis of the Bay. Within any region along the Bay’s axis sedimentation rates increase with depth. In the deeper waters sedimentation rates are more variable than in the shallows and increase notably toward the mouth.

Still unknown from these data is the situation with regards to sediment accumulation rates and accumulation volumes north of Annapolis, within the region that would most likely be impacted by increased sediment input from the Susquehanna River. Historical sediment budgets have suggested that most of the sediment supplied to this area of the Bay by the Susquehanna River remains in the northern portion. One of the more recent published works that reviewed and summarized radionuclide dated cores collected throughout the Bay estimated that 70% of the sediment supplied by the Susquehanna River was deposited on the bottom north of Tolchester (Officer, Lynch, and Setlock, 1984). This area north of Tolchester encompasses the estuarine turbidity maximum and was characterized by the clayey silt bottom sediment type shown in Figure 5. An earlier published budget estimated that 30% of the sediment bypasses the turbidity maximum in the outward flowing surface waters but stated that an unknown amount probably returns to the region as a result of estuarine reworking and gravitational circulation (Schubel, 1968). Overall 96% of the Susquehanna River supplied sediment was estimated to become deposited north of Annapolis-Kent Island Bridge (Biggs, 1970).

Using the recent sediment discharge estimates from the USGS that were shown in Figure 1 and historical bathymetric data I have attempted a first order sediment budget estimate for the northern portion of the Chesapeake. The basic mass breakdown is shown in Figure 8. We can eliminate sand sized sediments from this estimate. Sands that are transported by the Susquehanna River are either largely trapped behind the upstream dams, or if carried past the dams are almost entirely deposited in the Susquehanna Flats area. Little if any would come to be deposited in the turbidity maximum zone or beyond. Similarly, sands delivered by shore erosion are not transported beyond the nearshore zone into deeper portions of the Bay. As noted previously the Susquehanna River delivered an average of $1.31x10^9$ kilograms per year to the Bay over the past 21 years. Shoreline erosion in the Bay north of Annapolis supplies another $1.28x10^9$ kilograms (Kerhin, Halka, and others, 1988), and internal productivity another $0.01x10^9$ kilograms (Biggs, 1970). The total fine grained sediment delivered is approximately $1.60x10^9$ kilograms per year over the last 21 years. As summarized in Figure 8, the surficial bottom sediments of the northern Chesapeake Bay have an average water content of 58% and an overall bulk density of 1.35 g/cc. The mass of sediment particles contained in each cubic centimeter of sediment with this bulk density is 0.57 g/cc (570 kg/m^3). Deposition of all the fine grained sediment delivered to the northern Chesapeake Bay by the combined sources of the Susquehanna River, shoreline erosion and internal productivity would result in a bottom sediment volume of 2,807,000 m^3.

Because the acoustic profiling work did not extend into the region north of Annapolis another technique is necessary to estimate the thickness and volume of sediment that have historically accumulated in this area. Sedimentation rates for the Bay have been estimated by comparing historical bathymetric data from the mid- to late- 1800's with comparable data from the mid-1900's in a technique outlined in (Kerhin, Halka, and others, 1988) and (Byrne, Hobbs, and Carron, 1982). These data have been reworked to estimate the thickness of sediment that have accumulated within particular segments of the Chesapeake Bay, and are shown on Figure 9. Within the estuarine turbidity maximum region the average rate of fine grained sediment accumulation was 7.8 mm/yr as shown on Figure 9. Within the region extending to just south of Baltimore the average rate of accumulation was slightly lower at 6.2 mm/yr. Multiplying these rates by the area of bottom covered by fine grained sediments (see Figure 5) and calculating the equivalent mass yields 6.5×10^8 kilograms per year in the turbidity maximum zone and 9.7×10^8 kilograms in the region immediately to the south. Accumulation of bottom sediment in these two areas together account for approximately 100% of the sediment delivered to the northern Chesapeake Bay by all sources. This calculation provides confirmation of the earlier budget estimates and indicates that, on average, most of the sediment delivered by the Susquehanna River is probably deposited in this region. It should, however, be remembered that the Susquehanna River sediment inputs included in this calculation do not account for the potentially extremely high sediment inputs such as occurred during Hurricanes Agnes and Eloise.

