Watershed Landuse and Bay Sedimentation

John J. Rooney†, and Stephen V. Smith‡

†Department of Geology and Geophysics
School of Ocean and Earth
Science and Technology
University of Hawaii
2525 Correa Road
Honolulu, HI 96822, U.S.A.

‡Department of Oceanography
School of Ocean and Earth
Science and Technology
University of Hawaii
2525 Correa Road
Honolulu, HI 96822, U.S.A.

ABSTRACT


This paper discusses a unique synthesis of techniques used to examine sediment dynamics in a temperate watershed–estuary system. Sedimentation rates for Tomales Bay, California, were initially calculated using a geographic information system (GIS) and digitized bathymetric data from National Ocean Service navigational survey charts published in 1861, 1931, 1957 and 1994, with a public-domain Unix-based software package, Generic Mapping Tool (GMT). The surfaces were subtracted from each other to determine the volume of sediment that accumulated in the Bay between surveys. Average baywide accumulation rates, normalized by watershed area, were found to be about 94 t km\(^{-2}\) yr\(^{-1}\) for the 1861–1931 interval (Interval I), 357 t km\(^{-2}\) yr\(^{-1}\) for 1931–1957 (Interval II), and 101 t km\(^{-2}\) yr\(^{-1}\) for 1957–1994 (Interval III). GIS-derived rates for Tomales Bay were compared with results hindcast from rating curve equations that relate rainfall to sediment yield, in order to determine the effects of varying land use on sedimentation rates in the bay.

ADDITIONAL INDEX WORDS: Coastal sedimentation, erosion, landuse, geographic information system.

INTRODUCTION

It has been estimated that worldwide sedimentation rates in coastal waters have doubled since prehistoric times due to anthropogenic activities such as crop farming, grazing of livestock, logging, etc. (e.g., MILLIMAN and SYVITSKI, 1992). These estimates of elevated sediment delivery are in spite of the sediment trapping effects of reservoirs, which have greatly reduced sediment delivery from some river systems to the coastal ocean (MILLIMAN and MEADE, 1983). Increases in the influx of terrigenous sediment to coastal waters frequently have a significant and widespread influence on the nearshore marine environment. These enhanced inputs can have important consequences in terms of the geochemical cycling and biological interactions within coastal systems (e.g., HOLLIGAN and REINERS, 1992; HEATH, 1995).

Because alterations in land use have, in general, dramatically increased nearshore sediment loading, profound changes have occurred in coastal marine environments. To understand these changes, one must have knowledge of the sedimentation rates there over the period of time in which anthropogenic land use practices may have affected the system. On a regional scale, changes in sediment accumulation rates strongly influence processes such as nearshore carbon and nutrient loading, which in turn is linked to the role of the coastal ocean in the global carbon cycle (SMITH and HOLLIBAUGH, 1993; HEIP et al., 1995; HEATH, 1995).

The Tomales Bay, California watershed has experienced changes in land use which have affected nearshore sedimentation rates over historic times. The research reported here used a synthesis of techniques to examine sediment dynamics in this temperate estuary/watershed system. Sediment accumulation rates in the bay were determined, with the aid of a geographic information system (GIS), by comparison of bathymetric surveys at three descrete time intervals. These were compared with rates derived from a series of models that relate rainfall to sediment yield, in order to determine the effects of varying land use on sedimentation rates in the bay.

MEADE (1982) reports that probably greater than 95% of the riverine sediment delivered to the U. S. Atlantic coast is trapped in estuaries and coastal marshlands. This observation suggests that the methods described here may be applicable to a wide selection of coastal environments, at least those for which other sediment sources and sinks can be quantified.

