Combined Geomorphic and Numerical-Modeling Analyses of Sediment Loads for Developing Water-Quality Targets for Sediment

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Abstract

The principle objective of the study was to determine sediment loads for James Creek, Mississippi and for similar, but stable "reference" streams to develop water-quality targets for sediment. "Reference" sediment-transport loads were determined from stable streams with historical flow and sediment-transport data in the Southeastern Plains Ecoregion. Using the discharge that occurs, on average every 1.5 years ($Q_{1.5}$) as the "effective discharge," an initial "general reference" of 0.31 T/d/km^2 was obtained. This value, however, is skewed towards streams with sand beds and does not accurately reflect conditions along James Creek. A refined "reference" condition was developed for stable silt/clay-bed streams in the Southeastern Plains resulting in a "reference" suspended-sediment yield of 3.23 T/d/km^2 at the $Q_{1.5}$. A weighted-reference condition based on the percentage of the drainage area encompassed by the various bed-material types results in a reference yield at the $Q_{1.5}$ of 2.2 T/d/km^2. Similarly, a weighted-reference concentration of 160 mg/l was obtained. "Actual" sediment-transport loads were obtained by: simulations of flow and sediment transport using the model AnnAGNPS and by simulations of channel flow and sediment transport by the channel-evolution model CONCEPTS. Average sediment loads at the mouth of James Creek over the 35-year period are about 250,000 T/y with 88% emanating from channels and 12% from upland sources. This loading value, however, is somewhat misleading in that severe channel erosion occurred between 1967-1968 following channel clearing and snagging over the lower 17 km. Since this time, sediment loads attenuated and the contribution from channels and uplands over the period 1970-2002 shifted to 70% and 30%, respectively. "Actual" simulated suspended-sediment loads at the $Q_{1.5}$ show a 35-year average of 675 T/D/km^2; 155 T/D/km^2 over the past 10 years. Following the installation of low-water crossings in 1999 loads decreased to about 39 T/D/km^2. This value is more than an order of magnitude greater than the "reference" yield.

Keywords: sediment transport loads, reference conditions

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Introduction

The 1996 National Water Quality Inventory (Section 305(b) Report to Congress) indicates that sediments are ranked as a leading cause of water-quality impairment of assessed rivers and lakes. The maximum allowable loadings to, or in a stream that does not impair designated uses has been termed the "TMDL" (total maximum daily load). Three segments along James Creek, Mississippi are listed as having impaired conditions for aquatic life support due to sediment. The Mississippi Department of Environmental Quality (MDEQ) seeks a percent reduction in sediment loads such that the James Creek watershed is producing sediment at rates commensurate with those in a biologically unimpaired stream. This unimpaired stream is thus termed a “reference” stream or reach.

Because there are no historical sediment-transport data or “reference” reaches for James Creek, alternative methods are required. Additionally, the sediment-transport data must be expressed in the same form as those developed for reference conditions. To accomplish these tasks a combination of empirical and numerical techniques are used. Suspended-sediment loads from typical streams in the region with historical data can be analyzed by relating the geomorphic conditions at those streams with the conditions along James Creek (Simon et al. 2002). Water and sediment contributions from uplands areas can be obtained with the watershed simulation model AnnAGNPS (Cronshey and Theurer 1998). These data are supplied as boundary conditions for the channel-evolution model CONCEPTS (Langendoen 2000), used to determine channel contributions from main stem streambeds and banks.

A “reference” sediment loading condition can be defined as a concentration (in milligrams per liter; mg/l), load (in metric tons per day or year; T/d or T/y) or yield (in tons per day per square kilometer ($T/d/km^2$) representative of “natural,” stable, or non-impaired conditions. For James Creek and in the absence of a stable channel analog within the watershed, data from similar watersheds in the Southeastern Plains (Ecoregion 65) must be used. “Reference” sediment-transport conditions are established by (1) empirically determining sediment loads for the Southeastern Plains streams using historical flow and sediment-transport data; (2) determining the relative stability of each site where historical data is available; and (3) determining sediment loads for stable and unstable sites segregated by dominant bed-material size class.

“Actual” sediment loading in James Creek can be defined as the amount of sediment that is being transported through and out of the watershed outlet. Because no historical data on sediment transport is available for James Creek empirical and numerical-simulation models are used. To characterize the “actual” sediment load in James Creek, field and digital data are required as inputs to run the simulation models AnnAGNPS and CONCEPTS. The simulation period 1967-2002 was selected because this period coincides with periods of measured channel cross sections.

