Assessing the linkages among climate variability, land-use change and the sedimentary regime of the Upper Chesapeake Bay

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Abstract

The objective of this study was to assess the effects of climate variability and land-use change in the Susquehanna river basin on the sedimentary regime of the Upper Chesapeake Bay, USA. Historical precipitation, stream discharge, land use, suspended sediment and dam reservoir capacity data were used to interpret regional patterns of erosion and sediment transport on annual, decadal and centennial timescales. Sediment accumulation patterns in the Upper Chesapeake Bay were inferred from the analysis of four piston cores including 14C dating, magnetic susceptibility and laser particle analysis techniques. Core magnetic susceptibility profiles were found to be a useful tool for stratigraphic correlation on the order of centimeters. On annual to decadal time-scales, a strong relationship was found between sediment yield and regional rainfall-runoff patterns and land surface erodibility. However, on centennial time-scales, our research suggests that anthropogenic land-use change (e.g., clear-cutting of native forests) has caused up to an order of magnitude increase in sediment accumulation rates in the Upper Chesapeake Bay. As a result, the signature of extreme hydrologic events such as large floods and droughts, and thus "natural" climate variability, was "aliased" from the estuarine sedimentation patterns over the last 150 years. The construction of major dams around 1930 on the Lower Susquehanna River has resulted in a significant decrease in coarse fraction of sediment inputs into the estuary, further reducing our ability to separate flood episodes from average conditions.
1. Introduction

The original motivation for this work was to investigate whether sediment cores obtained from estuaries could be used to infer the history of extreme hydrological events in upstream watersheds. The idea was to interpret changes in sedimentation patterns and sediment lithology and texture as a proxy of the historical time-line of occurrence of major floods and droughts in coastal basins, and thus use this information in the reconstruction of past hydrologic regimes and climates.

The selected region of study is the Susquehanna river basin and its estuary, the Upper Chesapeake Bay. The Susquehanna is located in the Mid-Atlantic region of the Eastern U.S.A. extending across three different states (New York, Pennsylvania, and Maryland), and drains into the Chesapeake Bay at Havre de Grace, Maryland.

The estuary was created by drowning of the Susquehanna river valley as a result of rising sea levels following the peak of the last Ice Age, approximately 10,000 years ago [1].

The hydrologic and sediment transport regimes of the Susquehanna Basin and its major tributaries were characterized using historical precipitation, river discharge, land use and river suspended sediment data. Sediment accumulation patterns in dam reservoirs were tracked using the history of reservoir capacity decrease. Sediment accumulation patterns in the Upper Chesapeake Bay were interpreted using a set of four dated and correlated piston cores. In order to describe and correlate core stratigraphy as well as interpret the ages of core sediments'14C, magnetic susceptibility and laser particle analysis techniques were used. Core analysis results were integrated with historical bathymetric, tidal and suspended sediment data in order to assess spatial variability of sediment accumulation patterns in the estuary.

2. Data Analysis

2.1 Hydrology

The basin was divided into three regions coincident with the watersheds of three major tributaries to the Susquehanna main stem: the Juniata river, and the West Branch and the Main Branch of the Susquehanna river (Fig. 1). Streamflow records from the United States' Geological Survey (USGS) and suspended sediment measurements obtained from the Susquehanna River Basin Commission (SRBC) for selected locations were used to characterize regional runoff generation and sediment export patterns (Fig. 1).

Data on the location, size and original reservoir capacities of major dams in the Susquehanna Basin were obtained from the Susquehanna River Basin Commission. Because of their size and location, the three dams that contributed the most to disrupt the natural sediment input to the Upper Chesapeake Bay are Holtwood, Conowingo and Safe Harbor (not shown). Bathymetric surveys of sediment deposits in these dams between 1910 and 1996 can be used to derive the
time-evolution (i.e., reduction) of reservoir capacity, and thus sediment accretion [2].

2.2 Basin Erodibility

A land surface erodibility index $A(x,y,t)$ based on the Universal Soil Loss Equation (USLE, Wischmeier and Smith [3]) was used to establish temporal trends in sediment mobility across the Susquehanna basin. Spatial fields were obtained from the distribution of soil erodibility factors ($K$), slope-length ($LS$), and land-use factors ($C$) on a digital elevation map (DEM) at 1km$^2$ resolution: $[A(x,y,t) = K(x,y) * LS(x,y) * C(x,y,t)]$. Historical changes in land-use [i.e., $C(x,y,t)$] were retrieved from the U.S. Agricultural Census (1930 -1992) data-base and from historical land-use maps. An additional Apre-European settlement index was generated by assuming that the basin was entirely covered with native forest. Rainfall intensity and the potential effects of changing farming practices on regional
sediment mobility were not considered. However, on a regional basis, this index should be adequate to assess spatial variability and relative magnitude of soil loss. Further details can be found in Gordon [4].