The major impacts of increase sediment delivery by the Susquehanna River, in terms of physical characteristics only, can be expected to be largely confined to the Bay north of Annapolis, where sedimentation rates can be expected to increase. There should be little significant impact on the overall rate of sedimentation in the rest of the Bay because the long term major source of sediment (ie input through the Bay mouth) is not significantly affected by changes in watershed yield. In a similar context each of the smaller tributaries of the Chesapeake Bay system operate as their own smaller scale estuaries with their own turbidity maximum zones, above which most watershed derived sediment is deposited. Again, this analysis does not consider the impacts that may be associated with increased delivery of contaminants or nutrients to the system, components that often are strongly associated with fine grained sediment transport, nor does it consider the geochemical processes and transformations that may occur both in the water column and as the particulates are sedimented onto the bottom.

The lines of evidence and data described above suggest that most of the sediment delivered by the Susquehanna River are deposited north of Baltimore and, as a consequence, this is where most impacts that result from increased delivery can be expected to occur. The information provided should not be interpreted to mean that none of the sediment ever “escapes” this region. Certainly during major storm events the flow structure of the entire Bay system is altered radically as well as sediment delivery can increase well beyond the averages analyzed herein. As the presentation by Lawrence Sanford indicated there are differing interpretations on sediment transport in the system. He identified a background suspended sediment population that remains in suspension virtually indefinitely given its extremely slow settling velocity. Particulates this fine in nature are certainly capable of being transported throughout much of the estuary. Similarly, in the weeks and months following the 1996 winter thaw and high discharge loads from the Susquehanna, we could identify no layer of sediment on the bottom in the northern Bay that could be associated with this major event. This strongly suggests that the sediment was transported out of the northern Bay in the southward flowing fresher surface water. Whether or not this sediment would eventually be resuspended and transported back toward the turbidity maximum zone by gravitational circulation, as suggested by Schubel (1968) is unknown.