Study Area

Tomales Bay (Figure 1) is a straight, narrow, submerged section of the San Andreas Rift Zone, 50 km north of San Francisco. The embayment is about 20 km long and an average of 1.4 km across. It trends from southeast at the head of the bay to northwest at the mouth, has a watershed of 561
km², and a total surface area of about 28 km² (FISCHER et al., 1996; SMITH et al., 1996). The average depth in the bay is about 3 m with a deeper basin in the middle third of the bay and shallower areas at either end, particularly at the head. Both the head and mouth of the bay have intertidal mudflats and there is a predominant tidal channel up to 21 m deep that runs along the southwest side in the outer third of the bay. The average tidal range for the bay is 1.4 m between mean lower low and mean high water (Steve Lyles, National Ocean Service, pers. comm.). Two major streams flow into the bay; Walker Creek, 5 km from the mouth of the bay on the northeastern shore, and Lagunitas Creek at the head of the bay. Rainfall varies across the watershed from about 600 mm per year in the northeastern to about 1300 mm per year in the southern portion, with average runoff calculated as about 500 mm per year over the past 20 years (FISCHER et al., 1996). The highest point in the watershed is found in the western portion, the 794 m peak of Mt. Tamalpais, with several other peaks over 300 m found nearby. In general the watershed has fairly steep topography and high drainage density, as is typical of much of the Coastal Range. Roughly half the watershed is covered with shallow clay loam soils, primarily on the upland areas. The other soils are moderately deep and lie directly above bedrock (KASHIWAGI, 1985). The San Andreas fault divides the area into two distinctive geologic terranes. The area northeast of the fault is characterized by graywacke sandstone of the Franciscan Formation and the southwestern side by late Cretaceous granitic rock of the Salinian block, overlain in many places by a variety of more recent sedimentary rock types (IRWIN, 1990; KASHIWAGI, 1985). Pluvial input from Walker and Lagunitas Creeks is the major sediment source to Tomales Bay, with oceanic sediments, cliff erosion, and periodic landslides contributing minor amounts (DAETWYLER, 1966). Agricultural activity (mostly grazing by cattle) and use of the watershed as park and recreation areas dominate land use. There is only light residential and commercial development in the Tomales watershed, with a population of about 11,000 (SMITH et al., 1996).

Previous Research

This study was part of a larger research effort, the Land Margin Ecosystem Research/Biogeochemical Reactions in Estuaries (LMER/BRIE) program. The LMER/BRIE study evaluated the role of the land-sea interface (LSI) in biogeochemical processes and the importance of various forcing functions in altering these processes within the LSI (HOLLIBAUGH et al., 1988). It has been found that terrigenous sediments in runoff water are a major component of exogenous nutrient input to the bay (SMITH et al., 1996).

PLANT (1995) developed a particle aging model to calculate sediment accumulation rates for Tomales Bay. Dating of the younger portions of his sediment cores and estimates of bioturbation depth required by his model were done using 137Cs profiles. His modeled bay-wide sediment accumulation rates over the period of this study are equivalent to about 300 t km⁻² y⁻¹.

MUDIE and BYRNE (1980) used pollen grains as tracers in cores to study sedimentation rates at Drakes Estero, 5 km south of Tomales Bay. Sedimentation rates there were determined to be 0.5 mm per year for the period preceding the introduction of European-style agriculture, followed by an increase to 5 mm per year, between 1820–1860. This ten-fold increase in sediment accumulation apparently reflects accelerated erosion caused by overgrazing.

NIEMI and HALL (1996) compared charts and topographic maps of the head of Tomales Bay to document historical changes in tidal marshes there. They found a dramatic progradation of the tidal marshes between 1860 and 1954, particularly prior to 1918. They attributed this increase to enhanced sedimentation caused by the onset of European-style agricultural practices and logging in the watershed. From 1954 to 1982 they found no significant progradation, apparently the result of decreased sediment input due to sediment trapping by reservoirs in the watershed and revegetation of hillsides.

METHODS

Digitized bathymetric data were obtained directly from the National Oceanic and Atmospheric Administration (NOAA), National Ocean Survey (NOS) for navigational surveys of Tomales Bay conducted in 1931, 1957, and 1994. We digitized data for 1860–1 using NOS survey charts from those years. All soundings were converted to meters, adjusted to a common datum to allow for sea-level rise, and georeferenced to the North American Datum of 1983. The data files were analyzed with the aid of a software package with GIS capabilities called Generic Mapping Tools (GMT), Version 3.0 (WESSEL and SMITH, 1991; WESSEL and SMITH, 1995).
A gridded surface of the entire bottom of the bay was made for each survey, with grid dimensions of 0.02 minutes of latitude and longitude (about 30 x 36 m). The mean depth at each grid location for a given year was compared with the mean depth of that grid for other years. This yielded areal-specific bathymetry changes, or sediment accumulation volumes, for the entire bay for the intervals between navigational surveys. The head of the bay, approximately 3% of the bay area, was not surveyed during the 1931 survey, so these data were estimated from a time-weighted interpolation between 1861 and 1957.

