SUSPENDED-SEDIMENT CONCENTRATION REGIMES FOR BIOLOGICAL REFERENCE STREAMS IN TENNESSEE

Timothy H. Diehl, Hydrologist, U.S. Geological Survey, Nashville, Tennessee, thdiehl@usgs.gov; William J. Wolfe, Hydrologist, U.S. Geological Survey, Nashville, Tennessee, wjwolfe@usgs.gov

Abstract: Suspended-sediment-concentration (SSC) regimes of five biological reference streams in Tennessee were characterized from 15-minute SSC records spanning 1 to 4 water years (October 1 through September 30) between 2004 and 2008. These streams represent least-disturbed conditions for their respective ecoregions and have exceptional biodiversity in terms of fish or aquatic invertebrates. SSC regimes in streams, when plotted in terms of duration above a given SSC at a given annual frequency such as the annual maximum or the annual tenth longest duration, can be compared directly to published biological impairment thresholds derived from experimental trials. Based on such comparison, the SSC regimes of all five reference streams reached published impairment thresholds at least 10 times per water year for all years of record. The results suggest that the published impairment thresholds are not directly applicable to streams in Tennessee and, by extension, the southeastern United States.

INTRODUCTION

Many North American streams are impaired by elevated suspended-sediment concentration (SSC) or associated conditions, such as sedimentation or elevated turbidity (U.S. Environmental Protection Agency, 2006b). However, the level of SSC low enough not to cause impairment has not been defined. Natural streams contain some sediment, and SSC commonly increases during storms, even in pristine streams. Aquatic biological communities can tolerate, and may even depend on, some variation in SSC. Nonetheless, aquatic organisms are sensitive to SSC, in particular the duration, frequency, and timing that a given concentration is exceeded (Waters, 1995; Kerr, 1995; Reid and Anderson, 1999; Yount and Niemi, 1990). Newcombe and others showed with a metaanalysis of experimental data that both SSC and duration of exposure to a given SSC are important to biological health. (Newcombe and MacDonald, 1991; Newcombe, 1994, 1997, 2001, 2003; Newcombe and Jensen, 1996). These papers combine results from multiple experimental trials linking combinations of SSC or turbidity magnitude and exposure duration to behavioral or physiological effects on various aquatic organisms. The need for comparable field studies based on SSC measurements has been recognized (Gregory *et al.*, 1993; MacDonald and Newcombe, 1993), and the present study begins to address that need.

Newcombe and colleagues (Newcombe and MacDonald, 1991; Newcombe, 1994; Newcombe and Jensen, 1996; Newcombe, 1997) reviewed studies of single periods of artificially increased SSC in controlled settings. The results of experiments were plotted according to the duration (on the horizontal scale) and SSC used (Figure 1). Both axes were divided into discrete steps corresponding to natural logarithms, dividing the analytical space into cells. The severity of impairment produced by each experimental combination of conditions was assigned a score on a semi-quantitative "Severity of Effects" scale. This score was plotted in the appropriate SSC-duration cell; in cells with multiple experiments, an average was plotted. A subset of cells, shaded gray in Figure 1, was interpreted as the "threshold of lethal effects." At much lower levels of SSC, effects on organisms were minor, but too few results were available to define the lower threshold of impairment in detail.

Eggs and Larvae of Salmonids and Nonsalmonids

(A) Average severity-of-ill-effect scores (empirical)

mg SS/L	Duration of exposure to SS (loge hours): 0	1	2	3	4	5	6	7	8	9	10	loge mg SS/L
162755	-	-	-	-	-	-	-	-	-	-	-	12
59874	-	-	-	-	-	-	-	-	-	-	-	11
22026	-	-	-	-	-	-	-	-	-	-	-	10
8103	-	-	-	-	-	-	-	-	-	-	-	9
2981	-	4	-	8	-	-	-	-	-	-	-	8
1097	-	-	-	9	11	10	-	-	-	-	-	7
403	-	-	-	12	12	11	-	-	-	-	-	6
148	4	-	-	9	12	11	13	12	13	-	-	5
55	-	-	-	10	-	-	-	13	-	-	-	4
20	-	-	-	7	10	10	-	13	-	-	-	3
7	-	3	-	-	-	-	-	11	-	-	-	2
3	-	-	-	-	-	-	-	-	-	-	-	1
1	-	-	-	-	-	-	-	-	-	-	-	0
	1	3	7	1	2	6	2	7	4	11	30	
	Hours			Days			Weeks		Months			

Figure 4.--(A) Average severity-of-ill-effect scores for eggs and larvae of salmonids and nonsalmonids (freshwater and estuarine, group 4) in the matrix of suspended sediment (SS) concentration and duration of exposure.