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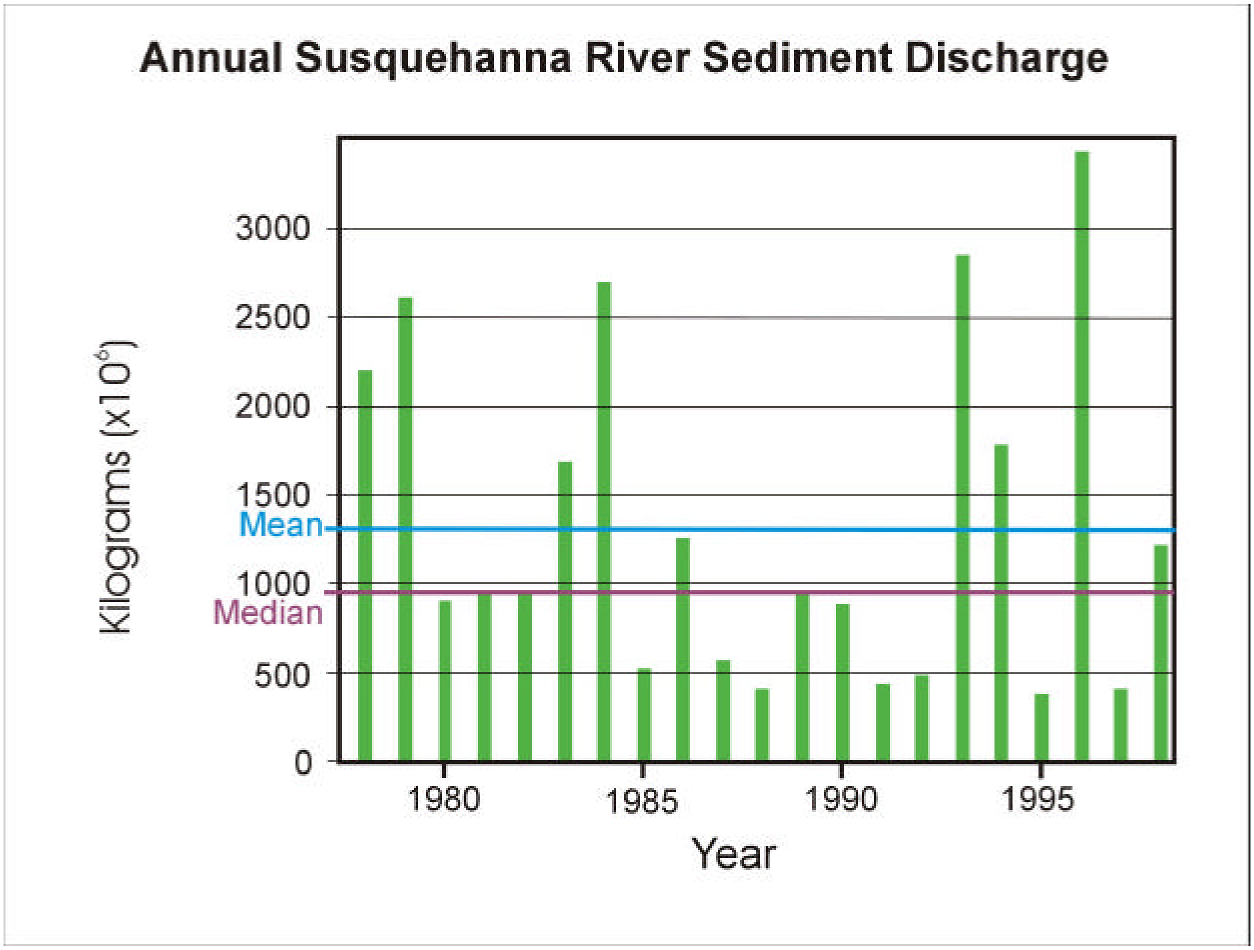
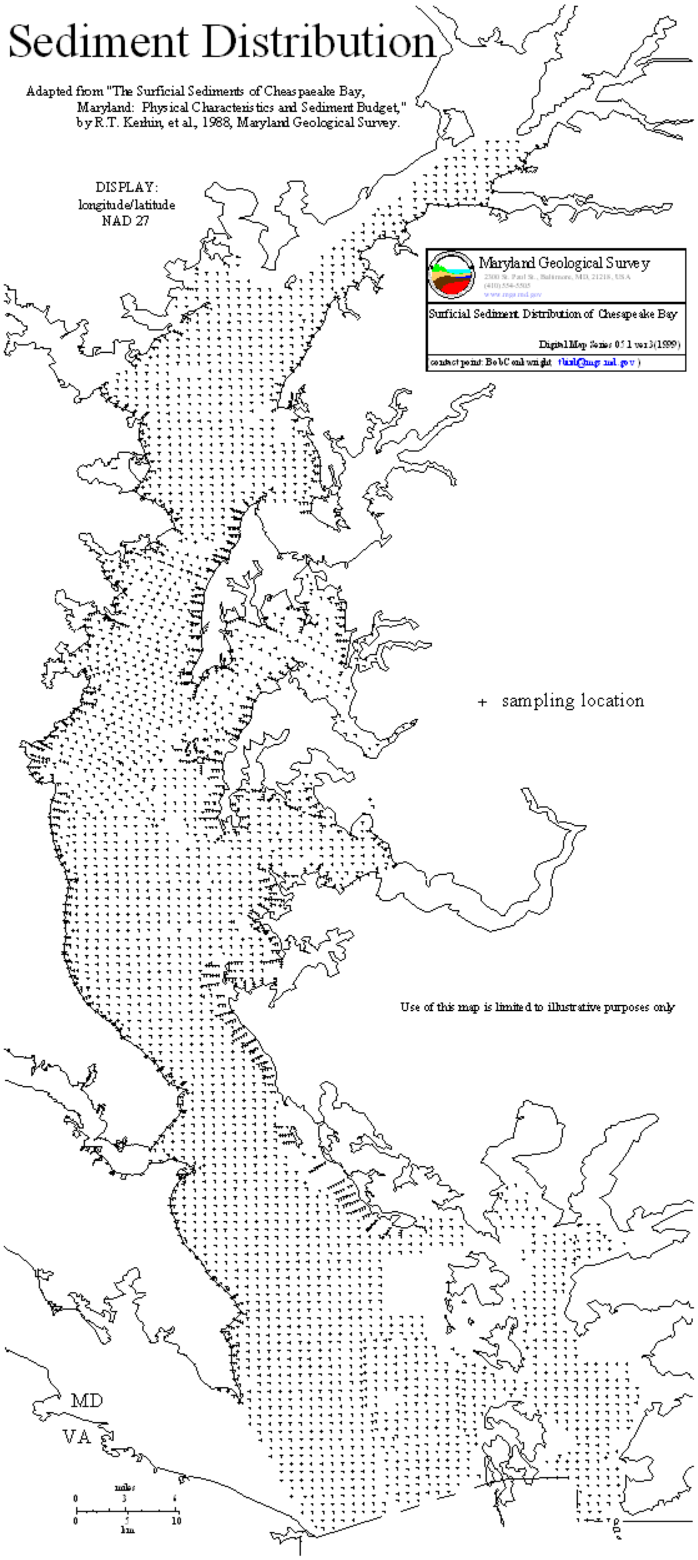

