HARPETH RIVER WATERSHED
SEDIMENT STUDY
Comprehensive Technical Report

David J. Wilson

and

Richard E. Lockwood

A Project of the

Harpeth River Watershed Association

and the

Cumberland River Compact

HARPETH RIVER
WATERSHED
ASSOCIATION

Cumberland River
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HARPETH RIVER WATERSHED SEDIMENT STUDY
COMPREHENSIVE TECHNICAL REPORT

EXECUTIVE SUMMARY

The Harpeth River Watershed Association and the Cumberland River Compact carried out a study of sediment in the Harpeth River watershed during the time period September, 2000 through August, 2002. Mean turbidities were calculated for forty-three stations, and ranged from a minimum of 0.87 to a maximum of 17.64 m^{-1}, with a median of 5.26. Twelve stations showed mean turbidities of less than 3.0; thirteen stations had mean turbidities between 3.0 and 6.0; and eighteen stations had mean turbidities between 6.0 and 17.64. A mean turbidity of 1.40 was calculated for data from five sites regarded as near-pristine. High turbidity levels appear to be associated mainly with damaged or nonexistent riparian vegetation and land disturbance during construction operations. The data should provide a baseline against which future data can be compared to assess progress in the control of sediment in the Harpeth River watershed.

Measurements of both turbidity T (m^{-1}) and Total Suspended Solids TSS (mg/L) were made at nineteen of the forty-three stations. Linear and log-log least squares curves were fitted to the data for each of the nineteen stations. Coefficients of determination were generally good (15 of the 19 stations had r^2 values greater than 0.8, 9 had r^2 greater than 0.9 for the linear plots, for example), but a few were substantially smaller. However, the parameters of the plots varied quite substantially from site to site, and it does not appear possible to correlate T and TSS by means of a single universal equation. Plots of the form $TSS = A \cdot T^b$ had b values averaging 1.32 +- 0.32, with a median of 1.23. The fact that b is generally > 1 is accounted for by a change in particle size distribution with changing stream flow rate, as analyzed in Appendix C.

The annual sediment loss of that portion of the watershed upstream from the Highway 100 bridge over the Harpeth in Bellevue was roughly estimated to be 53,000 tons/year, corresponding to a loss of 406 lb/acre/year. The method used neglects bedload contributions, and so provides a lower bound for the true sediment losses. The annual sediment loss for the entire watershed is estimated to be 113,000 tons; this, also, is a lower bound.

The project raw data file is available electronically as an Excel 97 file. Hard copies can also be provided. Contact djw1ls0n@sbcglobal.net, screendoor@bigfoot.com, or dorie@doriebolze.com and ask for Harpeth1.xls.

FIGURES **following page**

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HARPETH RIVER WATERSHED SEDIMENT STUDY

COMPREHENSIVE TECHNICAL REPORT

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Cumberland River Compact

1.0 INTRODUCTION

Erosion and sediment were identified in recent Tennessee State 305(b) and 303(d) reports as having a major impact on water quality in the Cumberland River Basin generally, including the Harpeth River watershed. Excessive suspended and deposited sediment interferes with the survival of fish and other aquatic organisms. Deposition of sediment in quiescent portions of a river raises the level of its bed, resulting in increased flooding. High levels of suspended sediment interfere with the operation of drinking water treatment plants. High levels of sediment often indicate stream bank erosion, with damage to streamside property. They also indicate loss of valuable topsoil in the watershed through erosion.

The Cumberland River Compact (CRC) therefore decided to do a study on suspended sediments. The Harpeth River watershed was selected for study because of the existence of a group, the Harpeth River Watershed Association, with which the CRC could collaborate, the presence of several gauging stations and a large number of bridges in the watershed, and the existence of a data base on this watershed (the CRC's brochure), which could be used in planning the effort. The impact of deposited sediment and embeddedness of gravel and cobbles is addressed in a report on stream visual assessment prepared by the Harpeth River Watershed Association (2002). The impact of bank erosion is being explored in a project currently in progress.

1.1 Objectives

Our first objective was adult public education with regard to protection of riparian (streamside) vegetation and erosion control, such protection to be accomplished through best management practices in agriculture, on construction sites, in stormwater management by municipalities, and by homeowners in the watershed.

A second objective was to provide useful data on suspended sediment levels to the TN Dept. of Environment and Conservation, the U.S. Army Corps of Engineers, the U.S. Geological Survey, and other agencies. The State of Tennessee is currently working with EPA on the development of Total Maximum Daily Loads for suspended sediment in the state's streams. These data should be useful in the development of those standards and as a baseline against which future trends can be measured.

A third objective was to get information about the factors affecting sediment dynamics. The study gives us a good idea of which watersheds are showing the most sediment loss, and when and where major changes are occurring in sediment mobilization. This information can then be correlated with land use and management practices. Such studies also permit us to make rough estimates of the quantities of sediment being discharged from a watershed like that of the Harpeth River.

A fourth objective was to make a rough estimate from the data of the quantities of sediment being discharged from the watershed.

2.0 LOCATIONS OF SAMPLING SITES AND SCHEDULING OF SAMPLING EVENTS

The number and locations of the sampling sites were determined by where the project was able to recruit volunteers, for the following reason. Most erosion and sediment transport occur during and shortly after relatively intense and significant rains, with the rising branch of the hydrograph (the period during which the water in the stream is rising, the so-called first flush) being of particular importance. This required that much of the sampling be scheduled by rainfall occurrence, rather than by dates and times set in advance by us for our convenience. This, in turn, required that sampling sites be located in the close vicinity of the volunteers doing the sampling.

Sampling on the smaller streams is triggered by approaching storms, as indicated by weather reports or weather radar information. In this way one attempts to catch the rising branch of the hydrograph, which is especially important. (This is when the stream carries the bulk of the sediment.) On the lower reaches of the main stem of the Harpeth, on the other hand, the rising branch of the hydrograph may be delayed by roughly 10-25 hours or more, so one usually has more time to prepare to sample from sites at these locations.

The locations of the sampling sites are shown in Figure 2-1, for which we are much indebted to the Tennessee Department of Environment and Conservation and to Dawn Lemke with the Southeast Watershed Forum. The coverage of the watershed is fairly comprehensive in the central portion of the watershed, but sparse in the northwest region and nonexistent in the southeast region. Efforts to obtain more adequate coverage in these two regions were unsuccessful.

2.1 Rainfall information

Our technical advisors urged that we record rainfall information. Volunteers were provided with rain gauges to do this. Initially we regarded any rainfall over ¼" inch in 24 hours as enough to trigger sampling, and a stream rise of 6 inches in 48 hours or less as triggering sampling. As we became more familiar with the watershed we relaxed these criteria somewhat, as it became apparent that a rainfall event of only ¼" rarely produced measurable changes. Rain gauges were placed in the yards of the volunteers, taking care to avoid interference from trees or buildings. Rain gauge data were taken for all turbidity measurements, and are listed in the available project data file, Appendix D.

2.2 Baseline sampling sites

Several sampling sites were located in watersheds which are the best available—as close to the original natural state as could be found. These provide baseline data—how much suspended sediment is "natural"? A few samples were taken during periods of normal flow; most sampling was carried out during and following significant rains. The best available (near-pristine) stream sites selected are as follows:

Table 2-1. Reference streams (near-pristine)

Site description	Site number	Latitude	Longitude
Leipers Fork at Baily Road Bridge	22	35°53'09"N	87°00'18"W
Newsom Branch at Hwy 70 east of Pegram	35	36°05'26"N	87°00'57"W
Slickrock Branch at Paul Sloan's place	11	35°54'21"N	87°05'50"W
Copperas Creek at Paul Sloan's place	10	35°54'19"N	87°05'53"W
Talley Branch at Neil Wilding's place	21	36°03'13"N	87°08'40"W

A total of 71 turbidity values were reported for these sites.

2.3 Other sampling sites

Other sites in the Harpeth River watershed were usually selected at locations where we had some indications of damage, either from official information (305(b) reports, etc.), anecdotal information (newspaper stories, word-of-mouth from local landowners, canoeists, fishermen, etc.), or personal observation. Comparison of the resulting information on sediment with results from the control sites was expected to yield information about the effects of change in riparian vegetation, agricultural and homeowner practices which do not minimize erosion, urban development, and inadequate management of erosion on construction sites. It is hoped that in future work some sites will also be selected at locations above which best management practices are in use, so that the effect of these BMPs can be documented.

The number of sites selected was determined by the number of volunteers who participated in the project; the quality and quantity of the resulting data were determined by the care and tenacity of the individual volunteers sampling at the various stations. Forty-three sites produced at least seven measurements and are included in the report.