Both matrix axes are expressed in logarithmic and absolute terms; loge is read as "natural logarithm." Dashes mean "no data." Shaded bands denote inferred (by manual interpolation) thresholds of sublethal effects (shading without a border) and lethal effects (shading with a border; see Table 3a. for criteria.)

A

Aquatic Invertebrates and Aquatic Flora

(A) Average severity-of-ill-effect scores (empirical)

mg SS/L	Duration of exposure to SS (loge hours): 0	1	2	3	4	5	6	7	8	9	10	loge mg SS/L
162755	-	-	-	-	-	-	-	-	-	-	-	12
59874	-	-	-	-	-	-	-	-	-	-	-	11
22026	-	-	-	-	-	-	-	-	-	14	-	10
8103	-	-	-	-	-	-	-	-	13	-	-	9
2981	5	-	13	-	-	13	-	-	-	12	-	8
1097	-	8	-	-	10	-	-	-	12	-	-	7
403	5	-	-	-	11	13	12	13	13	12	-	6
148	4	-	-	-	-	11	13	13	-	13	-	5
55	5	-	-	8	10	10	-	-	13	13	-	4
20	4	-	-	-	-	-	-	11	-	14	-	3
7	4	-	3	-	-	-	-	10	-	-	-	2
3	-	-	-	-	-	-	-	-	-	-	-	1
1	4	-	-	-	-	-	-	-	-	-	-	0
	1	3	7	1	2	6	2	7	4	11	30	
	Hours			Days			Weeks		Months			

Figure 7.--(A) Average severity-of-ill-effect scores for invertebrates and flora (freshwater, group 7) in the matrix of suspended sediment (SS) concentration and duration of exposure.

Both matrix axes are expressed in logarithmic and absolute terms; loge is read as "natural logarithm." Dashes mean "no data." Shaded bands denote inferred (by manual interpolation) thresholds of sublethal effects (shading without a border) and lethal effects (shading with a border; see Table 3b. Table 3c. for criteria.)

B

Figure 1 Illustrations of interpolated impairment thresholds; reproductions of (A) figure 4 and (B) figure 7 from Newcombe (1997), with author's original explanatory text.

The patterns of variation of SSC over time (SSC regime) at biological reference sites offer an alternative approach for examining aquatic organisms' tolerance limits to SSC level and duration (Diehl and Wolfe, in press). In this paper, biological reference conditions are defined as the "least disturbed condition"— the biological condition found in water bodies with the least amount of human disturbance in pervasively altered landscapes (Stoddard, *et al.*, 2006; U.S. EPA 2006a). In most of North America, least-disturbed biological reference sites represent the richest, most diverse aquatic communities available for observation. Such sites are characterized by aquatic communities that are exceptional for their region and basin scale. Detailed descriptions of SSC regimes at biological reference sites would thus begin to address the need for field studies to complement and test the experimentally based analyses of Newcombe and colleagues (Newcombe and MacDonald, 1991; Newcombe, 1994, 1997, 2001, 2003; Newcombe and Jensen, 1996). One obstacle to such field studies is the scarcity of continuous, short (less than 1 day) time-step SSC records at biological reference sites. This paper describes SSC regimes for five least-disturbed biological reference sites in Tennessee utilizing annual SSC-regime curves (Diehl and Wolfe, in press). The SSC regime curves are compared directly to published impairment thresholds (Newcombe and Jensen, 1996) and conventional cumulative duration plots.

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STUDY AREA

The study was conducted in five Tennessee streams with exceptional biological diversity for their regions (Figure 2; Table 1). Copperas Branch and Kelley Creek have exceptionally diverse fish communities (Rakes and Evans, 1998; A.K. Wales, Tennessee Valley Authority, written commun., 2008). Spring Creek and the Harpeth and Wolf Rivers have been identified by the State of Tennessee as ecoregion reference sites for aquatic invertebrates (Arnwine *et al.*, 2000).