2.3 Sediment Cores

Four piston cores were obtained on November 11, 1997, aboard the Maryland Geological Survey Research Vessel *Discovery*. Three of four total piston cores were extracted from the primary outflow channel of the Susquehanna in the Upper Chesapeake Bay (Fig. 2). Cores were extracted from relatively deep sites unaffected by dredging activity. Sediments were x-rayed prior to extraction at the Baltimore office of the Maryland Geological Survey. Core sediments were extruded by forcing a seal through the core liner, split longitudinally, photographed and logged. Half of each core was sampled every 2-cm, while the second half was archived.

![Figure 2 - Location of core sites in the Upper Chesapeake Bay.](image)

Magnetic susceptibility profiles in electromagnetic units (emu) at two centimeter intervals were determined using the archived core halves and the Barrington Magnetic Susceptibility Meter at Union College, Schenectady, New York. Because magnetic susceptibility results are related to sample mass, it was
necessary to apply a mass correction based on sediment porosity of the data. Grainsize distributions of the upper 120 cm of core SS were determined using a GALAI CIS-100 Laser Particle Analyzer with a particle size upper bound of 300 μm. The radiocarbon age of woody samples from 220 cm in core SS and 133 cm in core SQ were determined using the Accelerator Mass Spectrometry (AMS) radiocarbon techniques employed by the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole, Massachusetts.

3. Results

3.1 Sediment Yield - Watershed

In the Susquehanna river basin, extreme floods are generated by one of two types of storms: 1) tropical storms in the warm season; and 2) southerly air masses with intense rainfall and strong, warm winds that lead to the fast breakup and melt of the snowpack. The spatial patterns of warm season rainfall are normally concentrated on the western part of the basin [5]. On the other hand, wintertime floods originate predominantly in the northern basin (west and main branches of the Susquehanna) as described by Barros and Kuligowski [6]. The strong annual periodicity in stream discharge is related to the spring freshet, a regular spring increase in river discharge driven by snowmelt. Typically, spring flows are generally four to five times larger than the low flows in late summer. Although patterns of seasonal variability in stream discharge appear fairly uniform on regional scales, there is a shift in the relative contribution of major Susquehanna tributaries to total sediment yields at Marietta, Pennsylvania (Fig. 3). During the spring, most of the sediment flux at Marietta, Pennsylvania comes from the northern regions of the drainage basin; during the summer, the Juniata River becomes the dominant source of sediment to the main stem of the Susquehanna.

Modern regional sediment export regimes are complicated by the incomplete export of all sediment eroded from the land surface on annual to decadal time-scales [7] and [8]. Coarse sediment transport is episodic (floods), and thus coarse sediments have long residence times in the basin. Indeed, the grainsize distribution of the Susquehanna sediment load exhibits strong fining downstream. This observation is consistent with the hypothesis that the erosion and export of coarse sediments are not in balance on annual to decadal time-scales.

Decadal variability in sediment yields from the Susquehanna Basin has been related to major flood magnitude and frequency because very large floods transport multiple years worth of sediment in a few days [9]. For example, between 1966 and 1976, the Susquehanna River discharged approximately fifty million metric tons of suspended sediment to the northern Chesapeake Bay; about eighty percent of this volume was exported by the floodwaters associated with two hurricanes [10]. One way to describe decadal variability in Susquehanna Basin stream discharge is by focusing on the historical record of annual peak flows at Marietta, Pennsylvania. Periods of rapid Susquehanna Basin sediment export can than be associated with
periods of multiple and frequent large floods affecting the majority of the catchment, while periods of slow sediment export can be associated with periods of more infrequent and localized floods.

Figure 3 - Seasonal variability of runoff and sediment export.

Sediment accumulation patterns in downstream Holtwood, Safe Harbor and Conowingo Dam reservoirs were used to assess the validity of the hypothesis that the magnitude and timing of major floods is a good predictor of the decadal variability of sediment yields at Marietta. As expected, dam reservoir sediment accumulation patterns were found to closely correspond with the patterns of sediment yield from Marietta, Pennsylvania. Although these results imply that basin sediment export rates in the 1930\textasciitilde{}s and 1940\textasciitilde{}s were higher than those in the 1970\textasciitilde{}s, the data analysis may be confounded by the decrease in the capacity of upstream reservoirs. The 1930\textasciitilde{}s are the period during which major dam construction and closure was taking place on the Lower Susquehanna. Furthermore, post-1930 sediments are finer than pre-1930 sediments, consistent with the tendency of dam reservoirs to trap relatively coarse sediments. The
changes in estuarine depositional patterns around 1930 are attributed to the effects of upstream dam construction.