Vertical accumulation data were corrected for compaction and converted to mass accumulation rates in order to characterize sediment yield from the watershed. This was done using two linear regression equations (<40 cm; >40 cm depth) relating dry bulk density to depth of the sediment below the sediment-water interface. The sedimentation rate is referred to in this paper as the "mass accumulation" rate and may be expressed as the total mass of accumulated sediment, or be normalized by the surface area of the bay. The term "sediment load," as used in this paper refers to the total quantity of sediment being exported from the watershed. To facilitate comparisons between watersheds, the sediment load may be normalized by watershed area, and is then referred to as the "sediment yield" (e.g. GESAMP, 1993; MILLIMAN and SYVITSKI, 1992).

We also examined the data for evidence of sediment redistribution (on the time scales of our resolution-decades) after initial accumulation. We noted that there appeared to be areas of the bay that could be characterized by different types of sedimentological activity. The mouth of the bay and areas adjacent to Walker and Lagunitas Creeks appeared to have accumulated significant volumes of sediment. The middle portion of the bay actually appeared to deepen slightly over the period of time covered by this study, while in between the middle and the creek areas were transitions areas that appeared to be characterized by moderate sediment accumulation. Accordingly, the bay was divided into 6 sections along its length (Figure 2), and sediment accumulations for each time interval were calculated for each section.

Contemporaneous Estimates of Stream Sediment Yield

The sediment accumulation rates obtained by bathymetric comparison using a GIS, are compared with sediment yield estimates from hydrologic models. FISCHER et al. (1996) developed a multi-cell water balance model for the Tomales watershed. They used rainfall data from 1879-1992, to estimate runoff and calculate the following rainfall-runoff rating curve:

\[
\text{RUNOFF (mm/yr)} = -284 + 0.92 \times \text{RAINFALL (mm/yr)}
\]

Total volumes of annual runoff data were corrected to flow volumes using the equation:

\[
\text{FLOW} = \text{RUNOFF} - (\text{WATERUSE} + \text{GROUNDWATER})
\]

from SMITH et al. (1996). A sediment yield rating curve (SMITH et al., 1996), relates 7 years of daily total suspended solids (TSS) data to daily flow for a representative portion of the watershed, from 1987 through 1993:

\[
\text{TSS (g/m}^3\) = 17.8 \times \text{FLOW}^{0.997} (\text{mm/day})
\]

Equation 3 was used in conjunction with daily streamflow data from 1975–1993 to generate daily TSS values for that 19 year period, on the assumption that the rating curve was stable over that time interval. The daily data were accumulated into annual yields and fit by log-log regression. A rating curve from a log-log plot systematically underestimates material yield when compared with continuous measurements, but FERGUSON (1986, 1987) developed a theory to explain that underestimate and offered a correction factor. These considerations result in the following equation relating annual sediment yield to runoff:

\[
\text{YIELD (t km}^{-2} \text{yr}^{-1}) = 10^{-3.308} \times \text{FLOW}^{1.907} (\text{mm yr}^{-1})
\]

The rainfall record for the Tomales Bay watershed was used in conjunction with equation 4, to hindcast sediment yield to Tomales Bay from 1860 through 1994. The standard deviation is derived from fitting the annualized runoff to sediment yield data from 1975–1993 to Equation 4. This value was divided by the square root of the number of years in each time interval to produce the standard errors reported in Table 2. It must be stressed that Equation 4 is not expected to represent the actual sediment yield for this entire time period because it is based on a rating curve established during the
relatively dry period between 1987 and 1993. Rather, the equation provides an estimate of what the sediment yield would have been, if land use and hydrologic factors were constant over the entire period since 1860.

Error Analysis

The method described above has multiple sources of potential error associated with it. Soundings from navigational charts have a systematic error introduced because values between reported depth intervals are rounded to the next shallowest depth. This bias was compensated for by adding half the value of the depth increment to all soundings. For example, if soundings on a particular survey were reported in feet, 0.5 feet was added to all soundings from that survey. Horizontal and vertical uncertainties introduced during surveying and digitizing were used to calculate the mean depth uncertainty associated with bathymetric difference data (see Rooney, 1995 for details). The depth uncertainty multiplied by the bay area gives volumetric sediment influx uncertainty, which can then be converted to mass as outlined above. This introduces another source of potential error, which must be added to the total uncertainty.

