MAPPING VULNERABILITY TO UPLAND EROSION IN THE CHESAPEAKE BAY WATERSHED

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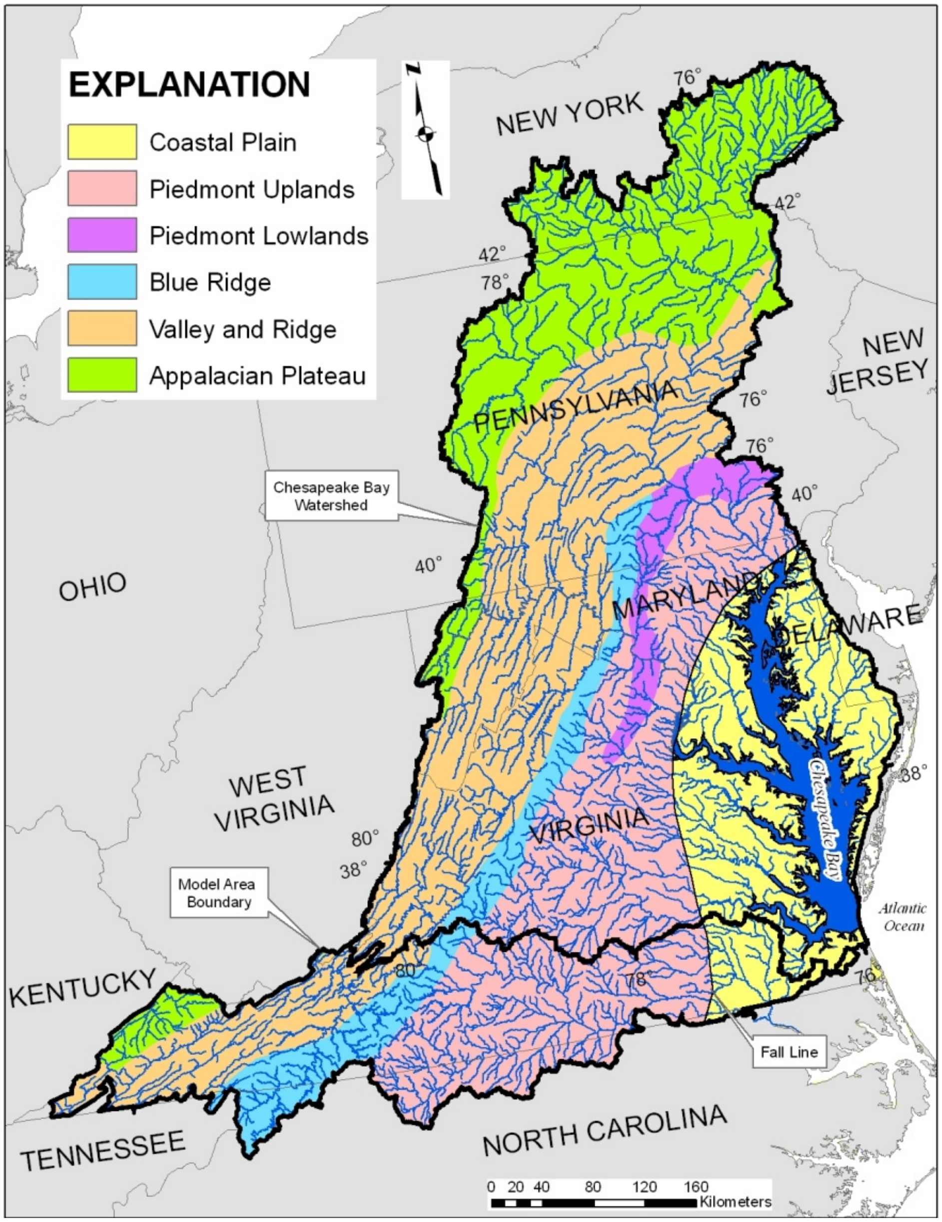
Abstract Management of suspended sediment in large watersheds is complicated by the complexity and spatial variability of landscape factors affecting sediment supply and transport. SPAtially Referenced Regressions on Watershed attributes (SPARROW) is a spatially explicit mass-balance watershed modeling technique that uses nonlinear regression equations to relate stream constituent flux to land and stream sources and transport factors. A calibrated SPARROW model was used to illustrate the cumulative effects of interacting landscape factors on sediment transport from uplands to stream corridors in the Chesapeake Bay watershed. Suspended-sediment transport to Chesapeake tributaries is observed to be more efficient in steeper areas with relatively impermeable soils and few impoundments. Sediment delivery to streams also is greater in the Piedmont Uplands than in other physiographic settings. Relatively erosive soils and high suspended-sediment yields have previously been reported in this region; however, the SPARROW model indicates that these yields are influenced by factors independent of slope and soil permeability. The cumulative effects of multiple factors affecting overland sediment transport have been mapped to illustrate relative upland erosion vulnerability. Erosion controls in areas especially vulnerable to upland erosion may be particularly effective at mitigating sediment flux to Chesapeake Bay.