3.2 Sediment Accumulation - Estuary

Regional sediment accumulation patterns were interpreted by a comparison of stratigraphic relationships and sediment ages among four Upper Chesapeake Bay piston cores. Stratigraphic units in core SP were defined based on the degree of correlation between core porosity and magnetic susceptibility profiles. Beds with highly correlative porosity and magnetic susceptibility profiles were coarser with more visible grain-size variability and irregular, wavy laminae. Beds with less strongly related porosity and magnetic susceptibility profiles were finer-grained with bedding-parallel laminae. Stratigraphic unit boundaries in core SP were directly translated to core SS by means of correlative magnetic susceptibility (Fig. 4).

Figure 4 - Stratigraphy and magnetic Susceptibility profiles for cores SS
The location of the Upper Chesapeake Bay MTZ was delineated based on the spatial distribution of the concentrations of total suspended solids (TSS) in the water column. These results are in good agreement with an interpretation of the location of the MTZ based on satellite images [11]. Core SP was extracted from a region upstream of the MTZ that could be classified as a turbulent bed-friction dominated delta, while core SS was extracted from the MTZ. Accordingly, sediments in core SP are alternately sandy and fine, while sediments are well-sorted in core SS (Fig. 4).

Textural differences between the two cores are attributed to a combination of downstream sediment fining and the effects of hydraulic sediment sorting by estuarine circulation at SS. Coarse SS beds are consistently thicker than correlative SP beds, and thinner than correlative fine beds, suggesting that MTZ sediment accumulation rates are more sensitive to changes in Susquehanna River sediment discharge than sediment accumulation rates in the Susquehanna Flats.

The rate of increase in cumulative magnetic susceptibility may also be useful as an indicator of the relative rate of sediment accumulation. Cumulative magnetic susceptibility increases more slowly in coarse beds than in fine beds in both core SS and core SP (Fig. 4). Coarse stratigraphic units would be expected to be associated with periods of relatively rapid sediment export. Assuming that some fraction of the total ferromagnetic load is delivered and accumulates in the subaqueous sediment surface, the association of coarse beds with a slower rate of increase in cumulative magnetic susceptibility implies a faster sediment accumulation rate.

Analysis of woody fragments from 220 cm in core SS and 133 cm in core SQ yielded respective 

\[ ^{14}C \] age-dates of -1010 and -2680 yrs. These estimates suggest sediment accumulation rates that differ by an order of magnitude on centennial time-scales. That is, sediment yields may have increased by up to an order of magnitude since basin settlement. Although sediment yields from the basin are complexly influenced by multiple forcing factors, historical changes in land cover alone could account for the disparity between modern and pre-settlement sediment accumulation rates as shown by the erodibility index results in Fig. 5 below.

4. Summary and Conclusions

The sediment yield from the Susquehanna river basin was considered on annual, decadal and centennial time-scales. Variability on annual to decadal time-scales was found consistent with regional rainfall-runoff hydrological patterns and land-surface erodibility. On annual time-scales, the majority of basin sediment export is accomplished during spring floods. Seasonal variability in the relative contributions of major Susquehanna tributaries to total basin yields has been attributed to seasonal variability in regional precipitation patterns. On decadal time-scales, temporal variability in basin sediment yields was related to the magnitude and timing of large rare floods. On centennial time-scales, our research suggests that anthropogenic land use change can explain the observed order of magnitude
increase in downstream sediment accumulation rates, thus masking the relationship between hydrologic extremes and regional sediment yields.

Since the construction and closure of major dams on the Susquehanna main stem, dam reservoir sedimentation patterns have corresponded with sediment yield patterns from upstream Marietta, Pennsylvania. Accordingly, sediment accumulation rates in the Upper Chesapeake Bay decreased dramatically, but with higher fraction of fine sediments. Alternate scouring and trapping of sediments in dam reservoirs would be expected to have amplified the effects of major floods on the sediment accumulation regime of the Upper Chesapeake Bay, but decadal variability in Upper Chesapeake Bay sediment accumulation rates could not be resolved from the sediment age-dating techniques.

Figure 5 - Integrated analysis of sediment accumulation patterns in the Upper Chesapeake Bay and erodibility changes in the Susquehanna river basin.
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References