RESULTS

Sediment Accumulation History

The accumulation rates derived from bathymetric comparisons are presented in Table 1 and Figure 2. The basic pattern is that the mass accumulation rate, normalized by watershed area, for 1861–1931 (Interval I, about 90 t km⁻² yr⁻¹) was quadrupled for the period from 1931–1957 (Interval II). It then dropped back to about the rate for Interval I during the 1957–1994 period (Interval III). The data are obviously insufficient to resolve the timing or maximum magnitude of the high sedimentation interval in greater detail.

Figure 2 also shows the area-specific sediment accumulation from 1861 to 1994. It indicates that the bulk of sediment accumulated in the deltaic regions fronting Walker and Lagunitas Creeks, and a few kilometers down the bay from Lagunitas Creek. The center portion of the bay appears to have deepened very slightly over the same period, probably reflecting resolution limitations of the technique.

Sediment accumulations for each time interval were calculated for each section of the bay in an effort to determine patterns of sediment redistribution following initial deposition. A plot of the different rates for each section (Figure 3) does indeed suggest evidence of a several decades-long delay in sediment redistribution within the Bay.

The Inner Basin (IB), the section most removed from the two creek deltas, shows the greatest increase in sedimentation rates between Interval I and Interval II, going from the lowest to the highest rate of any section. The most likely explanation seems to be that the buildup of sediment in the Lagunitas Creek delta during Interval I took decades to move downstream to the IB section. The Lagunitas Creek (LAGS) section shows an anomalous sediment accumulation rate trend relative to the other sections of the Bay. Its highest accumulation rate is during Interval I, followed by continual decrease. The other sections show an increase from Interval I to Interval II, following the overall bay-wide trend.

Differences between sediment accumulation rates determined by the GIS analysis and sediment yield determined by the rating curve equations are shown in Figure 4. The GIS method and sediment yield method agree rather well Interval
DISCUSSION

Variations in sediment delivery from the watershed to the bay are responsive to two major components: variation in runoff or other aspects of system hydrology and change in land use. If we accept that little sediment is transported into the bay from the ocean or exported from it, the GIS-derived data are an integration of all variation in sediment yield. Because the sediment yield calculations are based on present land use conditions, the difference between predictions based on the sediment yield rating curve analysis and the GIS analysis provide an estimate of how changing land use has affected the watershed-bay system.

Sediment yield calculations for the three different time intervals give very similar results (Figure 4), reflecting relatively similar estimates of runoff for each period. The Interval I and Interval III periods show insignificant differences between the GIS-based measurements and the calculations based on sediment yield. Essentially all of the discrepancy between these two sets of estimates occurred during Interval II.

Results from this study do not correspond well with bay-wide sedimentation rates calculated by Plant (1995). He analyzed several cores taken in the bay and found significantly higher sedimentation rates than those reported here. However, sedimentation rates were determined by the GIS methodology for rectangles several hundred meters on a side, within which Plant obtained his cores (Figure 2). The rates within these areas were found to be higher than those from the bay as a whole, and in fairly good agreement with Plant’s results. This finding illustrates both the variable nature of sediment accumulation within the bay and the potential problems associated with using measurements taken from a few points to characterize an entire area.

Processes Which are Assumed Not to Affect Results

There are two fundamental assumptions required in comparing the bathymetry from different years to determine sediment accumulation rates. One is that sediment entering the bay from the watershed remains there and is not contaminated by sediment from other sources. The other is that tectonic activity has not altered bay bathymetry significantly over this timeframe.

The first assumption, that the bay only receives sediment from the watershed and does not exchange it with the ocean, was examined as part of the LMER/BRIE program. Using the methodology reported in McMurry et al. (1995), Snidvongs completed an inventory of fallout-derived 137Cs erosion from the watershed and accumulation in the Bay. He concluded that the bay acts as a sink for fluvial sediment, retaining 96% or more of that sediment, while about 5% of the sediment in Tomales Bay originates from oceanic sources (A. Snidvongs, unpublished). This is consistent with Daetwyler’s (1966) conclusion, based on grain size analysis. He attributed the occurrence of sandy sediments in the mouth of Tomales Bay to southerly longshore currents which carried them in from Bodega Bay, outside the western end of Tomales Bay. He further concluded that the finer sediments found within the bay were derived from terrigenous sources. His diagram of the distribution of grain size modes for northern Tomales Bay suggests that the vast majority of this marine sand is trapped on the seaward side of Tom’s Point. For this reason we decided to eliminate the mouth section of the bay prior to determining bay-wide sediment accumulations and analyzing sectional sedimentation rates. Based on the above considerations and with the mouth section of the Bay eliminated, the assumption of a closed system with respect to sediment appears valid.

