A Derived-Distribution Approach to Estimating Daily Loads of Sediment in Coastal Plain Streamflow

Robert Hubbard, Joseph Sheridan, David Bosch

Abstract

Standards for allowable total maximum daily loads (TMDLs) of sediment are being assigned to selected streams and rivers across the US. Estimates of total daily loads (TDLs) of sediment are required for comparison with TMDLs for those streams which are deemed to have impaired water quality due to sediment, and are required for formulating plans to improve these streams. A TMDL is defined as a daily stream loading rate (e.g. kg day^{-1}). However, actual stream sediment data are collected in terms of concentrations (e.g. mg L^{-1}), thus requiring estimates of streamflow to make the necessary rate and load conversions. The USDA-ARS, Southeast Watershed Research Laboratory (SEWRL) in Tifton, GA has collected over 30 years of hydrologic and climatic data from the 334 km^2 Little River Watershed (LRW). The LRW is typical of heavily vegetated, slow-moving stream systems of the southeastern Coastal Plain. Field studies quantifying dissolved and suspended loads in LRW streamflow have been conducted during the 30 year period (1974-1978, 1984-1986), but a continuous record of measured loads does not exist. A "derived distribution" (DD) approach is being tested to estimate TDLs of total solids (TS) and suspended sediment (SS) loads in LRW streamflow. A "derived distribution" (DD) is the frequency distribution of the dependent variable that is "derived" from the distribution of independent variables through a monotonic functional relationship between the dependent and independent variables. This paper presents results of coupling a derived flow distribution with mean SS and TS concentrations to estimate TDLs for the LRW of the southeastern Coastal Plain.

Keywords: streamflow, sediment loads, TMDLs, Coastal Plain watersheds

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Introduction

Water quality of streams, lakes or other water bodies may be degraded by excessive amounts of sediment in surface runoff or base flows. Heavy loads of SS in streamflow reflect erosion from cropland or from roads and skid trails associated with clear cutting of forest land, both of which are of serious environmental concern. Numerous studies have reported sediment concentrations and loads for a variety of drainage systems (Long and Bowie 1963, McGuiness et al. 1971, Griffiths 1982, Neff 1982, Carling 1983), along with information relating loads to rainfall intensity and duration, runoff amount, drainage area, or land use (Dragoun and Miller 1966, Dendy and Bolton 1976, Costa 1977, Ostry, 1982).

Total daily loads (TDLs) of sediment must be assigned to watersheds across the US to quantify total assimilative daily loads and maintain water quality, to identify streams with impaired water quality (TDLs exceeding TMDLs), and for formulating plans to improve water quality (Bonta 2002). A TDL is a daily load rate (e.g., kg day^{-1}), but field data are collected in terms of concentrations (e.g., mg L^{-1}), thus requiring flow rates to make the necessary conversions. When discrete samples are obtained, often flow rates are not measured, or a qualitative description of flow is made (e.g. "low", "high", "numerical rank", etc.).

A "derived distribution"(DD) is the frequency distribution of the dependent variable that is "derived " from the distribution of the independent variable through a monotonic functional relationship between the dependent and independent variables. Derived distributions have identical probabilities for corresponding independent- and dependent-variables values.

The USDA-ARS, Southeast Watershed Research Laboratory (SEWRL) in Tifton, GA has collected over 30 years of hydrologic and climatic data from the 334 km^2 Little River Watershed (LRW). In addition, streamflow samples for determination of total solids (TS) and suspended sediment (SS) were collected from LRW flow-measurement locations for 1974 –1981, and again from 1984 –1986.

This paper presents the results of using a DD approach to estimating TDLs in LRW streamflow based on the flow duration probability curves and data from the TS and SS studies.

Methods

Study area description

The Little River Watershed is located within the Tifton Upland of the Southern Coastal Plain physiographic region of the southeastern USA, and typifies the topography, geology, soils, and land use of that region (Yates, 1978). The Tifton Upland lies within the outcrop area of the Miocene series Hawthorn Formation. The Hawthorn Formation is continuous and considered to be an effective aquiclude for the Tifton Upland (Stringfield 1966).