Table 2-2. Sampling stations and their locations

Site description	Site number	Latitude	Longitude
Garrison Creek, Garrison Rd Leipers Creek Rd	1	35°52’29”N	87°01’46”W
Burns Branch, Davis Hollow Rd Leipers Creek Rd	2	35°51’26”N	87°02’08”W
Leipers Fork at Floyd Rd bridge	4	35°53’41”N	86°59’45”W
West Harpeth River at Boyd Mill Rd bridge	5	35°55’51”N	86°58’09”W
Fieldstone Farms drainageway to Lynwood Creek	6	35°58’08”N	86°53’44”W
Lynwood Creek near confluence with Harpeth River	7	35°58’04”N	86°53’51”W
Harpeth River at Cotton Rd bridge	8	35°58’05”N	86°54’03”W
Kelley Creek at Paul Sloan’s place	9	35°54’22”N	87°05’47”W
Copperas Creek at Paul Sloan’s place*	10	35°54’19”N	87°05’53”W
Slickrock Branch at Paul Sloan’s place*	11	35°54’21”N	87°05’50”W
Little Harpeth River, #3, Edwin Warner Park	12	36°02’57”N	86°54’17”W
Little Harpeth River, #11, Edwin Warner Park	13	36°03’01”N	86°55’01”W
Little Harpeth River at Vaughn Rd bridge	13a	36°02’56”N	86°54’12”W
Harpeth River at Highway 100 bridge Bellevue	14	36°03’15”N	86°55’43”W
Flat Creek, Old Hickory Blvd, Bellevue	15	36°04’24”N	86°55’18”W
South Harpeth River at South Harpeth Rd bridge	16	36°03’40”N	87°03’16”W
Harpeth River, Joe Adams place near Pegram	17	36°04’58”N	87°04’57”W
Harpeth River, Harris St bridge, The Narrows	18	36°09’06”N	87°07’10”W
Little Harpeth River S of Concord Rd Brentwood	19	35°59’45”N	86°47’13”W
Turnbull Creek West Kingston Springs Rd bridge	20	36°06’03”N	87°07’35”W
Talley Branch at Neil Wilding’s Kingston Spgs*	21	36°03’13”N	87°08’40”W
Leipers Fork at Baily Road Bridge*	22	35°53’09”N	87°00’18”W
Murfrees Fork at Bear Creek Rd, Carters Cr Pike	23	35°51’56”N	86°57’38”W
West Harpeth River Carters Creek Pike bridge	24	35°52’37”N	86°56’30”W
West Harpeth River at Southall Rd bridge	25	35°53’55”N	86°58’01”W
West Harpeth River at State Route 96	26	35°56’37”N	86°56’37”W
Harpeth River at Old Hillsboro Rd bridge	29	35°59’35”N	86°54’10”W
Cartwright Creek at Blue Springs Rd	30	36°00’39”N	86°53’28”W
Sparks Creek at Mount Hope Rd, Franklin	31	35°55’41”N	86°52’30”W
Harpeth River at Moran Rd bridge, N of Franklin	32	36°01’01”N	86°53’58”W
Harpeth River at Highway 249 bridge W of Pegram	34	36°06’25”N	87°04’27”W
Newsom Branch at Hwy 70 east of Pegram*	35	36°05’26”N	87°00’57”W
Lynwood Creek at Meadowgreen Bridge	36	35°58’22”N	86°53’36”W
Harpeth River Highway 96 bridge Pinkerton Park	37	35°55’17”N	86°51’57”W
Murray Branch at 1109 Montpier Dr	38	35°58’42”N	86°56’20”W
Vaughn’s Creek at Warner Park Nature Center br	39	36°03’36”N	86°54’22”W
South Harpeth River at Highway 96 bridge	40	36°00’31”N	87°01’42”W
West Harpeth River at Del Rio Pike bridge	41	35°57’50”N	86°55’07”W
Turnbull Creek at Cliffside Golf Course ford	42	36°04’26”N	87°11’55”W
Beaverdam Creek at White Bluff Rd bridge	45	36°03’42”N	87°13’15”W
Beaverdam Creek at Hwy 96 bridge	46	36°02’43”N	87°16’50”W
Harpeth River at Shacklett Hwy 70 bridge	47	36°07’24”N	87°05’56”W
Trace Creek at Hwy 100 bridge	49	36°02’44”N	86°56’57”W

3.0 DATA COLLECTED

The data collected are of four types—rainfall measurements, sediment measurements (turbidities, some total suspended solids, a few Imhoff cone settleable solids measurements), river stage measurements, and observations and photographs. The volunteers were frequently reminded that with all types of data, complete documentation and record-keeping are essential. A data set consisted of the following information: Date and time, location of the sampling site, rain gauge reading, present and recent weather conditions, stream stage (water level—see below), narrative remarks, and turbidity (see below). Sampling sites not at a highway bridge are located for record on a Xerox copy of a topographic map, including specification of right or left bank or stream center. Latitudes and longitudes were measured on the electronic maps available at the Topozone.com web site, and some were also measured using a GPS. The raw data are included in Appendix D as an Excel file.

3.1 Measurements (estimates) of sediment

Turbidity tubes were used for analyzing most of the samples; these measure the length of a water column through which one can first definitely see a specified black and white quadrant figure at the bottom of the turbidity tube. A total of 1036 turbidities were reported. A gravimetric technique, Total Suspended Solids (TSS), was also used on a substantial number of the samples; Dave Wilson and Rick Lockwood did the gravimetric measurements. On selected samples Imhoff cone measurements, turbidity measurements, and TSS were made on the same water sample so that the three types of measurements could be correlated.

Triplicate turbidity measurements were normally made. From time to time Dr. Wilson picked up samples and checked turbidity measurements against those of some of the volunteers. Differences between his measurements and those of the volunteers were not statistically significant. An individual’s turbidity measurements on a sample typically showed a spread of about 10-15%

Imhoff cones were used to estimate volumetric sediment concentrations only in a limited number of the muddiest samples. The procedure was as follows. A water sample of about one gallon was taken by means of a bucket on a rope and quickly poured into a labeled gallon plastic bottle (such as a milk jug). The sample was also logged into the field book (sample number, date, time, site, weather, stream stage, remarks). Samples are then brought home, shaken vigorously (to get all the sediment thoroughly mixed into the water), and a one-liter portion of the sample immediately and quickly poured into an Imhoff cone. (An Imhoff cone is a 1-liter container in the shape of an inverted cone. The bottom of the cone is calibrated so that the volume of the sediment can be determined after it has settled out.) The sediment volumes were measured after 24 hours of settling and reported as mL/L.

3.2 Stream stage (river depth)

Timothy Diehl (USGS) suggested a convenient and accurate way to measure stream stage at bridges; we used his method routinely. One attaches a small (6 oz) weight to a 50 ft steel carpenter's measuring tape and lowers the weight on the tape down from the top of the bridge rail until the weight just touches the water surface. This is always done at the same location (marked with crayon on the railing) on the bridge. This distance is then subtracted from the distance from the bridge railing to the stream bottom to obtain the stream stage. (Distance to the stream bottom must be measured during a period of low water.)

In some locations we used existing USGS gauges; these report continuously to the USGS internet site, making them extremely convenient to use. In other locations, however, it was necessary to firmly fasten one or more plastic or metal gauges (often yardsticks) to a convenient root, tree trunk, post, etc., in a vertical position to use as a gauge of stream stage. The gauges were located where they were protected from damage by floating debris and not readily seen by vandals. (One gauge was lost to vandals.) One reports the depth to which the gauge is immersed in the water, along with the depth of immersion at normal low flow. If one is dealing with a station at which the variation in stage is greater than 3 ft, one makes a more extended gauge by marking an 8-12 ft 2 X 4 board with paint at 6" intervals and mounting it in a vertical position in the river where it is not likely to be knocked away by floating debris. One pair of volunteers painted marks on a bridge pier to use as a gauge; this was quite satisfactory.

On some quite small streams the volunteer used a yardstick to measure depth at some precisely specified location in the stream bed.

It was essential that stream stage information be available to correlate with the sediment data. Stream stage was measured and recorded immediately before or after sediment samples are taken. Information on the presence or absence of floating debris and the appearance of streamside vegetation often provided information as to whether a stream was rising or falling.

3.3 Rain gauge readings

Rain gauges were supplied to all volunteers, and each data set included a rain gauge reading taken at the volunteer's home. In a few cases (Beaverdam Creek sites, South Harpeth at South Harpeth Road) the rain gauge was at some substantial distance from the monitoring site.

3.4 Photographs

The project work plan originally called for the taking of a substantial number of documented photographs. While the sediment study was in progress, however, the Harpeth River Watershed Association (2002) carried out a very extensive stream visual assessment project which included the taking of a large number of photographs and excellent documentation. This phase of the sediment project was therefore dropped. The visual assessment project includes photographs of:

best available areas
areas in which best management practices are in use at sites of active bank erosion
areas in which livestock or vehicle traffic is damaging riparian vegetation
accumulations of logs and other debris in the stream
areas in which agricultural erosion or erosion from home sites is introducing sediment into a stream
sites where sediment is coming from improperly managed construction activities
sites where urban runoff is significant
sites where effluents are being discharged

For information about the report on the visual stream assessment project contact the office of the Harpeth River Watershed Association or the Tennessee Department of Environment and Conservation.

4.0 SUMMARY OF RESULTS AND STATISTICAL INTERPRETATIONS

In this section the results are summarized and statistically interpreted.

In section 4.1 the means of the turbidities at the various stations are ranked in order of size, along with their standard deviations. Two comparisons of the results from each station with the results from the five near-pristine sites are made to determine which stations show results that are significantly different from the near-pristine sites. Student's t-test is used because most people are familiar with it. However, this test requires that the data sets being compared be normally distributed with similar standard deviations. The turbidity data sets obtained in this study were not even approximately normally distributed, and the standard deviations varied over a wide range, raising some doubts about the appropriateness of the t-test. A non-parametric rank sum test (the Wilcoxon signed ranks test) was therefore also used in making the comparisons. See David J. Sheskin, Handbook of Parametric and Nonparametric Statistical Procedures, CRC Press, 1997 for detailed information on the statistical procedures used.

In section 4.2 the relationship between turbidity and total suspended solids is explored. A point of some interest was the extent to which turbidity (T) as measured by turbidity tubes correlates with gravimetric Total Suspended Solids (TSS) measurements, and the extent to which turbidity can be used as a surrogate for TSS. Linear least squares and log-log least squares fits were therefore calculated and are presented below along with the corresponding coefficients of determination.

4.1 Summary and Comparisons of Turbidity Data

The sites for which an adequate number of data sets are available (7) are listed in Table 4-1 in order of increasing arithmetic mean turbidity. P(t-test) is the probability that the difference between the data for the site and the data for the five near-pristine sites is due to chance as calculated by a one-tailed t-test. (See David J. Sheskin, Handbook of Parametric and Nonparametric Statistical Procedures, CRC Press, 1997, pp. 154-156.) P(rank sum) is the probability that the difference between the data for the site and the data for the five near-pristine sites is due to chance as calculated by a one-tailed Wilcoxon signed ranks test. (See Sheskin, pp. 83-94.)