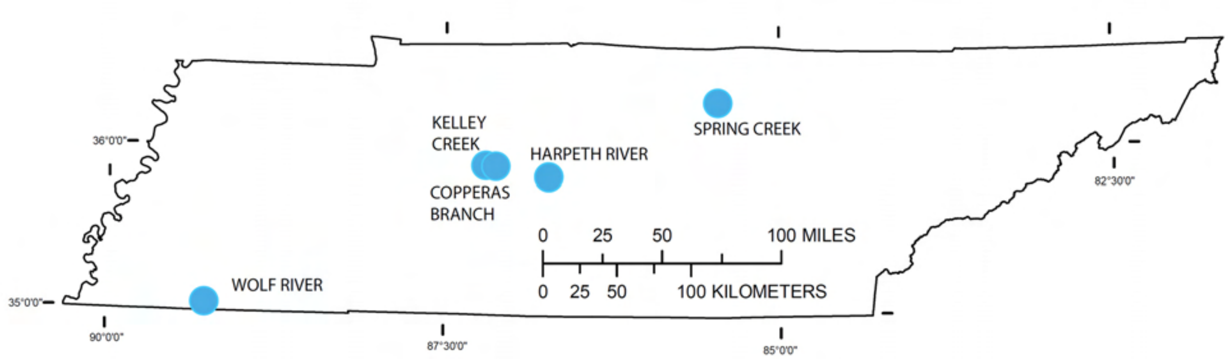

Figure 2 Map showing locations of biological reference sites used in this study.

Table 1 Characteristics of reference streams used in this study.

					Watershed Land Use[1] (percent)					Period of record analyzed	
Station name	**USGS station number**	**Station Latitude and Longitude**	**Water-shed area (km^2)**	**Main Channel Slope**	**Wet-land**	**Forest**	**Devel-oped**	**Grass**	**Crop**	**Start**	**End**
Copperas Branch near Kingfield, TN	03433640	N35° 54' 19" W87° 05' 56"	4.20	0.016	0.1	69	2.9	28	0.1	10/1/2004	9/30/2008
Kelley Creek near Kingfield, TN	03433641	N35° 54' 19" W87° 05' 52"	5.65	0.014		94	0.4	4.2	1.4	10/1/2004	9/30/2008[2]
Harpeth River at McDaniel, TN	03432100	N35° 49' 57" W86° 41' 56"	172	0.00111	3.4	38	4.5	45	9.4	12/17/2006	9/30/2008
Spring Creek near Dodson Chapel, TN	03418040	N36° 16' 23" W85° 25' 23"	66.3	0.00352	0.4	50	9.4	14	26	3/13/2007	9/30/2008
Wolf River at LaGrange, TN	07030392	N35° 01' 57" W89° 14' 48"	544	0.000873	25	43	3.6	12	17	3/7/2007	9/30/2008

[1] Homer *et al.*, 2004

[2] Data collection for Kelley Creek was suspended between 9/30/2006 and 6/7/2007

Copperas Branch and Kelley Creek are small streams in the Western Highland Rim subecoregion of the Interior Plateau (ecoregion 71f in Griffith *et al.*, 1998). The profiles of both channels are controlled by extensive exposures of bedrock, which are punctuated by bars and riffles of cobble and gravel. These two streams drain adjacent basins underlain by deeply weathered cherty limestones and siltstones of Ordovician and Mississippian age (Wilson, 1972); the soils are mostly deep and developed in residuum and colluvium (Soil Survey Staff, 2009). The Copperas Branch and Kelley Creek watersheds are mostly forested, with some hay pasture and cattle grazing on the ridges and stream terraces (Table 1). Copperas Branch and Kelley Creek represent the most diverse aquatic communities in the Western Highland Rim ecoregion (Rakes and Evans, 1998; A.K. Wales, Tennessee Valley Authority, written commun., 2008), which harbors the most diverse fish fauna of any region of comparable size in North America (Etnier and Starnes, 1993; Hughes *et al.*, 1986; Lisle *et al.*, 2004; The Nature Conservancy of Tennessee, 1998; Pollard, 2003; Tennessee Department of Environment and Conservation, 2006).

Spring Creek is a bedrock-controlled stream with scattered bars of gravel, cobbles, and boulders. Soils of the basin are mostly deep soils formed in residuum and colluvium derived from Mississippian and Ordovician limestones and dolomites, like those of Copperas Branch and Kelley Creek, with a smaller area of shallow rocky soils (Soil Survey Staff, 2009). Spring Creek has the largest proportions of cultivated and developed land of the five basins, interspersed with steep forested slopes.