Tomales Bay was formed by strike-slip movement along the San Andreas fault zone. Small relative vertical movements of different sides of the bay could drastically alter apparent sedimentation rates, but orders of magnitude greater horizontal movement would be required to cause the same effect. Several lines of evidence indicate that there has not been vertical tectonic movement in Tomales Bay over the time frame covered by this study. Horizontal coseismic movement during the 1906 earthquake in the Tomales Bay area is well documented (about 2.7 m) but despite efforts of at least two separate parties of geologists shortly after that earthquake, no convincing evidence of vertical displacement was found (Dickinson, 1993; Galloway, 1977). Two different seismic studies of Tomales Bay sediments were also unable to find any evidence of vertical faulting younger than several thousand years old (Daetwyler, 1966; Anima, pers. comm.).

Neimi and Hall (1992) report that “most or all of the late Holocene slip on the San Andreas fault has occurred on the 1906 trace.” They calculate that 1906-type earthquakes occur every 221 ± 40 years on the North Coast segment of the San Andreas fault, which includes Tomales Bay. This is consistent with lack of tectonic creep along the fault trace and the tendency of this area to experience large, infrequent earthquakes rather than smaller and more frequent ones (Galloway, 1977; Koenig, 1963). Based on the above, we assume...
that no tectonic displacement occurred over the timeframe of this study that had a significant impact on apparent sedimentation rates in the bay. We now move to processes which probably have affected the system.

**Land Use**

Landuse history in the Tomales Bay watershed was examined to gain a general appreciation for the degree of disturbance of the soil surface required to produce the observed changes in sedimentation rates in the bay. Prior to about 1840 the primary human inhabitants of the area were Native Americans, who subsisted by hunting and gathering. The land was then settled by Europeans and European Americans (MASON, 1971, 1976). With the advent of a predominantly non-Native American human population in the area, the primary form of land use changed to various forms of agriculture, especially dairy farming. The intensity of agricultural land use accelerated rapidly in the latter half of the 1800s, and then leveled out or declined (Figure 5).

The timing of the bathymetric surveys was helpful for determining the effects of varying land use on sedimentation rates. The 1860–61 survey essentially gives a bathymetric “snapshot” of the bay, prior to European impact. The 1931 survey shows the bathymetry after decades of both intensive land-use and high rainfall. The survey of 1957 shows the bathymetry of the bay after continued western influence, and a dry period, followed by wetter decades. The 1993–94 survey covers a period of lowered agricultural impact. Thus the surveys bracket time increments that can give some insight into the influence of different land-use practices on sediment accumulation rates in the adjacent bay.

We originally hypothesized that the greatest rate of sediment accumulation in the bay would coincide with the period of maximum land use alteration of the watershed. However, the peaks of these two rates do not coincide (Figure 5). We
believe that the explanation lies with sediment storage in the watershed. Changing land use almost certainly elevated watershed erosion, but the erosion products did not have an impact on bay sedimentation, measurable by the methodology presented above, until after 1931. By 1957, land use effects were no longer being reflected in bay sedimentation, which had returned to conditions closely resembling pre-European contact. We must look to additional information in order to reconcile these differences between bathymetric changes and sediment yield.

**Sediment Storage in the Stream System**

Some amount of sediment storage in the lower hillslopes, stream channels, and floodplains is known to occur in the Tomales Bay watershed. Olema Creek and Keyes Creek were at one time navigable up to the towns of Olema and Tomales respectively (HART, 1972). By the end of the nineteenth century they had become so choked with sediment that the head of navigable waters had migrated several kilometers downstream. This is still the case today, indicating that sediment has been stored in both stream systems for a century or more. Similar delays have been documented in other drainage systems (MEADE, 1982).

We found a sediment accumulation of $68 \times 10^5 \text{ m}^3$ for Interval I or about $10^6 \text{ m}^3 \text{ yr}^{-1}$. The annual sediment accumulation for Interval II was about $3.6 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$, or an excess of $2.5 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$ for 26 years. This requires a watershed storage capacity of about $7 \times 10^6 \text{ m}^3$, assuming no other mechanisms are at work to explain the peak in sedimentation during Interval II. An examination of topographic maps reveals that there is more than $10^7 \text{ m}^3$ of stream floodplain in the watershed (i.e., about 2% of the watershed area). Much of the floodplain contains an accumulation of $> 1 \text{ m}$ of apparently recent stream sediments, for a total volume in excess of $10^7 \text{ m}^3$ of sediments. Thus it seems reasonable to assume that the stream beds and floodplains could easily have stored the sediment from excessive erosion. This lends credibility to the notion of stream valley storage as a mechanism to explain the time delay between disruptive land-use activities and high sediment accumulation rates in the bay.