Table 4-1. Mean turbidities, standard deviations, significance levels by t-test and by Wilcoxon's summed ranks test

Site description	Site Number	Mean turbidity, m^{-1}	Standard deviation	P(t-test)	P(rank sum)	No. of data pts
Slickrock Branch	11*	0.87	0.72	3.53 E-1	8.23 E-2	10
Leipers Fork	22*	0.96	0.87	3.84 E-1	4.69 E-2	15
Newsom Branch	35*	1.15	0.70	3.09 E-1	3.73 E-1	20
Leipers Fork	4	1.33	1.21	5.00 E-1	4.69 E-1	17
(5 pristine streams)		1.40	1.22	5.00 E-1	4.95 E-1	71
Copperas Creek	10*	1.54	1.40	3.69 E-1	4.29 E-1	9
Talley Branch	21*	2.16	1.78	6.70 E-2	2.14 E-2	18
Murfrees Fork	23	2.48	1.74	1.02 E-2	1.14 E-3	15
Kelley Creek	9	2.67	2.20	1.70 E-2	1.20 E-1	10
Garrison Creek	1	2.77	3.55	2.53 E-3	1.48 E-1	33
W Harpeth Hwy 96	26	2.93	2.88	1.00 E-3	3.21 E-3	14
Little Harpeth WP3	12@	2.99	5.17	3.04 E-2	3.97 E-1	24
Vaughn's Creek	39	3.11	2.50	3.27 E-6	1.35 E-5	39
Little Harpeth WP11	13@	3.11	5.06	1.66 E-2	4.73 E-1	26
Fieldstone Farms drain	6	3.69	1.83	1.30 E-5	7.25 E-4	7
Sparks Creek	31	3.82	4.01	3.87 E-4	5.91 E-3	10
W Harpeth Boyd Mill	5	4.11	6.39	2.10 E-3	1.21 E-2	17
Murray Branch	38	4.64	4.82	3.10 E-12	6.11 E-13	55
S Harpeth, S H Rd	16	4.74	6.45	2.44 E-5	1.18 E-1	47
W Harpeth Southall	25	4.90	5.80	2.47 E-5	4.75 E-4	16
W Harpeth Carters	24	5.00	5.94	9.75 E-6	3.83 E-4	16
Harpeth River Pinker	37	5.26	5.08	1.23 E-7	2.23 E-5	24
Cartwright Creek	30	5.48	5.61	5.39 E-6	4.54 E-3	8
Beaverdam Creek 96	46	5.53	4.34	1.26 E-8	1.28 E-3	12
Beaverdam Creek WB	45	5.84	4.91	1.70 E-8	2.30 E-4	12
Lynwood Creek Meadow	36	6.51	8.59	1.30 E-5	2.19 E-2	7
Turnbull Creek Cliff	42	6.52	9.58	1.59 E-5	5.18 E-4	27
Harpeth River 249	34	6.87	10.92	4.75 E-5	7.74 E-5	21
Turnbull Creek Kings	20	7.27	8.90	3.05 E-7	3.14 E-4	25
Harpeth River Harris	18	7.44	6.18	6.77 E-11	7.60 E-7	18
Harpeth River 100	14	7.61	11.44	6.42 E-6	8.93 E-13	73
Lynwood Creek	7	7.84	7.19	3.43 E-10	1.55 E-4	15
S Harpeth Hwy 96	40	7.92	13.51	5.28 E-5	1.78 E-4	49
Little Harpeth Vaug	13a	8.46	11.80	1.09 E-6	8.49 E-9	53
Little Harpeth Conco	19	9.73	13.38	1.56 E-6	2.52 E-8	46
Harpeth River Kings	17	10.50	8.20	1.63 E-15	2.91 E-16	45
Harpeth River Cotton	8	10.66	10.57	1.21 E-10	5.73 E-7	21
Harpeth River Old Hi	29	10.78	11.91	8.39 E-9	3.55 E-10	22
W Harpeth Del Rio	41	11.08	9.92	3.66 E-12	2.56 E-5	19
Flat Creek	15	11.83	12.69	4.09 E-10	4.63 E-10	31
Harpeth River Moran	32	11.90	15.76	9.01 E-8	5.03 E-12	49
Harpeth River Shacklett	47	12.19	6.08	< 1 E-16	1.18 E-5	7
Trace Creek Hwy 100	49	17.64	13.66	3.98 E-16	2.45 E-5	9

* These sites are included in the near-pristine set used for comparisons.

@ These two sites could not be sampled when the Little Harpeth was in flood. The data are included to indicate the close agreement of results taken only two miles apart on the same stream. The data for these two sites are not an indication of overall sediment in the Little Harpeth; for this see Site 13a.

The results for the near-pristine sites indicate that a mean turbidity of approximately 1.4 m^{-1} can be regarded as more or less natural. It should be noted, however, that during the course of the study the volunteers working Talley Branch reported some soil disturbance in that subwatershed above their sampling site, so our value of 1.4 for natural mean turbidity may be a little high. The P(rank sum) values suggest that mean turbidities above 3.0 m^{-1} are very likely to be significant at the 95% confidence level ($P < 0.05$), so we accept 3.0 m^{-1} as the dividing line between essentially unimpaired streams ($T < 3.0$) and streams with noticeable non-natural sediment ($T >= 3.0$). The P(t-test) values are in essential agreement with this. Note that most samples were taken during or immediately after a rain.

Essentially unimpaired streams include Slickrock Branch, Leipers Fork, Newsom Branch, Copperas Creek, Talley Branch, Murfrees Fork, Kelley Creek, Garrison Creek, and the West Harpeth at Highway 96.

Streams mildly impaired with suspended sediment (mean turbidity between 3 and 6) include the West Harpeth at Boyd Mill Road, Southall Road, and Carter's Creek Pike; Vaughn's Creek in Percy Warner Park; a drainageway in Fieldstone Farms north of Franklin; Sparks Creek in Franklin; the South Harpeth at South Harpeth Road; Murray Branch; the Harpeth River at Pinkerton Park in Franklin; Cartwright Creek at Blue Springs Road; and Beaverdam Creek at Highway 96 and at White Bluff Road.

Streams substantially impaired with suspended sediment (mean turbidity greater than 6) include Lynwood Creek at Meadowgreen bridge; Turnbull Creek at Cliffside and at the West Kingston Springs Road bridge; the Harpeth River at the Highway 249 bridge, at the Harris Street bridge (the Narrows), at Highway 100, at Kingston Springs, at the Cotton Road bridge, at the Old Hillsboro Road bridge, at the Moran Road bridge, and at Shacklett; Lynwood Creek; the South Harpeth at Highway 96; the Little Harpeth at Vaughn Road and at Concord Road; the West Harpeth at Del Rio Pike; Flat Creek at Old Hickory Blvd in Bellevue; and Trace Creek at Highway 100.

On the basis of both the HRWA visual assessment, personal observations, and informal comments by volunteers, significant causes of excessive suspended sediment in streams in the Harpeth River watershed appear to be three:

(1) seriously impaired, at times nonexistent, riparian vegetation buffer zones (see, for example, much of the Little Harpeth, and the South Harpeth at the South Harpeth Road bridge),

(2) construction operations (Flat Creek, Turnbull Creek, for example), and

(3) bank and bed erosion resulting from very flashy tributaries with high percentages of impervious surface in the subwatersheds (see the USGS hydrographs of Spencer Creek, for example).

Further visual surveys of the substantially impaired streams are needed to more precisely determine the sources of these excessive loads of sediment.

4.2 Correlations between turbidity and Total Suspended Solids

One of the objectives of this study was to examine the relationship between turbidity (T) and total suspended solids (TSS) measurements. Measurement of turbidity with a turbidity tube is much simpler and requires much less costly equipment than measurement of gravimetric TSS. It was desired to determine the feasibility of using turbidity as a surrogate for TSS in volunteer monitoring; in particular, it was hoped that all T vs TSS data could be satisfactorily correlated with a single curve. Unfortunately this was not possible.

4.2.1 Linear correlations

Turbidity-TSS data pairs were available for 20 of the 42 sites. (Data from both sites on Turnbull Creek were combined, however.) The method of least squares was used to fit straight lines to plots of TSS (ordinate, mg/L) versus T (abscissa, m^{-1}). The results are given in Table 4-2.

Table 4-2. Slopes, intercepts, and r^2 values for linear least squares plots of T versus TSS, TSS = AT + B

Site description	Site Number	Slope (std. dev.)	Intercept (std. dev.)	r^2	No. of data pairs
Little Harpeth WP11	13@	17.9 (0.4)	- 16.0 (8.2)	0.976	7
Little Harpeth Vaug	13a	20.3 (1.3)	- 47.8 (8.1)	0.949	48
Harpeth River 100	14	21.9 (0.8)	- 57.4 (7.6)	0.974	51
S Harpeth, S H Rd	16	20.2 (1.7)	- 21.0 (5.8)	0.895	39
Garrison Creek	1	25.4 (1.2)	- 49.1 (7.7)	0.958	13
Harpeth River Kings	17	12.2 (5.2)	- 24.2 (70.3)	0.387	13
Harpeth River Harris	18	12.4 (2.1)	+ 16.6 (18.0)	0.690	14
Harpeth River Cotton	8	25.9 (5.1)	- 106.1 (67.6)	0.842	4
Little Harpeth WP3	12@	13.1 (0.7)	- 13.5 (4.5)	0.986	7
Turnbull both sites	20,42	13.8 (4.0)	- 16.2 (15.9)	0.583	26
Harpeth River Old Hi	29	35.6 (2.1)	- 180.1 (71.7)	0.823	8
Harpeth River Moran	32	11.8 (0.5)	- 10.6 (13.0)	0.957	18
Murray Branch	38	12.1 (2.9)	+ 23.6 (39.7)	0.441	7
Vaughn’s Creek	39	13.1 (2.4)	- 15.6 (6.1)	0.837	29
Beaverdam Creek WB	45	11.2 (1.6)	- 18.7 (7.4)	0.849	12
Beaverdam Creek 96	46	10.0 (1.7)	- 13.5 (6.6)	0.835	12
Harpeth River Shackl	47	10.5 (0.3)	+ 8.1 (3.3)	0.991	5
Trace Creek Hwy 100	49	18.7 (2.7)	- 185.3 (67.7)	0.915	4
Flat Creek	15	12.5 (0.7)	- 42.6 (13.8)	0.985	4

@ Not sampled during periods of major flooding.