General description of AGNPS modeling technology

The Agricultural Non-Point Source Pollutant (AGNPS) watershed simulation model (Bingner and Theurer 2001) is a tool to evaluate pollutant loadings within a watershed and the impact farming and other activities have on pollution control. To run AnnAGNPS, daily climate information is needed to account for temporal variation in the weather. The spatial variability within a watershed of soils, landuse, and topography, is accounted for by dividing the watershed into many homogeneous drainage areas. These simulated drainage areas are then integrated together by simulated rivers and streams, which route runoff, sediment and pollutants from each area downstream. Flow and sediment generated by AnnAGNPS can then be input into CONCEPTS as a boundary condition.

The type of landuse assigned to each AnnAGNPS cell was determined using the AGNPS ArcView interface procedure. This procedure assigned a landuse to each cell based on the predominant land use from the land use GIS layer. There are 41 soil types identified from the soil GIS layer in the James Creek watershed. Silty-clay and silt-loam soils dominate the basin. Most of the soils information was derived from the NRCS Soils 5 database. Individual event information describing measured precipitation for the years 1967-2001 was obtained from the Aberdeen, Mississippi National Weather Service climate station located within the James Creek watershed.

General description of CONCEPTS modeling technology

CONCEPTS simulates unsteady, one-dimensional flow, transport of cohesive and cohesionless sediments in suspension and on the bed selectively by size class, and bank-erosion processes (Langendoen 2000). Hence, it can predict the dynamic response of flow, sediment transport and channel form ‘channel evolution’ to disturbances including channelization, altered hydrologic regime, or in-stream hydraulic structures. The model assumes streamflow to be one-dimensional along the centerline of the channel.

The model calculates total-load sediment-transport rates by size fraction from a mass conservation law, and by taking into account the differing processes governing entrainment and deposition of cohesive and cohesionless bed material (Langendoen 2000). For graded bed material, the sediment transport rates depend on the bed material composition. Following Hirano (1971), CONCEPTS divides the bed into a surface or active layer and a subsurface layer. For cohesive materials, the erosion rate is calculated by an excess shear-stress approach (Hanson and Simon 2000) while the deposition rate is calculated following the method of Krone (1962).

Channel-width adjustment is simulated by incorporating the physical processes responsible for bank retreat: (1) fluvial erosion of bank-toe material, and (2) mass-failure by gravity (Simon et al. 1999, Langendoen 2000). CONCEPTS accounts for streambank stratigraphy by allowing variable geotechnical properties to be assigned to bank materials. Bank stability is analyzed via the limit-equilibrium method**.** CONCEPTS performs stability analyses of planar slip failures and cantilever failures of overhanging banks by dividing the bank into slices, and evaluating the balance of forces on each slice in vertical and horizontal directions. The slope of the failure surface is defined as that slope for which the factor of safety is a minimum.

Methods

Channel surveys

Channel-geometry data surveyed in 1967 are available at 10 cross sections along James Creek and were used as inputs for the initial 1967 CONCEPTS simulations. Additional sections were synthesized between those surveyed in 1967 based on the average top width and channel depth of the adjacent measured cross sections. A total of 47 cross sections were surveyed along James Creek in 2002 to establish current channel geometry and to provide a means of directly comparing 1967 channel geometries. Bed erosion of about 2 m occurred between the mouth of James Creek and about rkm 10.5 over the 35-year period. This implies that tributaries entering the main stem in the lower 10.5 km experienced up to a 2 m overfall and much steeper slopes at their mouths resulting in re-incision. Bed erosion attenuated from 2 m to negligible amounts from rkm 10.5 upstream to the structure at rkm 12.3.

Streambed erodibility and composition

CONCEPTS requires information on the relative resistance of streambed materials for calculations of sediment entrainment and transport. For cohesive streambeds, a submerged jet-test device is used to estimate erosion rates due to hydraulic forces (Hanson 1990, Hanson 1991, Hanson and Simon 2001). A critical shear stress (τ_c) for the material is calculated from field data as that shear stress where there is no erosion. The rate of erosion $\dot{\varepsilon}$(m/s) is assumed to be proportional to the shear stress in excess of τ_c and is expressed in terms of an erodiblity coefficient (*k*). *k* is obtained in the field or can be estimated as a function of τ_c (Hanson and Simon 2001). τ_c for sites along James Creek characterized by streambeds of sand and gravel are based on the Shields criteria derived from streambed samples and particle counts.