Assuming that the delay in sediment accumulation in the bay is due to sediment storage, it is useful to know the duration of storage as precisely as possible. An examination of the various land usages (Figure 5) shows that the peak in erosion is unlikely to have occurred prior to 1850 or after 1890. The GIS-derived rates (Figures 2 and 4) indicate that the peak in sediment delivery to the bay occurred during Interval II. That pulse of sediment is therefore most likely to have been in storage for between, roughly, four to eleven decades. The number and timing of the bathymetric surveys preclude resolving the duration of sediment storage more precisely.

**Sediment Yield From Other Systems**

Given the multitude of variables that affect sediment yield from a watershed, comparisons from one system to another can be problematic. MILLIMAN and SYVITSKI (1992) addressed this problem by comparing sediment yield and load versus area and runoff for 280 rivers throughout the world, and for each of 7 different topographic categories of river basins. These plots show that Tomales Bay has slightly lower than average runoff. When plotted as a function of runoff, the sediment load and yield is very typical of other systems of comparable size. Tomales Bay fits into their “upland” topographic category, with a maximum elevation of 500–1000 m. When compared to other “upland” river basins with similar runoff, the sediment yield at Tomales is slightly above the norm.

In numerous studies of other systems, anthropogenic impacts, particularly crop farming, have been found to be responsible for elevated sediment erosion or export rates of up to an order of magnitude, or more (e.g., MEADE, 1982; LEHRE, 1982; MILLIMAN et al., 1987; SHEFFIELD et al., 1995). In that respect, the rates found at Tomales Bay are comparable to others. LEHRE (1982) calculated a sediment budget for the Lone Tree Creek watershed, a small (2 km$^2$) drainage basin 35 km southeast of Tomales Bay. The climate, rock type, vegetation, and topography in the two areas are relatively similar. Lehre found that landslides were the most important erosional agent and that mobilized sediment tended to be removed from the basin during extreme rain events, and stored within the basin under other conditions. He calculated an average annual sediment yield of about $210 \text{ t km}^{-2} \text{ yr}^{-1}$, noting that landslides apparently increased ten fold over the 100 years preceding 1974. These rates are roughly comparable with those from Tomales Bay, with average rates of $150 \text{ t km}^{-2} \text{ yr}^{-1}$ and $100 \text{ t km}^{-2} \text{ yr}^{-1}$ for 1861–1994 and 1957–1994 respectively. MILLIMAN and MEADE (1983) report that smaller drainage systems have less ability to store eroded sediment than do large ones. The higher yield from Lone Tree Creek is probably explained by its tendency to store less of the mobilized sediment than does the much larger Tomales Bay watershed.

**CONCLUSIONS**

Perhaps the single most important lesson out of this study is the reminder that sediment yield in a watershed over any period of time is not synonymous with erosion or sediment denudation. There is an additional storage reservoir between erosion in the watershed and yield from the watershed: streambed storage. Even in a relatively small watershed like Tomales (560 km$^2$) the streambed storage time can be several decades and this storage can obfuscate strongly expected relationships between land use and erosion.

In the Tomales watershed, it was found that although the disruptive landuse practices apparently did increase erosion and deposition in the Bay, there was a decades long delay between the maximum level of soil surface disruption and maximum sediment deposition. A similar delay was found between initial deposition of sediments at stream deltas and subsequent redistribution to other areas of the Bay more graphically remote from stream deltas, although areas closer to the mouth of the Bay experienced markedly faster sediment redistribution.

Methodologically, this study demonstrates that GIS can be an effective tool for investigating anthropogenic impacts that may be of too short a duration to be approached using classic geological techniques such as radiometric dating or core analysis and yet are too variable to be adequately characterized by measuring current rates. GIS estimates of sedimentation rates offer the advantage of a potentially high degree of spatial data density as well, allowing integration of
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LITERATURE CITED


 UNEP, 1982. River inputs to the west and central African marine environment. UNEP Regional Seas Reports and Studies, Number 5.