The median value of the slope values is 13.1 m mg/L, and the values range from 10.0 to 35.6. The wide spread in the values of the slopes (and also the intercepts) for these 19 data sets indicates that there is not a single plot that relates T to TSS. The accuracy of the linear fit is generally fairly good (15 of the r^2 values exceed 0.8, 9 exceed 0.9), but this cannot be taken for granted, as indicated by four r^2 values in the range 0.387–0.690.

By way of illustration, Figure 4-1 shows the plot for data taken at Site 14, the Harpeth River at the Highway 100 bridge. This is one of the best linear correlations found. On the other hand, Figure 4-2 shows the plot for data taken at Sites 20 and 42, both on Turnbull Creek. For this data set the correlation between T and TSS is obviously quite poor.

4.2.2 Log-log correlations

The negative values of most of the intercepts in the linear T vs TSS plots, the fact that one expects the curves to pass through the origin (0,0), and the appearances of several of the plots of the data pairs (which appeared to have positive curvatures) suggested that log-log least squares plots be made. In these the relationship between T and TSS is assumed to be TSS = $\exp(A)T^B$, where B is a constant greater than unity.

Table 4-3. Slopes, intercepts, and r^2 values for log-log least squares plots of T versus TSS, $\log_e TSS = A + B\log_e T$

Site Description	Site Number	Slope (std. dev.)	Intercept (std. dev.)	r^2	No. of data pairs
Little Harpeth WP11	13@	1.23 (0.08)	+ 1.97 (0.15)	0.961	7
Little Harpeth Vaug	13a	1.33 (0.03)	+ 1.65 (0.07)	0.970	48
Harpeth River 100	14	1.26 (0.04)	+ 1.91 (0.10)	0.937	51

Site Description	Site Number	Slope (std. dev.)	Intercept (std. dev.)	r^2	No. of data pairs
S Harpeth, S H Rd	16	1.24 (0.04)	+ 2.07 (0.07)	0.953	39
Garrison Creek	1	1.64 (0.17)	+ 1.40 (0.26)	0.889	13
Harpeth River Kings	17	1.14 (0.30)	+ 1.89 (0.79)	0.531	13
Harpeth River Harris	18	1.23 (0.09)	+ 2.07 (0.14)	0.898	14
Harpeth River Cotton	8	1.71 (0.07)	+ 0.81 (0.12)	0.981	4
Little Harpeth WP3	12@	1.23 (0.17)	+ 1.59 (0.40)	0.852	7
Turnbull both sites	20,42	1.01 (0.12)	+ 2.14 (0.19)	0.831	26
Harpeth River Old Hi	29	2.14 (0.15)	- 0.26 (0.44)	0.835	8
Harpeth River Moran	32	1.25 (0.04)	+ 1.59 (0.13)	0.955	18
Murray Branch	38	0.88 (0.21)	+ 2.91 (0.52)	0.441	7
Vaughn's Creek	39	1.14 (0.11)	+ 1.74 (0.14)	0.822	29
Beaverdam Creek WB	45	1.18 (0.09)	+ 1.51 (0.14)	0.906	12
Beaverdam Creek 96	46	1.15 (0.06)	+ 1.59 (0.05)	0.965	12
Harpeth River Shackl	47	0.93 (0.03)	+ 2.60 (0.08)	0.992	5
Trace Creek Hwy 100	49	1.97 (0.12)	- 0.87 (0.37)	0.964	4
Flat Creek	15	1.43 (0.06)	+ 0.98 (0.17)	0.980	4

@ Not sampled during periods of major flooding.

For the log-log plots 17 of the 19 data sets have r^2 values of 0.8 or above, and 11 have r^2 values of 0.9 or above. The arithmetic mean of the slopes of the log-log plots is 1.32 (std. dev. of values = 0.32, std. dev. of mean = 0.08), the median is 1.23, and the range is 0.88 to 2.14. The arithmetic mean of the intercepts is 1.54 (std. dev. of values = 0.87, std. dev. of mean = 0.20), the median is 1.65, and the range is – 0.87 to + 2.91.

The relatively large values of the coefficients of determination r^2 indicate that $\text{TSS} = \exp(A)T^B$ is a good function for correlating T and TSS for data from a single site. However, the wide range in the values of both A and B indicate, as before, that parameters calculated for one site cannot necessarily be used for interpreting data from another stream or even for interpreting data from another site on the same stream.

4.2.3 Discussion of the relationship between T and TSS

Figure 4-3 shows the plots $\text{TSS} = \exp(A)T^B$ (no data points shown) for twelve of the above data sets. Obviously it is not feasible to use a single curve to approximate all of these with adequate accuracy. The curves are concave upward ($B > 1$) for all plots shown and, indeed, for 17 of the 19 data sets summarized in Table 4-3. The theoretical explanation for this is presented in some detail in Appendix C. Briefly, the light-stopping power of a given mass concentration (mg/L) of particles decreases as the particles become larger—a handful of marbles thrown into the air has less light-stopping power than a similar mass of dust. As the flow rate of a stream increases the water velocities increase, making it possible for the stream to carry larger particles. A flooding, very turbid stream is carrying particles which are, on the average, larger than those carried by the stream at lower flow rates. One therefore expects to observe TSS increasing more at high flow rates (and turbidities) than one would expect if TSS were directly proportional to turbidity. This superlinear behavior is in fact observed.

The variation in the curves from stream to stream is also very probably associated with particle size. With smaller average particle size one expects TSS to be lower for a given turbidity than would be the case with larger particles. Both Turnbull Creek sites (20, 42) and both Beaverdam Creek sites (45, 46) showed quite noticeable bleed-through of near-colloidal fines on filtration, indicating the presence of fine particles in these sediments. All these sites had relatively small slopes for their TSS versus T plots (13.8 [both Turnbull sites], 10.0, 11.2), as one would expect from the above analysis.

A possible explanation for the wide variation in TSS versus T plots is the presence of suspended algae in some of the streams. Algae particles are often quite small, and can be expected to contribute heavily to turbidity but relatively little to TSS, particularly since algae cells are composed principally of water lost when the sediments are dried at 105^{o}C. However, the TSS filters showed a greenish cast only a few times and then under conditions of very low summer flows when the turbidity was quite low. Volatile Suspended Solids (VSS) were run on a number of the Garrison Creek (site 1) samples taken under conditions of relatively high flow mostly in the fall, winter, and spring. Under these conditions one would expect VSS to contain a significant contribution from decomposing leaves and wood, with a relatively minor contribution from algae; the mean percent VSS in 13 samples was 17.6 +- 5.8%. The maximum value, 30.3%, was obtained when the TSS was 17.5 mg/L and T was 3.29 m^{-1}. Algae may contribute significantly to turbidity when the days are long, stream flows are low, and the water is relatively clear, but are probably of minor importance when one is looking at storm events.

4.2.4 Relationships between Nephelometric Turbidity Units, Turbidity, Transparency, and TSS

Nephelometric turbidimeters (turbidimeters) are often used to measure turbidities; these turbidities are reported in Nephelometric Turbidity Units (NTUs). One would like to be able to relate turbidities measured with turbidimeters (NTU) to transparencies (transp) and turbidities (T) measured with transparency/turbidity tubes. [Recall that tube turbidity and transparency are related by the equation T (m^{-1}) = 100/transp (cm)]. A set of 22 pairs of measurements (NTUs and tube turbidities/transparencies) made on samples obtained at various sites in the Harpeth River watershed was obtained, and least squares straight lines were fitted to log-log plots of NTU against transparency and against tube turbidity T. Figure 4-4 shows the log-log plot of the NTU against transparency (cm) data, together with the least squares best fit straight line. The relationship obtained between turbidimeter turbidity (NTU) and transparency (transp, cm) is

$$\mathrm{NTU} = 3537 \cdot \mathrm{transp}^{-1.376}$$

The coefficient of determination r^2 for the log-log relationship is 0.9931, indicating an extremely good fit between the equation and the data.

Substitution of the relationship transp = 100/T in this equation then yields the relationship between turbidimeter NTU and tube turbidity T:

$$\mathrm{NTU} = 6.261 \cdot T^{1.376}$$

with the same coefficient of determination as above.

These equations permit one to relate tube transparencies or turbidities to turbidimeter measurements in NTUs with a good deal of accuracy. Note, however, that one has no guarantee that these relationships are valid for other watersheds. The relationships are fairly well satisfied by some data (Globe, kaolin data; Fenwick School, formazin data; Timothy Diehl, synthetic muddy water samples; Wisconsin stream data) but not by others (Minnesota river data). Prudence therefore dictates that the above equations not be regarded as universal relationships, but be calibrated on a watershed-by-watershed basis.

In Section 4.2.2 data are given that permit one to develop a rather inaccurate relationship between TSS and T:

$$\mathrm{TSS} = 4.6646 \cdot T^{1.32}$$

This equation is obtained by using the arithmetic means of the slopes and intercepts given in Table 4-3, both of which exhibit a substantial spread. Solving this equation for T and substituting the result in the above equation for NTU then yields

$$\mathrm{NTU} = 1.257 \cdot \mathrm{TSS}^{1.015}$$

for the relationship between turbidimeter turbidities and TSS. Note, however, that the rather large spreads in the slopes and intercepts given in Table 4-3 are reflected in a correspondingly large uncertainty in this equation, which should therefore be used with caution.