Upland soils are classified primarily as fine-loamy (or loamy), siliceous, thermic Plinthic Paleudults (Calhoun 1983), generally having infiltration rates in excess of 5 cm hr^{-1} (Rawls et al. 1976). Internal drainage of upland soils is good to very good. Bottomland soils adjacent to drainage networks are primarily loamy, siliceous, thermic Arenic Plinthic Paleaquults with some Fluvaquents and Psammaquents (Calhoun 1983). Drainage of bottomland soils is poor to very poor with water standing on the surface during portions of the year. Major soil series are the same from the upper, or headwater areas, to downstream portions of LRW, although relative percentages vary somewhat between watersheds.

Topographically, the region has been described as an area of floodplains, river terraces, and gently sloping uplands, with moderately wide interstream divides separating relatively broad valleys. The divides are nearly level, gently sloping, or undulating. Valley bottoms are nearly level and typically swampy, while valley sides are gently sloping. Channel slopes are generally < 0.1 %, whereas upland side slopes generally range up to 5 % (Yates 1978). The low-lying, poorly drained areas (the most prominent feature of the Coastal Plain region) are characterized by short hydroperiods, an alluvium substratum, and mixed tree and shrub-type vegetation (Kitchens et al. 1975). Drainage systems such as these have been variously termed river floodplain swamps (Kitchens et al. 1975), floodplain wetlands (Kibby 1978), seasonally flooded wetlands (Johnston et al. 1984), forest wetlands (Leitman et al. 1983), and blackwater swamp systems (Wharton 1978).

The LRW (Figure 1) has mean sea level elevations ranging from 85 to 122 m. Small watersheds in this region typically have intermittent flow, with nonflow periods generally occurring in the late summer or fall.

Hydrologic measurements and streamflow sampling

The LRW was instrumented by USDA-ARS beginning in 1966 for Coastal Plain hydrologic research. Hydrologic data available includes both precipitation and streamflow observations. Streamflow stage was recorded at seven flow-measurement locations where horizontal, broad-crested weirs with V-notch center sections were located in conjunction with highway bridge or culvert installations. Weir ratings were based on extensive stream discharge measurements at each site (Yates 1978, Mills et al. 1984).

Streamflow samples were collected at LRW flow-measurement locations from August 1974 through August 1978 for determination of total solids (TS) concentrations (Sheridan and Hubbard 1987). The 1974 to 1978 LRW data contained information on TS transported in streamflow from Coastal Plain watersheds, but information was not available for that period on the relative proportioning of the dissolved and suspended components. Data on SS were available from later environmental and water quality studies conducted on LRW from 1979-1981 (unpublished data). Although this

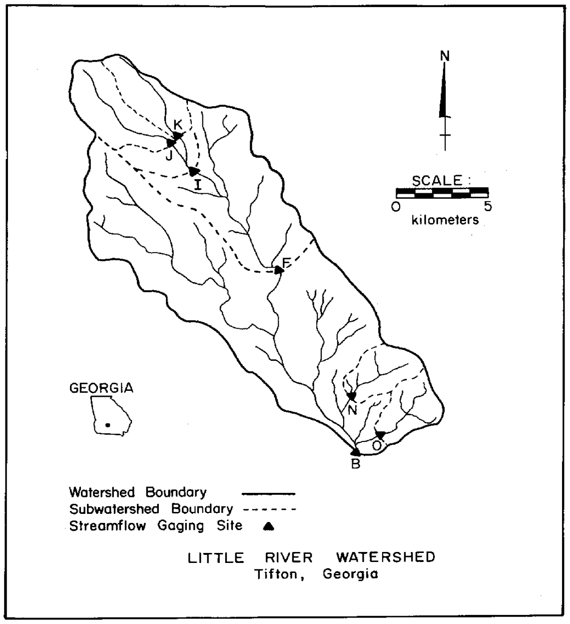

Figure 1. Map of Little River Watershed.

SS data was not from the same period, it was indicative of the magnitude of the suspended fraction of TS for these watersheds.

Total solids concentrations in runoff from the study areas for 1974-1978 averaged 96 +- 81 mg L^{-1}, with a maximum observed value of 859 mg L^{-1}. Total solids concentrations were examined by hydrologic seasons (March-May, June-August, September-November, December-February). The TS concentrations were significantly lower for March-May and December-February than for June-August and September-November. The March-May and December-February months also had the greatest per unit area runoff, indicating that dilution of transported solids by increased rainfall and runoff was the dominant effect.