Annual Susquehanna River Sediment Discharge
Kilograms (x10⁶)
3000
2500
2000
1500
Mean
1000
Median
500
0
1980
1985
1990
1995
Year


BATHYMETRY OF THE
CHESAPEAKE BAY

Figure 3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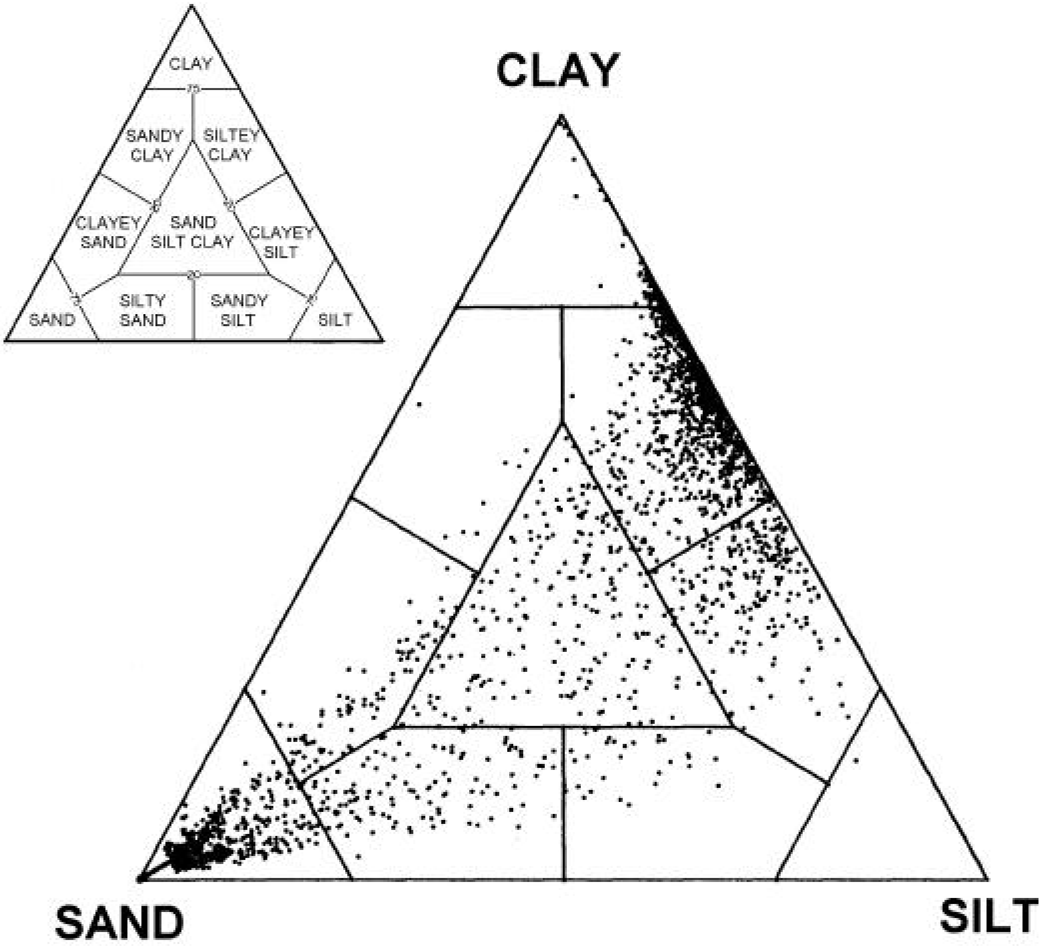
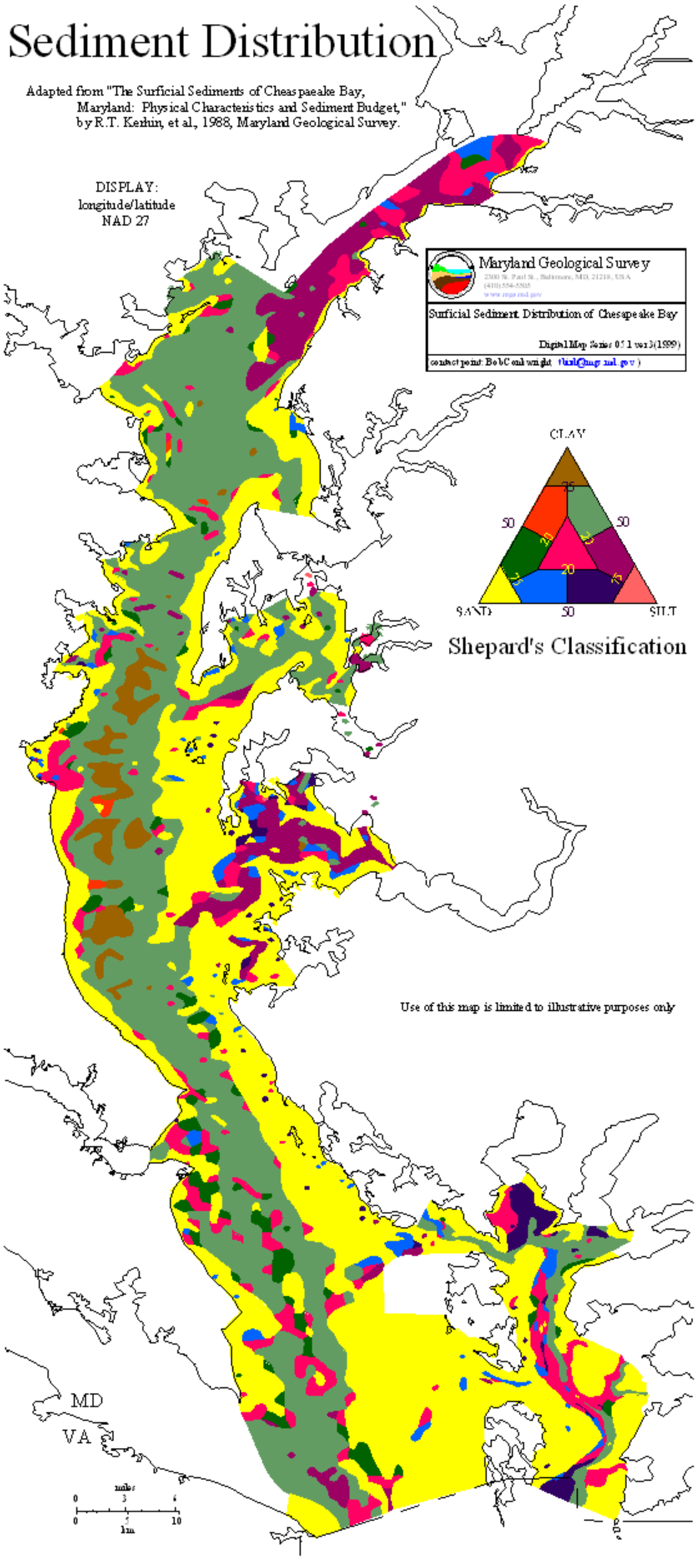
DISPLAY:
longitude/latitude
NAD 27
Maryland Geological Survey
2300 St. Paul St., Baltimore, MD, 21218, USA
(410) 554-5505
www.mgs.md.gov
Surficial Sediment Distribution of Chesapeake Bay
Digital Map Series 05 1 ver3(1999)
(contact point: Bob Conkwright tbird@mgs.md.gov)
+ sampling location
Use of this map is limited to illustrative purposes only
MD
VA
miles
0
3
6
0
5
10
km

Figure 4


CLAY
75
SANDY CLAY
SILTEY CLAY
CLAYEY SAND
SAND SILT CLAY
CLAYEY SILT
20
SAND
SILTY SAND
SANDY SILT
SILT
CLAY
SAND
SILT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longitude/latitude
NAD 27
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Surficial Sediment Distribution of Chesapeake Bay
Digital Map Series 05.1 ver3(1999)
contact point: Bob Conkwright
CLAY
SAND
SILT
75
50
50
30
20
20
75
75
50
Shepard's Classification
Use of this map is limited to illustrative purposes only
MD
VA
miles
0
3
6
0
5
10
km