5.0 LAND USE PATTERNS IN THE HARPETH RIVER WATERSHED

About half of the Harpeth River's watershed is in one of the fastest growing regions of the country with some of the most sprawled forms of suburban development; namely, Williamson County. The county's population doubled in the past 10 years and is projected to increase half again by 2020. Similar growth rates are occurring in the other smaller cities and towns in the watershed. This growth is of such low density that large amounts of agricultural and forested lands are being converted into developed areas, based on recent land use patterns studied in *Cumberland Region Tomorrow: A Report to the Region 2003*. Such urbanization is generally associated with elimination of riparian vegetation, a marked increase in the fraction of the land surface which is impervious (streets, roofs, parking lots, etc.), and increased stormwater management problems.

The Harpeth River watershed is one of the Group I watersheds out of five groups that TDEC (Tennessee Department of Environment and Conservation) created for its Watershed Management Approach. Of the ¾ of stream miles assessed by TDEC in the Harpeth, 28% were not meeting water quality standards according to the 2004 305(b) report. With the 2002 303(d) list, 40 miles of streams, mostly on the mail stem were added, for a total of 334.6 river miles, including 79 miles of the mainstem from the headwaters to the confluence with the South Harpeth. As of the 2004 305(b) report, an additional 35.3 miles were added for a total of 369.6 stream miles that are not meeting water quality standards. Most all of the 303(d) segments are listed for siltation and habitat alteration, with the subset along the mainstem and headwaters also listed for organic enrichment and low dissolved oxygen. Most all of the 303(d) segments in Williamson County are associated with the developed interstate corridor of Brentwood and Franklin, and the historical agricultural areas. The remaining 303(d) segments are also mostly associated with development in the city of Dickson and the booming Bellevue area of Davidson County.

6.0 ESTIMATION OF THE MASS OF SEDIMENT DISCHARGED FROM THE HARPETH RIVER WATERSHED DURING THE PERIOD OF THE STUDY

In this section an approach is made to estimating the total mass of sediment discharged from the Harpeth River watershed during the two-year duration of this study. The approach is flawed in at least three ways in such fashion that it can be expected to give only a lower bound to the total sediment mass discharged.

(1) The sampling technique used measures suspended sediment only, not bed load.

(2) "First flush" measurements, which tend to show especially high sediment concentrations, were often missed.

(3) The use of average daily flow rates instead of near-instantaneous flow rates is expected to underestimate the extent of sediment movement by stream bank and bed scouring during periods of flash flooding.

It is therefore believed that this calculation underestimates, perhaps substantially, the total quantity of sediment washed from the watershed during the past two years.

6.1 Methodology

The procedure is as follows.

The mass of sediment passing Site 14 (Harpeth River at Highway 100) in 24 hr on the date of the *i*th measurement, m_i, is assumed to be given by

$$m_i\ (\text{kg/day}) = Q_i \times 28.32\ \text{L/ft}^3 \times 86{,}400\ \text{sec/day} \times TSS_i \times 10^{-6}\ \text{kg/mg} \qquad (6.1)$$

where Q_i = mean stream flow rate (ft^3/sec) on the date of interest
TSS_i = TSS (mg/L) measured or calculated from the turbidity on the date of interest

Thus

$$m_i\ (\text{kg/day}) = 2.447 \times Q_i \times TSS_i \qquad (6.2)$$

and

$$m_i \text{ (tons/day)} = 0.002697 \text{ X } Q_i \text{ X } TSS_i \quad (6.3)$$

yields the mass of sediment passing daily in terms of the average flow rate and the measured TSS for that day.

From Table 4-3 the equation

$$TSS_i = \exp(1.91) \text{ X } T^{1.26} = 6.75 \text{ X } T^{1.26} \quad (6.4)$$

permits the calculation of TSS values from turbidities. So, alternatively,

$$m_i \text{ (tons/day)} = 0.01821 \text{ X } Q_i \text{ X } T_i^{1.26} \quad (6.5)$$

yields the mass of sediment passing daily in terms of the average flow rate and the measured turbidity on that day.

Now m depends on Q, both directly and through the rather strong positive correlation between turbidity and flow rate. We therefore assume the following relationship between m and Q:

$$m = DQ^G \quad (6.6)$$

where G is a number larger than unity. One then does a log-log least squares fit of the m_i values calculated above to the Q_i values to obtain the values of D and G. This was done in two ways, (1) using m_i values calculated from observed TSS values with Eq. (6.3), and (2) using m_i values calculated from observed turbidity values with Eq. (6.5). The resulting equations are

$$m \text{ (tons/day)} = 0.007065 \text{ X } Q^{1.4518} \text{ (observed TSS values)} \quad (6.7)$$

$$r^2 = 0.8376$$

and

$$m \text{ (tons/day)} = 0.003854 \text{ X } Q^{1.5227} \text{ (TSS values calcd. from turbidities)} \quad (6.8)$$

$$r^2 = 0.8941$$

The coefficients of determination refer to the least squares fits of the log-log plots. Despite the shakiness of the assumption, Eq. (6.6), and the other factors which have been ignored, the coefficients of determination are reassuringly large. Log-log plots of m versus Q are shown in Figure 6-1 and Figure 6-2.

The next step involves the use of Eq. (6.7) or (6.8) with the USGS daily mean flow rates for every day of the study period to calculate the masses of sediment passing Site 14 each day. These estimated daily masses are then summed to obtain the total amount of sediment passing Site 14 during the study period.

Lastly, the total mass of sediment passing Site 14 during the study period is multiplied by 873/408, the total area of the Harpeth River watershed divided by that portion of the watershed that is upstream from Site 14. This allows a rough estimate to be made of sediment discharge from the entire watershed.

As one can see from the above description, this method is fraught with a number of uncertainties the magnitudes of which are largely unknown. As mentioned above, we expect that this approach gives an estimate that is too low. This analysis is presented in the belief that any estimate is better than none.

6.2. Results, total sediment

For the 710-day study period the total mass of sediment passing Site 14 (the Harpeth River and the Highway 100 bridge in Bellevue) is estimated to be 104,000 tons by means of Eq. (6.6) and 102,500 tons by means of Eq. (6.7). Given the magnitudes of the coefficients of determination, the closeness of these two values must be regarded as quite fortuitous. We use a figure of 103,000 tons in subsequent calculations.

The area of the Harpeth River watershed upstream from the Highway 100 bridge USGS gauging station is 408 sq. mi. The average amount of soil lost per acre during the study period is then given by

$$\frac{103{,}000 \text{ tons X } 2{,}000 \text{ lb/ton}}{408 \text{ sq mi X } 640 \text{ acre/sq mi}} = 789 \text{ lb/acre in } 710 \text{ days}$$

The average soil loss per acre per year is then obtained by multiplying 789 lb/acre by 365/710, which yields 406 lb/acre year. Obviously there must be a good deal of variation around this mean value, depending on slope, land use factors, land disturbance, riparian vegetation buffer condition, etc.

Of the roughly 103,000 tons of sediment discharged during the 710-day study period at Site 14, some 52,700 tons were discharged on the 45 days on which TSS measurements were made, and 61,100 tons were discharged on the 62 days on which turbidity measurements were made. (Note that these last include all of the days on which TSS measurements were made.) That is, 51% of the sediment was discharged during only 6.3% of the study period, and 59% was discharged during 8.7% of the study period. Examination of the raw data shows that 23.6% of the sediment was discharged during only three days (12/02/01, 25/01/02, and 17/03/02). As one would expect, the bulk of the sediment in the watershed is moved during periods of intense storms, particularly as the stream is rising.

The area of the entire Harpeth River watershed is 873 sq mi. One can therefore obtain a rough estimate for the total discharge of sediment per year from the Harpeth River watershed as follows:

$$103{,}000 \text{ tons X } (365 \text{ days}/710 \text{ days}) \text{ X } (873 \text{ sq mi} / 408 \text{ sq mi}) = 113{,}300 \text{ tons/yr}$$

This estimate should be taken with some caution, since it assumes that watershed characteristics in the northwest half of the watershed are identical to the watershed characteristics in the southeast half.

7.0 UNFINISHED BUSINESS

Here we list some additional work that would give a clearer picture of the sediment problems in the Harpeth River watershed.

1. Apparently little is known about bank and bed erosion in the Harpeth River watershed. A study of the rates of erosion of the stream banks at some of the sites identified in the HRWA's visual assessment report could give useful information on this. Such a study is currently being carried out by the HRWA.

2. The presence of a gauging station on the Harpeth at Highway 100 permitted the extraction of a great deal more information from the sediment data than was possible at sites that were not gauged. Reactivation of the gauging station on the South Harpeth River at the South Harpeth Road bridge would be very helpful in this regard, as would the establishment of gauging stations on the Little Harpeth at the Vaughn Road bridge, the West Harpeth at Del Rio Pike, and Turnbull Creek at the West Kingston Springs Road bridge.

3. Focused visual assessments should be carried out on the more heavily impaired tributary streams to see where the excessive amounts of sediment are coming from in these subwatersheds. Such assessments could easily be carried out by volunteers.

4. Sediment monitoring in the northwest and southeast quarters of the watershed was inadequate in this study due to a lack of volunteers in those areas. Efforts should be made to carry out sediment work on the tributary streams in these areas.

5. The impact of extremely flashy streams (such as Spencer Creek) in generating sediment should be investigated. A planned monitoring site on Spencer Creek was, unfortunately, not productive of data. This creek is gauged, so the data could readily be interpreted.

6. In a few years another comprehensive study should be carried out to ascertain the extent to which the situation with regard to sediment in the Harpeth River has changed.