The Harpeth River at McDaniel, TN, is a meandering stream with bedrock control and abundant coarse bed material; the stream flows through a wide pastoral valley bottom. The basin is underlain by Ordovician limestones of the Stones River Group. Soils are about equally divided among deep upland soils, shallow rocky soils, and deep alluvial soils. Most valley bottoms are in pasture, and cultivation is concentrated in drained wetlands with organic-rich soils (Soil Survey Staff, 2009).

Spring Creek and the Harpeth River both have widespread bank erosion except where rock ledges protect the bank, but trees persist on most banks despite the erosion. Point and lateral bars are rare in their channels, giving both streams an apparent widening trend. Both are prevented from downcutting by extensive exposures of bedrock.

The Wolf River reference reach is a dynamically stable, tightly meandering sand-bed stream with natural levees and a wide swampy floodplain. Gravel and cobble bars are absent, and the aquatic invertebrates are less diverse than in Middle Tennessee. The basin is mostly dissected hills of poorly consolidated sands with some clay and lignite, originally covered with a mantle of loess (Soil Survey Staff, 2009). This landscape was modified by agriculture, severe erosion, and subsequent conversion of most stream channels to drainage canals. Valley plugs are present throughout the drainage network, covering the valley bottoms with extensive wetlands that apparently trap most of the sediment eroded upstream from them. The uplands are mostly forested on the hillsides, with agriculture on ridges and less dissected areas.

METHODS

Records from five USGS sediment stations (Table 1) were used in this analysis. The SSC records are based on relating SSC measurements to turbidity and applying that relation to a continuous 15-minute turbidity record following methods described by Rasmussen *et al.* (2009). SSC records for periods when turbidity exceeded the detection limits of continuous turbidity probes were excluded. Discharge records were examined to determine the relative wetness of different years for stations where multiple years were compared to each other.

Annual SSC regimes are characterized by curves (Figures 3, 4, and 5) that capture the exposure of organisms in streams to suspended sediment in terms that can be compared directly to experiment-based impairment thresholds. Diehl and Wolfe (in press) discuss the conceptual basis and construction of these curves in detail, but a few points are worth noting here. The curves are defined by a series of points, each of which represents the duration of a single SSC excursion—a period of time in which SSC reaches, exceeds, and returns to a given level. Which SSC levels are plotted is somewhat arbitrary, but they are selected to plot evenly on a log scale and cover the range of SSC observed at a site.

Several types of SSC-regime curves are presented in this paper. Each paired concentration and duration on the *annual-maximum* curve represents the duration of the longest period in the water year during which that concentration was continually exceeded. Each point on the *annual tenth-longest* curve represents the duration of the tenth longest such period. The annual maximum curves are inversely monotonic; duration increases as concentration increases. The annual tenth-longest curves generally follow a similar pattern, but brief periods of exceptionally low SSC can produce large departures towards to low end of the concentration scale.

All annual analyses presented in this paper refer to water years (October1-September 30). Annual maximum and tenth-longest SSC-regime curves were plotted for Copperas Branch for 2005 through 2008, for Kelley Creek for 2006 and 2008, and for the other three sites for 2008 only. The tenth-longest duration of excursions above each selected SSC in each year was chosen as an indicator of an exposure to elevated SSC that occurs fairly frequently and can occur in any season. In addition to the annual SSC-regime curves, seasonal curves were plotted for Copperas Branch by dividing the 4 years of record into fall (September through November), winter (December through February), spring (March through May), and summer (June through August) periods, with 12 months of record in each period. These composite 12-month seasonal periods were treated in a way analogous to the annual analyses, with 12-month maximum and tenth-longest curves for each season.

SSC regime curves were compared to lethal impairment thresholds (Newcombe, 1997) by plotting the SSC-regime curves and impairment-threshold cell boundaries along common axes. Newcombe's (1997) lethal impairment thresholds are represented as discrete cells of equal width and height on a log scale centered on integer powers of *e*, plotted as brown boxes in Figures 3, 4, and 5. A given curve reaches the threshold if it plots within or to the right of the box. SSC regime was also expressed as cumulative duration plots of concentration versus days per year, summing all the frequency and continuous duration information into a single total amount of time for which each SSC was exceeded.