Streambank stability

Bank-toe materials are composed predominantly of cohesive materials inter-mixed with sand. The submerged jet-test device (modified to operate on inclined surfaces) is used to determine values of τ_c and *k.* To determine the resistance of cohesive materials to erosion by mass wasting, data is acquired on those characteristics that control shear strength; cohesion, angle of internal friction, pore-water pressure, and bulk unit weight. Cohesion and friction angle data are obtained with a borehole shear-test (BST) device (Lohnes and Handy 1968, Thorne et al. 1981, Simon 1989). The BST provides, direct, drained shear-strength tests on the walls of a borehole.

Texture of bed and bank materials

CONCEPTS uses information on sediment texture to determine sediment routing and sorting processes. Bulk samples of streambed and bank materials were collected at the 17 sampling sites to be analyzed for particle-size distributions. Although James Creek is considered to have a fine-grained streambed several sub-reaches are dominated by sand and gravel. Downstream reaches are dominated by gravel transitioning to sand through rkm 12 to 13, indicating depositional conditions. The reach between rkm 13 and rkm 23 is erosional with beds dominated by fine-grained materials. Average composition of the bank materials is 12% sand, 37% silt, and 51% clay.

Developing a "reference" sediment-transport condition

To determine the amount of sediment that impacts a given stream, one must first determine the sediment load in an un-impacted stream of a given type and location. To define this "reference condition" the scheme used in this study relies on the channel evolution framework set out by Simon and Hupp (1986) and Simon (1989), with stages I (pre-modified) and VI (re-equilibrated) used as stable morphologies.

Analysis of the impacts of suspended sediment requires a database of suspended-sediment concentrations with associated instantaneous water discharge. Data of this type permit development of rating relations (Glysson 1987). The USGS has identified more than 2,900 sites nationwide with at least 30 matching samples of suspended sediment and instantaneous flow discharge have been collected (Turcios and Gray 2001); 148 sites in nine states are in Ecoregion 65: the Southeastern Plains region James Creek is in. A suspended-sediment transport rating is developed for each of the 148 sites by plotting discharge versus concentration in log-log space and obtaining a power function by regression.

Because the "effective discharge" is that discharge or range of discharges that transport the most sediment over the long term it serves as a useful indicator of regional suspended-sediment transport conditions. In many parts of the United States, the effective discharge is approximately equal to the peak flow that occurs on average, about every 1.5 years ($Q_{1.5}$; e.g. Andrews and Nankervis 1995).

Suspended-sediment yields at the $Q_{1.5}$ were calculated for each site in the Southeastern Plains, and geomorphic assessments were carried out at 97 sites in the ecoregion. "Reference" stage I sites were found at 15 while 33 sites were characterized as stage VI. Data from the 48 "reference" sites were separated from those characterized as unstable to create sediment-transport distributions representing unstable and "reference" sites. The median value for stable sites is termed the "general reference" (0.3 T/d/km^2; 48 mg/l at the $Q_{1.5}$).The distributions are heavily influenced by sand-bed streams, representing the majority of the studied sites.

The central 50% of the reference distribution provides a "general reference" load at the mouth of James Creek of between 18.9 and 114 T/d at the effective discharge. The central 50% of the distribution for unstable sites in the Southeastern Plains ranges from 0.34 to 17 T/d/km^2 at the effective discharge.

Refinement of estimates of "reference" sediment discharge

The data set for both unstable and stable sites was sorted by dominant bed-material size class: gravel, sand, and silt-clay. "Reference" suspended-sediment yields for gravel-, sand- and fine-bed streams are 0.27, 0.42, and 3.2 T/d/km^2, respectively. The best estimate of the "reference" suspended-sediment yield or concentration for James Creek should be based on weight-meaning of the reference- parameter values. Utilizing the particle-size data we can identify those reaches that are dominated by the major textural size classes (gravel, sand and fines) and determine the percentage of the drainage area that is encompassed by those reaches. By assuming that tributaries entering the main stem have the same bed-material characteristics as the trunk stream we find that 65% is silt and clay, 21% is sand and 14% is gravel. The resulting "reference" values are 2.2 T/d/km^2 and 160 mg/l at the $Q_{1.5}$ or the effective discharge. Again if we multiply the reference yield by the drainage area of James Creek we obtain a "reference" load at the outlet of about 250 T/d at the $Q_{1.5}$.

Results from evaluations of "actual" sediment loading

Results from AnnAGNPS provide loadings data from gullies, fields and tributaries. Direct comparison of measured cross-sections between 1967 and 2002 provide strong evidence of channel contributions over the period. These data are compared with simulated channel contributions over the same reach and time period by CONCEPTS. Together, the AnnAGNPS and CONCEPTS simulations provide total loadings values for the James Creek watershed. AnnAGNPS simulations using a scenario of unstable tributaries indicated bed and bank erosion nearly seven times greater than the sediment produced from fields. The total sediment load simulated by AnnAGNPS at the outlet of James Creek for reduced tillage and indicated unstable reaches was 110,000 T/y.