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We have drawn on the Tennessee Department of Agriculture Nonpoint Source Program's Tennessee Instream Education Manual, EPA's Volunteer Stream Monitoring: A Methods Manual, and TVA's Clean Water Initiative Volunteer Stream Monitoring Methods Manual for help in planning the project.

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Appendix A:

HARPETH RIVER WATERSHED SEDIMENT STUDY 21/12/00

SURVEY AND SAMPLING PROCEDURES, PROTOCOLS FOR TURBIDIMETRY DETERMINATIONS AND IMHOFF CONE SEDIMENT MEASUREMENTS

David J. Wilson
Cumberland River Compact

This material has been developed from the Tennessee Department of Agriculture Nonpoint Source Program's manual, Tennessee Instream Education Manual, and from the Tennessee Valley Authority's Clean Water Initiative Volunteer Stream Monitoring Methods Manual. The CRC thanks these agencies for the opportunity to utilize these documents, and recommends them as most useful references for this project. The TVA manual is particularly comprehensive. Material has also been taken from Standard Methods for the Examination of Water and Wastewater (APHA), from the Ben Meadows Company Catalog, and from the Globe Teacher's Guide Water Transparency Protocol.

I. Equipment and supplies

Home: a cheap rain gauge, Imhoff cones and rack (optional—CRC supplies these if needed for very muddy waters), turbidity tube and rack (if samples were taken at night)

For the trip: maps (road and topographic, if needed), pencils, waterproof field book, field data sheets, camera and film (day trip), wet weather gear, sample jugs (about 10-12; 1-gal milk jugs are fine), labels, sampling bucket with rope, measuring tape with weight (if sampling at a bridge), turbidity tube and rack (if day trip), traffic safety vest with reflecting strips, life jacket (if necessary), traffic cones (if necessary), large flashlight (night trip), snack and drink, first aid kit.

Safety - We discuss safety matters in a separate document.

II. Visual assessments: windshield and walking surveys

A great deal of useful information can be obtained by driving around your area of the watershed and keeping your eyes open—a windshield survey. One gets a good deal more detail, but covers a much smaller area, by making a walking survey or by canoeing a stretch of a stream. TVA's Clean Water Initiative Volunteer Stream Monitoring Methods Manual has an excellent section on these activities which starts on p. 47. Most of the following is taken from this manual. For any type of survey, by all means get the landowner's permission if you go on private land.

a. Windshield surveys

These are normally done in early spring, late summer, and late fall. Expect to spot problems such as poor management practices at construction sites, agricultural erosion, damage to streamside (riparian) vegetation, etc. It's best to go with a partner, so one can drive while the other looks and records. Besides your car, you'll need the following:

local road map (preferably a county map)
topographic map(s), perhaps with some Xerox copies to record land uses and characteristics, stream characteristics (including banks and riparian vegetation), possible sources of pollution. TopoZone.com is a great source of maps.
field data sheets (CRC will provide these)
notebook and pencils
camera(s) and film (we need both prints and slides)

Look for land use activities that might affect the stream. These include construction sites, parking lots, closely mowed lawns, farming, cattle crossings, industrial and sewage plant discharges, dumps and landfills, logging, graveling, signs of flooding, etc. Also look for forested land, wetlands, pasture, and healthy riparian zones.

b. Walking and canoeing surveys

You can learn much about the health of a stream by walking along its banks or floating it. In addition to normal hiking or canoeing gear, you'll need the following:

topographic map(s), or, better, some Xerox copies of topo maps to record land uses and characteristics, stream characteristics (including banks and riparian vegetation), possible sources of pollution. I find that it's best not to take my topo sheets on canoe trips...
field data sheets (provided by CRC)
notebook and pencils (a small water-resistant engineer's field book is great)
camera(s) and film (we need both prints and slides)
pack (hiking) or dry bag (canoeing)

Keep your eyes open and your nose at full cock. How does the stream smell? Is it strewn with debris? Any oily sheen, color, or foam? What have you got in the way of riffles and quiet pools? Is the stream clear or turbid? Are the banks eroded or caving in? Are trees falling into the stream? What is there in the way of vegetation along the banks? What about livestock access to the stream? Any outfall pipes or other signs of discharges or potential discharges to the stream? Fish? Recreational uses?

We need to obtain a large number of photographs, both slides and prints, in the watershed. Canoe float trips and hikes along stream banks are probably the best ways to get such pictures. Get permission from landowners before going on private land, however.

We need shots of:

best available areas
areas in which best management practices are in use
sites of active bank erosion
areas in which livestock or vehicle traffic is damaging riparian vegetation
accumulations of logs and other debris in the stream
areas in which agricultural erosion or erosion from home sites is introducing sediment into a stream
sites where sediment is coming from improperly managed construction activities
sites where urban runoff is significant
sites where effluents are being discharged
fish kills
etc.

It adds interest if one includes one or more people in the photo. If you are photographing something small, include an object (a coin, key, ruler, etc.) to give the size scale.

These photos will need to be documented in detail (date, precise location [preferably marked on a Xerox copy of a topo sheet], present and recent weather conditions, stream stage, significant activities in and upstream of the area, etc.), what is notable about the photo. All this should be logged into your field book, along with information that will permit you to match up the field book entry with the correct photograph.

c. Post-survey activities

After your survey, complete filling out the field data sheets and do a narrative report (nothing fancy) describing what you found that is of interest. We will use this information in making decisions about possible new sampling sites, and will also use it in the preparation of a brochure and slide talks on sediment in the Harpeth River watershed. If you find anything of particular importance, call the Harpeth River Watershed Association at (615) 790-9767.

III. Sampling procedure

1. Sample bottles (typically 1 gal. plastic jugs) are thoroughly washed and inspected to make sure they contain no traces of mud before the trip is made. The sampling bucket is also washed and inspected. Take plenty of sample bottles; a dozen is not unreasonable. Better too many than too few. Put labels (date and sample number) on the jugs while they're dry and at room temperature—the labels stick better that way. Label with pencil or ballpoint pen, since the labels WILL get wet.

2. Collect the sample in the bucket in mid-stream if possible—bridges are excellent sampling sites. Avoid stagnant water; it is best if the water is turbulent or at least roiling. If sampling from the bank, sample as far from the shoreline as is safe. Avoid collecting sediment from the bottom or side of the stream. In fast water or floods, do NOT tie the bucket rope to your wrist or let your feet get tangled in it.

3. If you are standing in the stream to sample, face upstream and hold the bucket upstream from you and facing upstream while it is being filled.

4. Stir the water in the bucket very vigorously immediately before pouring a sample into a jug. Pour the sample quickly, to avoid sediment settling to the bottom of the bucket.

5. Immediately after the sample has been poured into the jug, log the sample into your field book. Your field book entry for each sample should include sample number, site location, date, time of day, stream stage (see 6 below), weather conditions, and narrative remarks. Where multiple samples are taken, ditto marks in the field book are OK.

6. Determine the stream stage. This should be measured and recorded for every single sample. These measurements are extremely important.

   a. If there is a gauge station at your site, record the stage of the stream by reading the position of the water on the gauge and recording the number or mark just visible.

   b. At a bridge without a gauging station, stream stage is easily measured by using a long measuring tape with a small weight attached. Always make the measurement at the same place on the bridge. (A crayon mark on the bridge railing is useful.) The weight is lowered on the tape until it just touches the water. The distance between the water and the top of the bridge railing is then determined and recorded. Subtract this figure from the figure obtained when the stream is measured under conditions of low water and the weight actually is touching the stream bottom (your reference point) to get the stream stage; show this calculation in your field book.

   c. If your sampling site is not at a bridge, you must put in a gauge yourself. Purchase a plastic or metal yardstick or stream gauge and mount it solidly on a post, tree trunk, etc. in the stream. Very fancy and official-looking stream gauges can be purchased from the Ben Meadows Company for a price—contact Dave Wilson if you're interested. Most of the gauges I've installed have been plastic yardsticks from Home Depot. The gauge must be in a vertical position and located where you can readily read it and where floating debris will not damage it. Mount it low enough so that the bottom of the stick (starting at 1", not 36") is in the water under conditions of low flow. If rises of more than 3 ft are expected, you may need to put marks and numbers (inches and feet) on a 2 X 4 board of suitable length. I did this using a black marking pen and then coating the board with clear spar varnish.

The stream stage is then given in feet and inches by the reading just visible above the water. Record this in your field book.

7. If you are giving some or all of your samples to us (Dave Wilson or Rick Lockwood) for gravimetric analysis or are sharing samples with us for QA/QC, call me at 297-4620 (h) or 250-1248 (w) after you get back from your trip—or e-mail me at djwilson@brwncald.com. But no phone calls after 11 PM or before 6 AM, please! Don't leave samples where they may freeze and burst the jugs. Samples should be analyzed within 30 hr after they have

been collected. If this is not possible, we'll do them anyway, but we'll have to qualify them as exceeding the allowed holding time.

IV. Turbidimetry determinations

1. Make sure that the sun is at your back, that the turbidity tube is mounted vertically and is underlain by the white tile on the tube rack, and that the turbidity tube is shaded from direct sunlight (perhaps by your body) while measurements are made. Don't try to make turbidity tube measurements at night or in artificial light—the results are extremely unreliable. Samples taken at night should be run for turbidity the next day at home.

2. Mix the sample in the jug or sampling bucket by shaking vigorously to distribute the sediment uniformly in the water. In particular, there should be no mud whatsoever adhering to the bottom of the jug.

3. Immediately fill the turbidity tube with water from the jug or bucket; pour it quickly, so that settling does not occur before the sample has been poured into the tube.

4. Release water from the drain at the bottom of the turbidity tube while looking down vertically through the tube until the white-black pattern at the bottom of the tube is first definitely visible. Immediately stop the water flow. Record the length of the water column to the nearest 0.2 cm, as indicated on the scale on the side of the tube.

5. If there's sediment left in the bottom of the tube, rinse it out.

6. Repeat this procedure two more times, for a total of three measurements. Record all measurements, and calculate the average, b.