The relationship between TS concentrations and rate of flow at the time of sampling was examined by plotting TS concentration vs. instantaneous flow rate converted to a per unit area basis (Figure 2). Correlation analysis showed that the relationship between TS concentrations and discharge rate was poor ($r = -0.16$, $p<0.0001$, $n = 1872$). Elevated values of TS concentrations were observed only at relatively low-to-moderate flow rates (Figure 2).

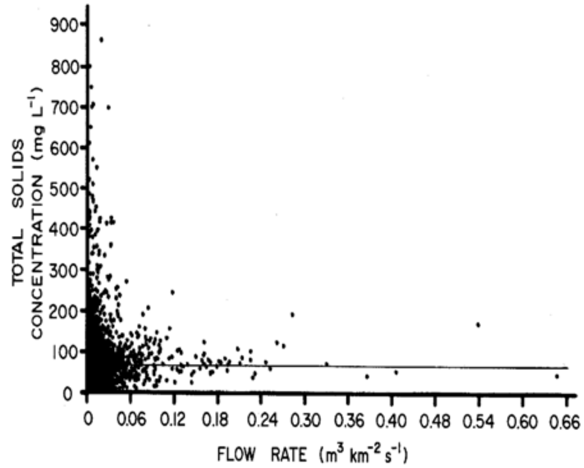

Figure. 2. Total solids concentrations vs. instantaneous per unit area flow rate.

The mean SS concentration in streamflow from LRW for 1979-1981 was 15 +- 20 mg L^{-1} (Sheridan and Hubbard 1987). Examination of the data by hydrologic seasons showed that average SS concentrations were significantly higher from March-August, when agricultural activity was greatest. A plot of SS concentration vs. instantaneous per unit area flow rate at the time of sampling is shown in Figure 3 for 1979 to 1981. Suspended sediments were poorly correlated with the instantaneous per unit area rate of flow ($r = 0.22$, $p <0.0001$, $n = 1608$).

Figure 3. Suspended sediment concentration vs. per unit area flow rate.

The TS and SS concentrations for the LRW from the 1974-1981 study compared favorably with a limited number of measurements (U.S. Geological Survey 1973-1981) for a 1720-km^2 Coastal Plain drainage adjacent to the LRW (the Alapaha River near Alapaha, GA). Mean SS and dissolved solids concentrations for 17 streamflow sanples from the

Alapaha between January 1973 and August 1981 were 29 and 62 mg L^{-1}, respectively. The LRW SS concentrations were also compared to published SS data for Coastal Plain streams in Georgia (Perlman 1985). The average SS concentration for 1769 samples (33 sampling sites in seven river basins) for streams heading within the Coastal Plain physiographic region of Georgia was 13 mg L^{-1}. The low average SS concentration in streamflow from other watersheds in the Coastal Plain region indicated that the low SS concentrations observed on the LRW were typical of the region (Sheridan and Hubbard 1987).

Observed SS concentrations for 1984-1986 ranged from 1-137 mg L^{-1}. Mean SS concentrations from subwatersheds B, F, and K were 14, 17, and 14 mg L^{-1}, respectively. Based on Duncan's multiple range test (SAS Institute 1985), differences in mean SS concentrations between the three subwatersheds were not significant. This confirmed the earlier 1979-1981 finding that SS concentrations in this region of the Coastal Plain are generally independent of watershed size due to the characteristics of the watershed drainage and transport systems (Sheridan and Hubbard 1987). Suspended sediment concentrations showed only a slight increase with increasing per unit area instantaneous discharge.

Results

The long-term (30+ years) LRW mean daily streamflow records were analyzed to develop a regional flow duration curve (FDC). The FDC is a cumulative frequency curve that gives the daily mean discharge that is equaled or exceeded as a percentage of the total record period. The USGS statistical program SWSTAT (Flynn et al. 1995) was used to develop FDCs for the LRW watersheds. The FDCs were then normalized by the respective watershed mean annual flow (MAF) and averaged to produce a regional FDC.

The regional flow duration curve for the LRW with 95% confidence intervals is plotted in Figure 4. Flows ranged from approximately 26,620,000 L min^{-1} at the 1 % probability level to 5800 L min^{-1} at the 99% probability level. This means that based on analyses of 30+ years of flow records on the LRW, flows in excess of 26,620,000 L min^{-1} occur less than 1 % of the time, while flows in excess of 5800 L min^{-1} occur 99% of the time.