INTRODUCTION

Sedimentation is a common cause of ecological and economic degradation of streams and coastal estuaries (McCave, 1987; Howarth et al., 1991; Phillips, 2002) and causes an estimated $16 billion worth of physical, chemical, and biological damages each year to surface waters in North America (Pons, 2003). Chesapeake Bay (Figure 1), the largest estuary in North America and a vital regional economic and ecological resource, has been degraded over recent decades by excessive sediment (Cronin and Langland, 2003). Ecological effects of excessive suspended sediment in the Bay and its tributaries include significant reductions in submerged aquatic vegetation, reduced vitality of filter-feeding benthic organisms, and enhanced delivery of associated chemical constituents and pathogens (Wolman, 1964; Wolman and Schick, 1967; Cronin and Langland, 2003). Economic impacts of sedimentation in Chesapeake Bay include disruption of commercial shipping and degradation of fisheries (Phillips, 2002; Langland et al., 2003).

Chesapeake tributaries contribute more than 4 million metric tons of sediment annually from the watershed to the Bay (Cronin et al., 2003). Watershed sediment is derived from erosion of uplands and stream corridors, which occurs naturally, but is significantly enhanced by human activities at the land surface (Gellis et al., 2003), including agriculture (Wolman and Schick, 1967; Costa, 1975), mining (Biesecker et al., 1968; Williams and Reed, 1972; Staubitz and Sobashinski, 1983; Reed and Hainly, 1989), and especially construction activities (Guy and Ferguson, 1962; Wark and Keller, 1963; Wolman, 1964; Wolman and Schick, 1967; Vice et al., 1969; Roberts and Pierce, 1974; Yorke and Herb, 1978; Dougherty et al., 2006).



Base map from U.S. Geological Survey data; 1:2,000,000; Albers equal area projection

Figure 1 Location and generalized physiography of the Chesapeake Bay watershed.

The Chesapeake Bay has been the focus of Federal, State, and local restoration efforts since the 1980s (Phillips, 2002; Langland et al., 2003). In 2000, the Bay was listed as “impaired” under the Clean Water Act due, in part, to excessive sediment (Langland et al., 2003). Of the major sources of suspended sediment to the Bay, upland watershed sources have the greatest potential for reduction through restoration and conservation actions (Cronin, 2007). Management of sediment in large areas like the Chesapeake Bay watershed, however, is complicated by the multitude of interacting sources and factors affecting the generation, movement, and retention of sediment from uplands to the estuary (Howarth et al., 1991; Smith et al., 2003). Efficient and effective targeting of areas within the watershed for application of limited conservation assets requires a consistent, comprehensive, and regional-scale understanding of erosion vulnerability, along with the occurrence of agriculture, mining, construction, and other potential erosive activities (Langland et al., 2003).

In this paper, we demonstrate the cumulative effects of multiple landscape properties on the transport of suspended sediment from uplands to streams in the Chesapeake Bay watershed. This interpretation is based on overland-delivery coefficients estimated as part of a Spatially-Referenced Regressions on Watershed attributes (SPARROW, Schwarz et al., 2006) model previously calibrated to mean annual suspended-sediment flux at 129 stream locations in the Chesapeake Bay watershed and vicinity (Figure 1) (Brakebill et al., in press). SPARROW models have previously been applied regionally, nationally, and internationally to assess the fate and transport of nutrients and sediment (Smith et al., 1997; Alexander et al., 2008; Hoos and McMahon, 2009; Preston and Brakebill, 1999; Schwarz, 2008; Elliott et al., 2008). A map of the Chesapeake Bay watershed showing areas of different relative upland erosion vulnerability is presented and discussed. Delivery coefficients used to generate the map are not conceptual estimates based on values in the literature, but rather are based on spatial correlations between observed mean-annual suspended-sediment flux, watershed sediment sources, and landscape factors affecting sediment transport. This multivariate empirical (statistical) approach supports a consistent, comprehensive, and objective evaluation of the relative importance and statistical significance of each landscape delivery factor, along with a similar understanding of sediment sources and fate within the watershed and stream corridor. The importance of each significant landscape factor is discussed, along with the approach used to map their combined effect in the watershed, and the application of such information for Chesapeake Bay restoration and management.

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METHODS

Selected results of a SPARROW model previously calibrated to illustrate and quantify sources, fate, and transport of suspended sediment (Brakebill et al., in press) were used to understand and delineate relative upland erosion vulnerability at the regional scale in the Chesapeake Bay watershed. SPARROW is a spatially-explicit, mass-balance, watershed modeling technique that uses a nonlinear-regression approach to quantify the spatial relation between observed constituent (such as suspended sediment) flux in nontidal streams (the response or dependent variable) and sources and watershed characteristics affecting overland and instream fate and transport (explanatory or independent variables) (Smith et al., 1997; Schwarz et al., 2006; Preston et al., 2009). Response and explanatory variables for SPARROW models are geographically referenced to a digital network of hydrologically connected stream reaches and associated subwatersheds. The network topology allows for the simulation and routing of water (and associated constituents) throughout the landscape. For each stream reach in a model, SPARROW predicts long-term mean annual constituent flux as a function of sources and overland and instream fate and transport. Specifically, the instream constituent flux at the downstream end of any network stream reach is expressed as the sum of the flux generated within the subwatershed for that reach and similar flux transported from any upstream reaches.