Figure 6

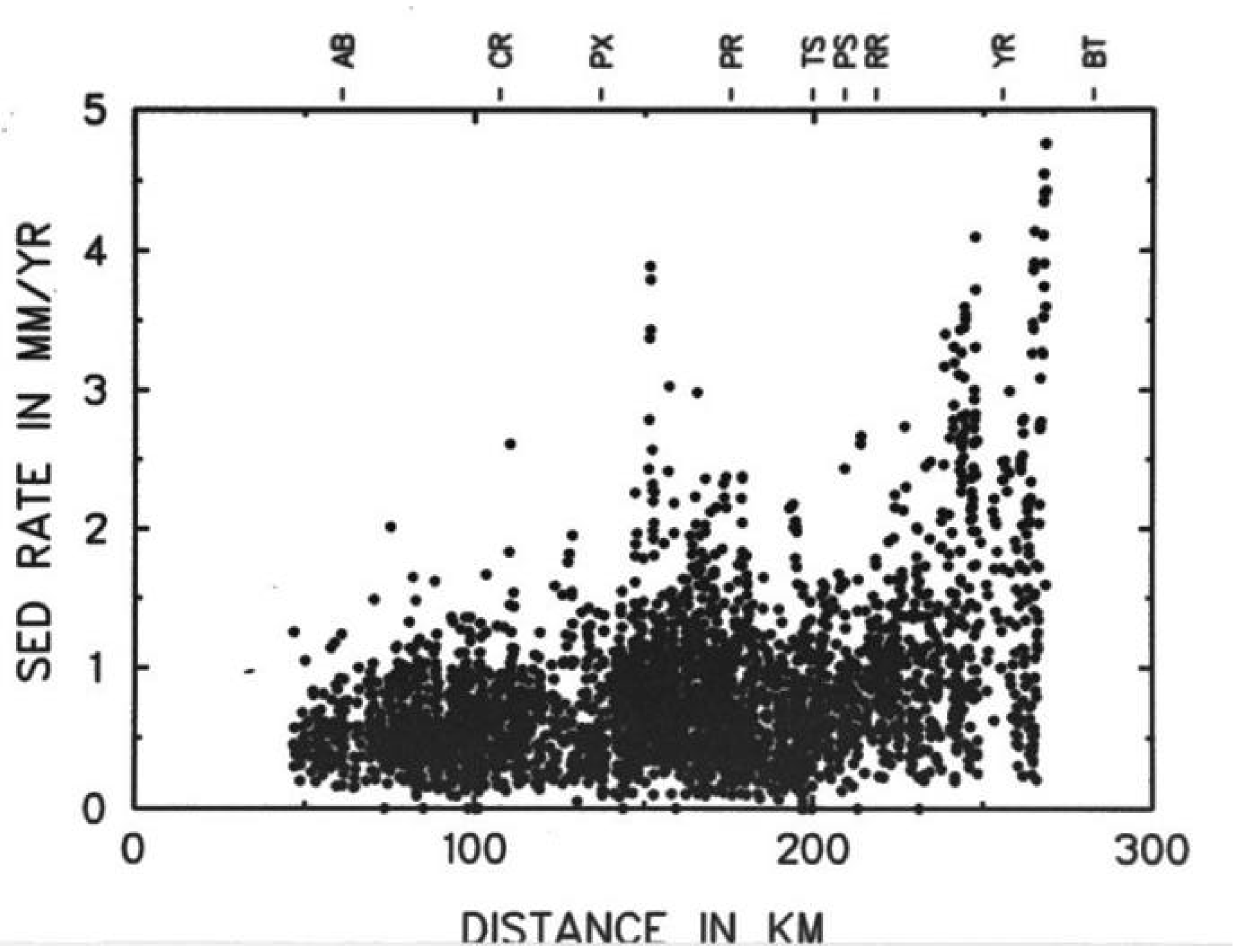
AB
CR
PX
PR
TS
PS
RR
YR
BT
SED RATE IN MM/YR
0
1
2
3
4
5
0
100
200
300
DISTANCE IN KM