7. The turbidity T is calculated from the formula $T = 100/b$. For very clear samples, b may be greater than 122 cm ($T < 0.82\ m^{-1}$); for extremely muddy samples, b may be 5 cm or less ($T > 20$). If b is 10 cm or less, save a jug of the water for gravimetric analysis by Dave Wilson or Rick Lockwood.

V. Imhoff cone measurements

When the water is very muddy (too thick to drink, too thin to plow), Imhoff cone measurements are called for. You do these at home, as they take 24 hr. The measurements are made as follows.

1. Make sure that the cones are thoroughly cleaned—a bottle brush can be helpful for this. The white plug at the bottom can be removed. No mud, no crud!

2. Place the cones in the cone rack. Make sure that they are vertically oriented, and that the plugs at the bottoms are CLOSED. Put numbered labels on the cones or on the rack corresponding to the numbers on the sample jugs. Masking tape can be used for these; it sticks best if the cones are dry.

3. Mix the sample in the jug VERY vigorously to distribute the sediment uniformly in the water. In particular, there should be no mud whatsoever adhering to the bottom of the jug. This may require some effort if the samples have stood around for a few hours.

4. Immediately pour 1 liter of water sample from the jug into the corresponding cone; use the 1-L mark on the cone to determine how much is required. Do this quickly, to avoid settling.

5. Let the cone stand undisturbed for 1 hr, then measure the volume of sediment which has accumulated in the bottom of the cone (at its tip). Use the calibration marks on the side of the cone for this. Record this in your field book or notebook and mark it "1 hr". The units of your measurement are mL/L (milliliters per liter).

6. Let the cone stand undisturbed for a total of 24 hr, and repeat the measurement of the volume of settled sediment. Record the result in your field book or notebook and mark it "24 hr".

7. Remove the plug at the bottom of the cone, drain the water sample from the cone and immediately flush the cone thoroughly to avoid having mud dry and harden in the tip of the cone. There must be no residue left in the bottom of the cone. Bottle brushes and hose jets are helpful for cleaning obstreperous cones. Make sure that the plug at the bottom of the cone is firmly back in place when you're through.

VI. Rain gauge measurements

Place the rain gauge well out in the open—not near or under trees, porches, etc. Place it where you will not hit it with your lawn mower; a couple of our rain gauges have perished this way. Record the reading to the nearest 0.1" after each storm, and empty the gauge. Do not leave your rain gauge out in freezing weather, as the expanding ice will burst the gauge. We have lost six gauges this way.

VII. QA/QC - Quality assurance/quality control

The value and utility of our data will be no better than we make them. If we develop good data, well-documented, and supported by adequate quality assurance measures, these data will be a valuable contribution. This will require considerable effort on the part of all of us who are participants in the project. Quality assurance requires attention to the following points:

1. We must be adequately trained to do what we are going to do. Keep your eyes and ears open at our training sessions. If you don't understand or if something seems wrong, ask questions. In this project there are no stupid questions. What is stupid is not to ask a question when one comes to mind. Review the protocols for the procedures you're about to do, and review them every time you're going to do them. I have tried to give you very detailed, accurate, clear recipes for each procedure, and we have had these recipes reviewed by experts. But I am not perfect, and if something puzzles you at any time, ask.

2. Keep complete, detailed, clear records, even when you're cold, wet, and miserable. Don't wait to record things until you get home from the trip, or until the next day; record them immediately. It's very important that you keep your records in timely fashion. Don't record anything on loose pieces of paper; these almost invariably get lost. Everything, absolutely everything, goes into your field book, except for the labels you put on sample jugs and Imhoff cones. Make sure that you do your labeling carefully and completely. An unlabeled or mislabeled sample may as well be thrown away—it is useless. Record dates, times, precise sampling locations (including bank or middle of stream), weather conditions, your rain gauge reading, data and calculations of stream stage, any narrative comments, turbidity tube measurements. And make your records clear enough that you (or I) will easily understand them six months later. When you submit data to me, please check to make sure that your report is (1) complete, and (2) legible. E-mail is very convenient for this; some volunteers are sending me Excel spread sheets of their data, which is very nice but not necessary. Faxes of your field book are OK PROVIDED that they are legible.

3. Duplicate and triplicate samples. It is standard scientific practice to take replicate samples, because scientists do not trust each other not to make mistakes, and they do not trust themselves. This helps make science work. In our initial phase of this study, I'm asking everyone to take triplicate measurements every time you measure turbidity. If you have Imhoff cones, take duplicate samples. Occasionally I will ask you to take one or more samples in triplicate, and I will take one of the three to run it. Initially, for every 6 samples you collect, take one in triplicate, and give the third one to me.

4. Further training. In the early stages of the project I shall try to go out sampling and testing with each of you. And next spring I shall plan to have a training session for any new volunteers we may acquire, as well as for the grizzled veterans of the project.

If our data are to be of any use to the agencies, we must demonstrate that we have made every effort to insure that these data are as accurate as possible, given the limitations within which we must operate. This is extra bother, but is well worth the effort. And it is the way that science works.

Appendix B:

HARPETH RIVER WATERSHED SEDIMENT MONITORING PROJECT SAFETY CONSIDERATIONS

A sediment monitoring project on the Harpeth is not a particularly hazardous activity compared with whitewater canoeing or kayaking, water-skiing, stock car racing, rock climbing, driving in interstate traffic, or crossing a busy street. Nevertheless, there are opportunities for accidents in connection with the project. In an effort to forestall these I shall have to play the role of a mother hen, a worry wart, a wimp. Sorry. But, for your own safety, bear with me, and keep the following points in mind when you're sampling.

1. Driving safety. In addition to normal driving hazards, you will often be driving in the rain, perhaps at night, with conditions of poor visibility and wet, slippery roads. You'll probably be driving on narrow, winding, secondary roads of dubious repair. Drive no faster than road and visibility conditions permit, and BE CAREFUL. My guess is that the greatest hazard in this entire operation is from auto accidents.

2. Parking safety. If you drive a car to your sampling site(s), make sure that it is safely parked well off the road. This is particularly important during storms and at night when visibility is poor. You may want to put your blinker lights on. Be careful getting into and out of your car and loading samples; at night or in the rain you may be quite invisible to an oncoming driver. Also, don't block any farmers' gates or drives when you park unless you want to run the risk of being shot. At the very least….

3. Lightning. If lightning hazard is severe, stay in your car or in the house until the lightning has moved on. We are not in such a hurry to get samples that you need to run the risk of being struck by lightning.

4. Drowning. Avoid sampling from steep, muddy banks, where you may slide into a fast-moving stream and be swept downstream into a "strainer" tree where you could be drowned. This can happen even if you're a strong swimmer. We really mean it. This is a No-No.

   Wading in rain-swollen, muddy streams is dangerous and should never be done. You can't see what you're doing, the current is swift, and you may be knocked down by passing debris (down tree, dead cow, etc.). If you need a sample and there is no bridge, toss out a bucket on a rope. (Hang on to the other end of the rope, but don't tie it to your wrist!)

   If you drop a piece of equipment into a flooding stream, don't risk your life trying to recover it. None of the equipment you'll have will be as valuable as your own scalp. At least that would be my guess.

   Wear a life jacket if there's any question of hazard from drowning where you're sampling. Ditto if you're doing a survey by canoe.

5. Bridges. A good deal of our sampling will be done from bridges. This is convenient, but has potential for great evil. If the bridge has walkways beside the roadway, stay on a walkway at all times, and keep all equipment on the walkway. Under conditions of poor visibility carry a good light. Wear a safety vest with reflecting strips. If the bridge does not have a walkway, you are truly a sitting duck for cars, and the season on you is always open. On such a bridge, sample with a partner whose job is to keep his eye out for cars, and get yourself and your equipment off the bridge when a car is approaching. This is particularly important at night or in the rain, when you may not be seen. You may want to put out some orange traffic cones to alert oncoming drivers. When sampling from a bridge, DO NOT tie the rope attached to the bucket to your wrist, and do not get your feet tangled up in that rope; should the bucket get caught on a tree floating past, you would suddenly be in desperate trouble.

6. Poison ivy, snakes, hornets, etc. Of the "lesser hazards", the one you are almost certain to encounter unless you sample only from bridges is poison ivy. "Leaflets three, let it be." Tennessee is the poison ivy capital of the world. Learn what the stuff looks like, avoid it whenever possible, and wash thoroughly with soap and change clothes after you think you may have been exposed.

In moist areas you may run into nettles—painful, but for a short time only, and no lasting damage. One experience with nettles and you'll quickly learn to identify and avoid them!

Most of our snakes are harmless, but I've seen copperheads and an occasional rattler in Middle Tennessee. Be alert, watch what you're doing and where you're stepping, and don't put your hands or feet anyplace where you can't see what's there. If you're in a particularly snaky area, you may want to wear boots. Never shoot a snake on rock or in the bottom of your boat—this is a bad mistake! Avoid bulls, dogs, and rabid skunks, coons, and bats. If you're not sure whether they're rabid, ask them...

Avoid hornet and wasp nests, particularly the large paper nests which one sometimes sees in trees along streams. The results of disturbing one of these are extremely unpleasant—something like proposing a state income tax.

In Tennessee, chiggers and ticks come with the territory during the warm weather. Pre-trip insect repellant (external only, please) and careful self-examination after the trip are good ideas if you have to go through grass and brush.

7. Where are you? When you go sampling, let someone know where you're going, and when, approximately, they can expect you back. It's best if this information is left in writing, so there are no mix-ups if there's a problem. Leaving a map marked with your route and station(s) is a good idea. If you have a cell phone, take it along.

8. Children. When you are sampling, your attention will be focused on sampling and your own safety. Both road and water hazards will generally be present. Therefore, do not take young children along unless there is another responsible person with you who can devote full time to keeping the kids safe. The situation, of course, is different if you're planning to use them for bait.