Constituent flux from uplands to streams and within streams is not assumed to be conservative, but rather is weighted by landscape factors affecting overland and instream fate and transport (Schwarz et al., 2006; Hoos and McMahon, 2009).

The SPARROW model was calibrated to estimates of annual suspended-sediment flux in 129 stream reaches within the Chesapeake Bay watershed and adjacent areas of southern Virginia and northern North Carolina (Figure 1) during 2002 (Brakebill et al., in press). These flux estimates were generated using a multiple-regression approach based on observed sediment concentrations and streamflow data collected by Federal, State, and local agencies from 1970 through 2004 (Langland et al., 2004). Because of spatial variability in hydrologic conditions within the watershed during 2002, flux estimates were standardized based on long-term streamflow data, and provide an estimate of the sediment flux that would have occurred in each stream during 2002, if long-term mean hydrologic conditions for 1970 through 2004 had occurred during that year (Brakebill et al., in press). Because the model is calibrated to annual suspended-sediment flux, significant terms are interpretable as factors affecting long-term, steady-state sediment sources and transport, rather than, for example, transport during particular seasons or individual storm events.

Explanatory variables in the calibrated SPARROW model explain 83 percent of the variability in suspended-sediment flux in streams of the study area (Brakebill et al., in press). Drainage area and associated scaling effects account for a portion of this explanatory power, although the yield-R^2 (the R^2 of the logarithm of constituent yield, Schwarz et al., 2006) indicates that included source and overland and instream transport variables explain 57 percent of the variability in sediment flux. Explanatory variables were selected for consideration on the basis of available mapping data and existing knowledge of sources of sediment within the watershed and factors affecting sediment fate and transport (Gellis et al., 2003). Regression diagnostics (variance inflation factors and eigenvalue spread) were monitored to ensure multicollinearity among such selected explanatory variables does not significantly affect model interpretation (Schwarz et al., 2006). Upland sediment sources represented in the model include agriculture, forest, and areas of recent (1992 to 2002) urban development (U.S. Environmental Protection Agency, 2008); stream length was included to represent stream corridor sources of sediment. Overland delivery factors in the model include watershed soil (Schwarz and Alexander, 1995), topographic (U.S. Geological Survey, 1999), and physiographic (U.S. Geological Survey, 2004) characteristics (Figure 1). The areal density of dams (U.S. Army Corps of Engineers, 2005) on small streams (those too small to be represented in the 1:500,000-scale digital watershed network) also were included to represent the effects of numerous small impoundments. Physiography was modeled as a binary variable representing subwatersheds predominantly inside or outside of the Piedmont Uplands (Figure 1), where relatively high sediment yields have been previously reported (Trimble, 1975; Gellis et al., 2003). Sediment retention within streams was modeled separately for large impoundments (those represented on the digital watershed network) and for flowing (non-impounded) reaches (Brakebill et al., in press).

The cumulative effect of four significant (α=0.10) landscape factors (variables) that mitigate or exacerbate the overland delivery of sediment from uplands to streams was interpreted as an indicator of relative upland erosion vulnerability (RUEV) (Schwarz et al., 2006; Hoos and McMahon, 2009; Brakebill et al., in press). This cumulative effect was calculated for each reach subwatershed (i) as:

APPLICATIONS

The consistent, comprehensive, regional-scale understanding of the spatial variability of sediment erosion vulnerability (Figure 3) has broad applicability within the context of regional watershed management and restoration efforts. The map shows that some of the most vulnerable areas of the watershed are located in the northern part of the Piedmont Uplands. This area is relatively close to the Bay, and opportunities for retention of fluvial sediment from uplands within the tributary network before reaching the estuary are limited. This is also an area of intensive agriculture and suburban development, both significant sources of suspended sediment in the watershed (Gellis et al., 2003; Brakebill et al., in press). Similarly, soil, topographic, and other conditions contribute to relatively high erosion vulnerability within the watershed in other areas of the Piedmont Uplands and in parts of northern Pennsylvania. Targeted application of conservation resources or land-use planning or zoning designed to limit erosion in these areas may be particularly effective at mitigating sediment in Chesapeake Bay. Conversely, although agricultural intensity in parts of the Eastern Shore is comparable to the Midwestern United States, the erosion vulnerability suggests that this area may be a lower priority for such management or mitigation approaches, at least for suspended sediment.

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