Figure 7

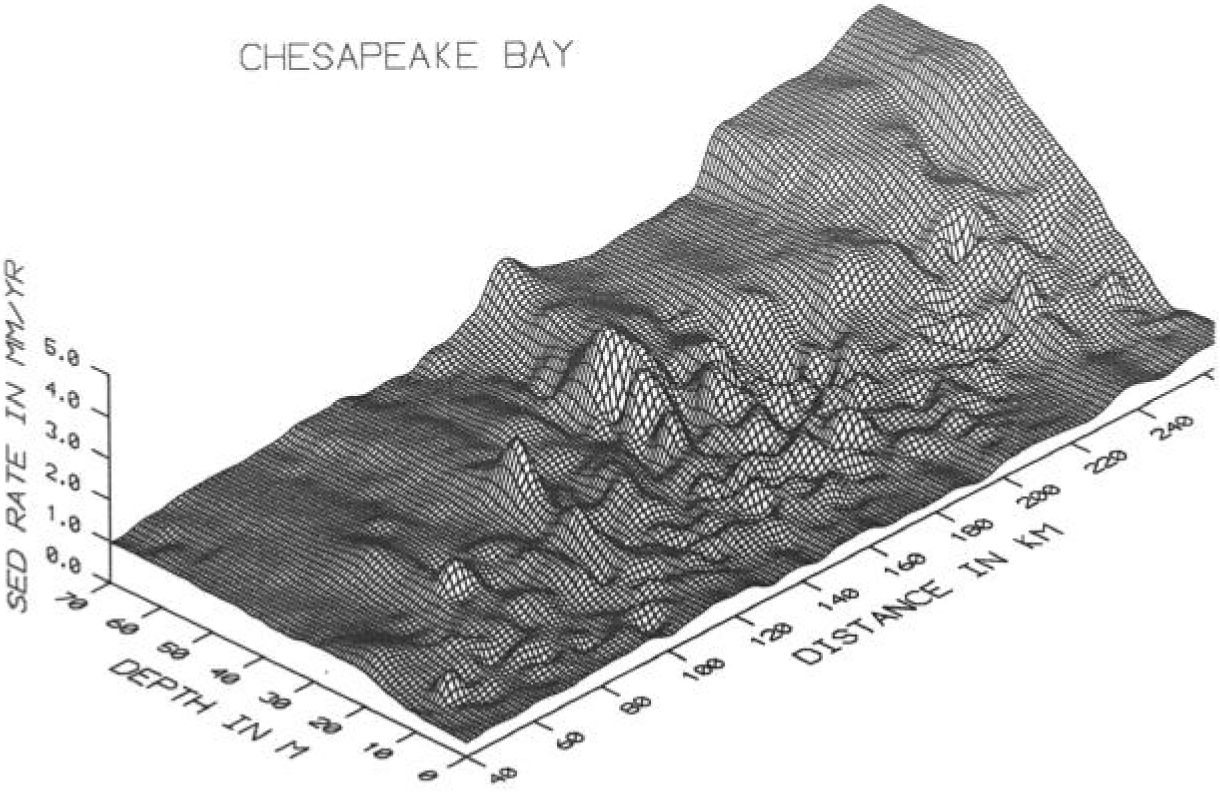
CHESAPEAKE BAY
SED RATE IN MM/YR
0.0
1.0
2.0
3.0
4.0
5.0
DEPTH IN M
70
60
50
40
30
20
10
0
DISTANCE IN KM
40
60
80
100
120
140
160
180
200
220
240

Figure 8

ANNUAL SEDIMENT INPUT	
Susquehanna River (silts and clays)	1.31 x 10^9 kg/yr
Shoreline Erosion (silts and clays)	0.28 x 10^9 kg/yr
Internal Primary Productivity	0.01 x 10^9 kg/yr
Total (silt and clay sized)	1.60 x 10^9 kg/yr
Shoreline Erosion (sands)	0.27 x 10^9 kg/yr
TOTAL	1.87 x 10^9 kg/yr
VOLUME	
Surficial Sediment Characteristics	Water Content = 58% Bulk Density = 1.35 g/cc Porosity = 79%
Mass of Sediment Particles	570 kg/m^3
Volume of Fine Grained Sediment	2,807,000 m^3

Sediment Accumulation and Northern Bay Inputs