The upper confidence interval at the 1% flow probability level is flow in excess of 33,260,000 L min^{-1} while the lower confidence interval at the 1% flow probability level is flow in excess of 20,000,000 L min^{-1}. At the 99% flow probability level the upper confidence interval is flow in excess of 15,000 L min^{-1}. Calculated values for the lower confidence interval became negative by the flow probability level of 75% and hence are not plotted.

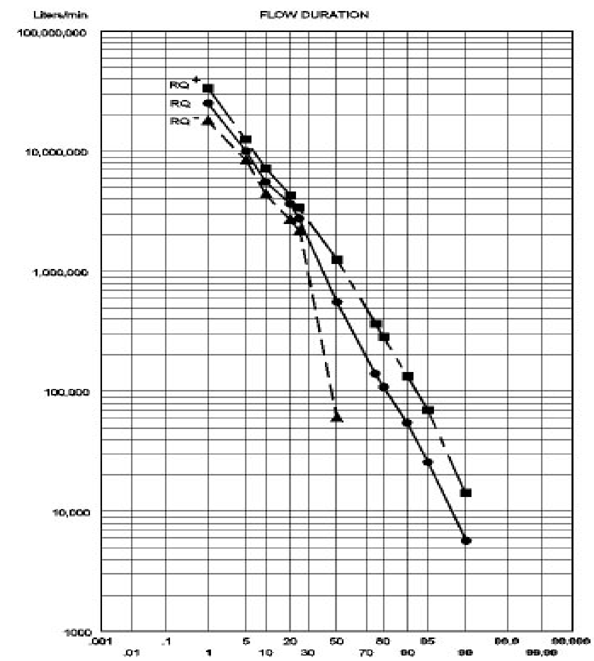

Figure 4. Regionalized flow duration probability curve with confidence limits.

Total daily loads (TDLs) were calculated using the regional flow duration curve by multiplying flow rate by mean SS or TS concentration. This in effect assigns a probability (% exceedance or risk) of exceedance of daily SS or TS loads in Coastal Plain stream systems.

For SS we multiplied the flow duration information by the mean value of 15 mg L^{-1}. For TS we used the mean value of 96 mg L^{-1}. We then converted the data to a TDL by summing for 24 hours. Table 1 shows the results for both SS and TS.

Calculated TDLs of SS ranged from 125 kg day^{-1} at RQ 99 to almost 575,000 kg day^{-1} at RQ1. Calculated TDLs of TS were 6.4 times as great. At RQ50 (mean annual flow rate) the SS load over a one year period computes to 736 mg yr^{-1}. This compares with the T-value (4 tons $acre^{-1}$) of 4494 mg yr^{-1}. In other words our computed annual losses based on our assumption of MAF rates and measured mean SS concentrations showed that SS loads for LRW would be only about 16% of estimated annual T-value losses. The TDL of SS, the pollutant of primary concern to environmental regulators, is quite low in southeastern Coastal Plain streamflow as compared to that of streams of other regions of the country.

Table 1. Total daily loads of suspended sediment and total solids for the Little River Watershed.

Flow Probability	TDL of SS	TDL of TS
	Kg day^{-1}	Kg day^{-1}
RQ1	574,992	3,679,976
RQ5	215,519	1,379,328
RQ10	133,188	852,409
RQ20	77,701	497,290
RQ25	61,256	392,004
RQ50	11,854	75,872
RQ75	3,022	19,346
RQ80	2,408	15,409
RQ90	1,203	7,698
RQ95	605	3,871
RQ99	125	798

Conclusions

A DD approach was used to develop probabilities of exceedance (1 to 99%) of daily loadings of SS and TS transported in streamflow from southeastern U.S. Coastal Plain watersheds. The DD was developed using a normalized regional flow duration curve and results of previous regional studies on concentrations of SS and TS from gauged agricultural watersheds in the Coastal Plain region.

Results indicate that this approach to developing daily stream loadings as required for TMDLs is effective for applications in the Coastal Plain region and provides probabilities of exceedance, or risk, information useful for water quality management. This approach provides land managers and regulators with a tool for predicting TDLs based on risk probabilities calculated from actual flow rates and sediment concentrations.

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