Channel erosion 1967-2002: Measured changes in channel geometry

The area between the 1967 bed profile and the 2002 bed profile represents the amount eroded from the channel bed in m^2. On average, about 12% of the materials eroded from the channel came from the channel bed, with 88% coming from the banks. Over the period about 624,000 m^3 of channel sediments were eroded from James Creek between river kilometers 0.27 and 17.2. This converts to 1,136,000 tons (T) using the average saturated density of 1,820 kg/m^3 and an average-annual load of eroded channel materials of 32,500 T/y over this reach or 1,910 T/y/km or 1.91 T/y/m of channel.
To compare measured channel erosion with that simulated by CONCEPTS a shorter reach is used: river kilometers 7.29 to 17.3. Using the same techniques and conversion factors as previously we obtain the following erosion values for this approximate 10 km reach: 252,000 m^3; 459,000 T; 13,100 T/y; 1,320 T/y/km; and 1.31 T/y/m.

Combined AnnAGNPS and CONCEPTS simulation of main channel evolution and transport rates: 1967-2001

CONCEPTS was used to simulate channel hydraulics and morphology of James Creek between rkm 7.29 and 24.02. In the first 10 years, large amounts of sediment were eroded above at the upper end and upstream of the 1967 clearing and snagging work. The simulated thalweg profile is in good agreement with the 2002 measured profile ($r^2 = 0.99$). Up to three meters of incision in the upstream reach initiated mass-bank instabilities. Average sediment loads at the mouth of James Creek over the 35-year period are about 250,000 T/y with 88% emanating from channels and 12% from upland sources. This loading value, however, is somewhat misleading in that severe channel erosion occurred between 1967-1968 following channel clearing and snagging over the lower 17 km. Since this time, sediment loads attenuated and the contribution from channels and uplands over the period 1970-2002 shifted to 70% and 30%, respectively.

Simulated sediment-transport rates and yields

CONCEPTS provides detailed concentration and load estimates at 10-minute time intervals that are associated with discharge values to produce sediment-transport relations for each of the modeled cross sections. To provide a comparison between "actual and "reference" suspended-sediment loads we subtract the gravel portion from the total transport rate. Sediment-transport results are provided where simulated results are validated with measured flow and channel geometry data and, where reference sediment-transport conditions are established. CONCEPTS sediment-transport output was sorted by year and individual sediment-transport relations were derived for each year of simulation. Suspended-sediment loads and yields were calculated by substituting the $Q_{1.5}$ (86.8 m^3/s) into each equation. Yields are shown to approach the "reference", and the minimum values shown by the last data points in the time series represent attenuation of sediment yields, and are representative of relatively consistent sediment transport rates over the last three years (1999 – 2001). These lower rates of sediment transport beginning in 1999 can be attributed to the installation of several LWCs that year whose effects are reflected in the CONCEPTS simulations. Thus, we can state with greater certainty that the "actual current" suspended sediment yield at the $Q_{1.5}$ is in this range. Taking the average for the most-recent three-year period gives an "actual current" yield of 38.9 $T/d/km^2$ at the $Q_{1.5}$, which is still an order of magnitude greater than the "refined-reference" yield.

Conclusions

A combination of geomorphic and numerical-simulation analyses (AnnAGNPS and CONCEPTS) are shown to be powerful tools in evaluating the severity of sediment-transport conditions in James Creek, Mississippi. To develop water-quality targets for sediment in James Creek and in the absence of sediment-transport data in the watershed, historical flow and sediment transport data from similar streams in the Southeastern Plains were used to develop "reference" or un-impacted sediment-transport rates. These values are expressed in terms of the $Q_{1.5}$, or effective discharge. A "refined reference" yield was obtained by sorting the data by dominant bed-material size class, obtaining the median "reference" value by bed-material size class and by taking the weighted mean based on the percentage of drainage area encompassed by channels of particular bed-material types. The resulting "weighted-reference" values for James Creek are about 2.2 $T/d/km^2$ and 160 mg/l at the $Q_{1.5}$.

"Actual" suspended-sediment yields at the $Q_{1.5}$ as simulated with AnnAGNPS in combination with CONCEPTS show a 35-year average of 675 $T/d/km^2$.

However, the average over the past 10 years is 155 T/d/km^2 and, following the installation of additional low-water crossings in 1999 further reduced yields to about 39 T/d/km^2, still an order of magnitude greater than the calculated "reference" yield.

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