9. Canoe trips. Canoe float trips are excellent for getting a good look at a stream, but can involve hazards. Trips should be done by experienced, responsible boaters with proper equipment (including life jackets and a safety rope). Do not make reconnaissance trips by canoe in periods of cold weather, flood water, or electrical storms—check the forecast. And beware of down "strainer" trees in the Harpeth and its tributaries; these can create all sorts of excitement and tales to tell your grandchildren.

10. Common sense. In connection with safety, use your head. Look at each situation, size it up in terms of potential hazards, and figure out what you can do to avoid injury. Play it safe. We want you to be sampling with us next year.

ACKNOWLEDGMENTS

I have drawn on the Tennessee Department of Agriculture Nonpoint Source Program's Tennessee Instream Education Manual and TVA's Clean Water Initiative Volunteer Stream Monitoring Methods Manual for much of this material. If you are involved in volunteer stream monitoring these documents make excellent reading.

Appendix C:

THE MATHEMATICAL PHYSICS OF MUDDY WATER. IV. THE RELATIONSHIP BETWEEN OPTICAL DENSITY (TURBIDITY) AND TOTAL SUSPENDED SOLIDS

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Introduction

In the course of examining plots of gravimetric Total Suspended Solids (TSS) concentrations (mg/L, ordinate) versus turbidities (T, m-1, abscissa) it was observed that the plots are noticeably concave upward; that the slope of a plot of TSS versus turbidity T increases with increasing T. Our earlier analysis indicated that these plots would be linear, having a constant slope. The discrepancy indicates that one or more of the assumptions in the earlier approach must be incorrect. A probable source of error is the assumption that the sediment particles all have the same effective radius. Here we carry out the analysis for the case in which the sediment particles are assumed to have a distribution of radii. The resulting formula relating volumetric TSS to optical density (O.D.) is then converted to practical units (mg/L gravimetric TSS, m^{-1} turbidity).

The practical formula suggests that the correlation between TSS and turbidity might better be approximated by a segment of a parabola or by an equation of the form $TSS = A*T^b$ ($b > 1$) than by a straight line. Experimental results from the Harpeth River Watershed sediment study are presented which suggest that this is indeed the case. The parabolic correlation formula provides a significantly better experimental correlation between TSS and
turbidity than one finds using a linear relationship. Use of the parabolic correlation formula would appear to permit more accurate estimation of TSS values from turbidity measurements than one would obtain with the linear relationship.

Analysis

In an earlier calculation, in which the sediment particles were all assumed to have the same effective radius, the following formula was obtained which relates TSS (mg/L) to turbidity T (m^{-1}):

$$TSS = 2.303 \; X \; (4/3) \; X \; d \; X \; r \; X \; T \qquad (1)$$

Here d is the density of the solid of which the sediment is composed, gm/cm^3 and r is the effective radius of a sediment particle (microns). It is also assumed here that one can see the bottom of the tube at 10% transmission.

From practical experience, however, we know that the sediment particles do not all have the same effective radius, but are distributed over a range of sizes. In the following analysis we examine the situation which arises when this distribution of particle size is taken into account.

Let $c(r)dr$ be the number of sediment particles per unit volume having particle radii in the range $(r, r + dr)$, m^{-3}. Initially we focus on just these particles. Consider a light ray which is passing through a length L (m) of water in the cell, our turbidity tube. If the centers of one or more particles are within a distance of r from this light ray, it will be blocked by the particle. See Fig. 1. The cylindrical volume v within which particles block the ray is given by

$$v = \pi r^2 L \tag{2}$$

Let V be the volume of the cell. Then the probability p_1 that a given particle is NOT in the little volume v is given by

$$p_1 = 1 - \pi r^2 L/V \tag{3}$$

The number N of particles of the desired radius in the cell is given by

$$N = c(r)dr \cdot V \tag{4}$$

The probability that none of the N particles in the cell are in v is given by

$$P_N(r)dr = \left| 1 - \frac{\pi r^2 L}{V} \right|^N \tag{5}$$

Solve Eq. (4) for V and substitute into Eq. (5) to get

$$P_N(r)dr = \left| 1 - \frac{\pi r^2 L c(r) dr}{N} \right|^N \tag{6}$$

N is very large, so

$$PN(r)dr = \exp[- \pi r^2 L c(r) dr] \tag{7}$$

This gives the probability that the light beam is NOT intercepted by a particle having its radius in the range $(r, r + dr)$.

The probability P_k that the light beam is not intercepted by particles having their radii in the ranges $(r_i, r_i + dr)$, $i = 1, 2, 3, \ldots, k$ is just the product of the individual independent probabilities obtained from Eq. (7),

$$P_k = \prod_{i=1}^{k} \exp[- \pi r_i 2 L c(r_i) dr \tag{8}$$

which can be written as

$$P_k = \exp\left| - L \sum_{I=1}^{k} \pi r_i 2 c(r_i) . dr \right| \tag{9}$$

or, on passing to the limit and replacing the sum by an integral,

$$P_k = \exp\left| - L \int_0^{r_{max}} \pi r^2 c(r)\,dr \right| \qquad (10)$$

Let C(r)dr be the volumetric concentration distribution; then

$$C(r)dr = (4\pi r^3/3)c(r)dr \qquad (11)$$

and

$$c(r) = \frac{3C(r)}{4\pi r^3} \qquad (12)$$

So

$$Pk = P = \exp\left| - \frac{3L}{4} \cdot \int_0^{r_{max}} \frac{C(r)}{r} \cdot dr \right| \qquad (13)$$

Define the probability distribution p(r) by

$$C_{tot}p(r)dr = C(r)dr \qquad (14)$$

Note: p(r) is the volumetric distribution function for the particle radii; p(r)dr is the fraction of the total volume of sediment which has radii in the range (r, r + dr). Then

$$P = \exp\left| - \frac{3L}{4} \cdot C_{tot} \int_0^{r_{max}} \frac{p(r)}{r} \cdot dr \right| \qquad (15)$$

Note that the integral in Eq. (15) is just the average value of (1/r), calculated using the distribution function p(r). Denote this by $<r^{-1}>$. So

$$P = \exp[- (3/4)<r^{-1}>LC_{tot}] \qquad (16)$$

Let us assume that we can see the Secchi disk pattern at 10% transmission, so that the incident and final light intensities are related by I(L)/I(0) = 0.1. Optical density, O.D., is given by $\log_e[I(0)/I(L)]$, so

$$O.D. = \log_e(10) = 2.303 = (3/4)<r^{-1}>LC_{tot} \qquad (17)$$

C_{tot} is in units m^3/m^3. We would like to replace C_{tot} by TSS, total suspended solids, in mg/L. Let d be the mineral (particle--NOT the bulk) density of the suspended solids. A straightforward conversion then gives

$$C_{tot}\cdot d(g/cm^3).(1000\ mg/g).(1000\ cm^3/L) = TSS,\ mg/L \qquad (18)$$

Solve Eq. (18) for C_{tot}, substitute into Eq. (17), and rearrange to obtain

$$TSS = 2.303\cdot\frac{4d\cdot 10^6}{3}\cdot\frac{1}{\langle r^{-1}\rangle}\cdot\frac{1}{L} \qquad (19)$$

where r and L are in meters, d is in g/cm^3, and TSS is in mg/L. Now 1/L in m^{-1} is the definition of T, the turbidity tube turbidity. So finally,

$$TSS(mg/L) = 2.303\cdot\frac{4d\cdot 10^6}{3}\cdot\frac{1}{\langle r^{-1}\rangle}\cdot T(m^{-1}) \qquad (19)$$

or, if particle radii are given in microns (10^{-6} m),

$$TSS(mg/L) = 2.303\cdot\frac{4d}{3}\cdot\frac{1}{\langle r^{-1}\rangle}\cdot T(m^{-1}) \qquad (19')$$

Eq. (19) provides the rationale for why plots of TSS (ordinate) versus T (abscissa) are approximately linear but are often concave upward. High values of T are generally associated with the quite muddy waters found during and shortly after substantial rains. These waters are moving rapidly and with a good deal of turbulence, so can carry larger, more dense particles than can more slowly-moving, less turbulent waters. If the particles in suspension are larger, they have larger values of r, which is associated with smaller values of $\langle r^{-1}\rangle$. Since $\langle r^{-1}\rangle$ appears in the denominator of Eq. (19), the coefficient of T on the RHS of Eq. (19) increases with increasing T, causing the values of TSS associated with large turbidities to be larger than expected, causing the plot of TSS versus T to be concave upward.

Comparison with experimental results

The practical formula, Eq. (19) suggests that the correlation between TSS and turbidity would be better approximated by a segment of a parabola or by $TSS = A*T^b$ than by a straight line. We present experimental results from the Harpeth River Watershed sediment study which suggest that this is indeed the case. A straight-line correlation of TSS and turbidity data from Site 14 (Harpeth River at Highway 100) is shown in Fig. 2; it gives a coefficient of determination of 0.974. Fig. 3 shows a parabolic fit of these data; this gives a coefficient of determination of 0.983, indicating a somewhat better fit. The parabolic fit also yields a positive coefficient of the quadratic term (T^2), as expected from the theoretical analysis. The quadratic correlation formula

$$TSS = a + bT + cT^2$$

provides a significantly better experimental correlation between TSS and turbidity than does the linear correlation formula. Use of the quadratic correlation formula would therefore appear to permit more accurate estimation of TSS values from turbidity measurements.

One would also expect that the correlation formula TSS = $A*T^b$ would be quite satisfactory, and, as indicated in Fig. 4, this is indeed the case. The value of the exponent b, 1.2578, is significantly larger than one, resulting in the expected positive curvature of the plot. The coefficient of determination, calculated for the log-log plot, is 0.937; it is not directly comparable to the coefficients of determination for the other two plots.

Appendix D. Project Raw Data File

Available upon request as an Excel file.