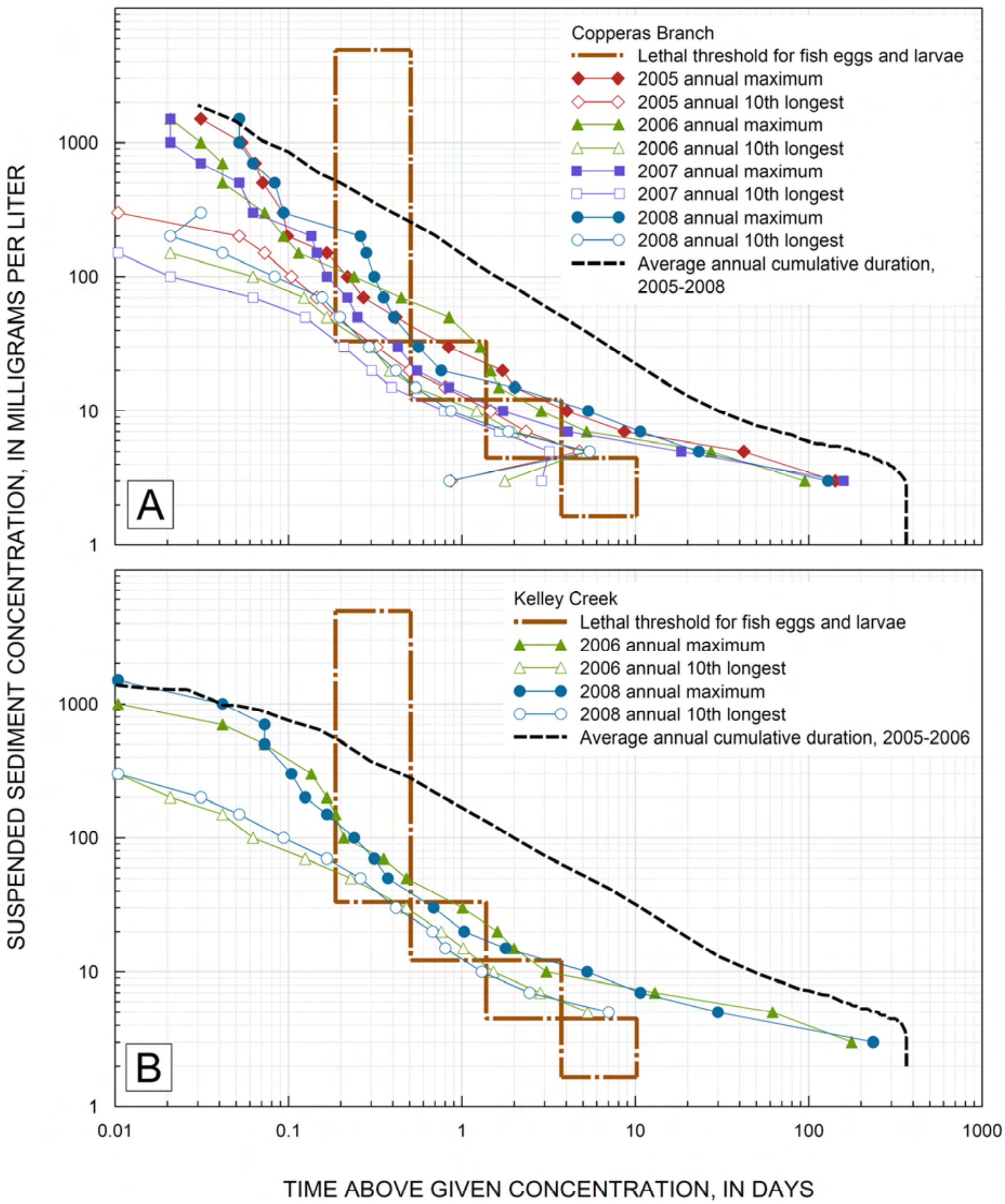

Figure 3 Plots of annual maximum and tenth-longest SSC-regime curves and cumulative-duration distributions and comparisons of SSC-regime curves to a published threshold for lethal effects on fish eggs and larvae (Newcombe, 1997) for A) Copperas Branch water years 2005-2008 and B) Kelley Creek water years 2006 and 2008.

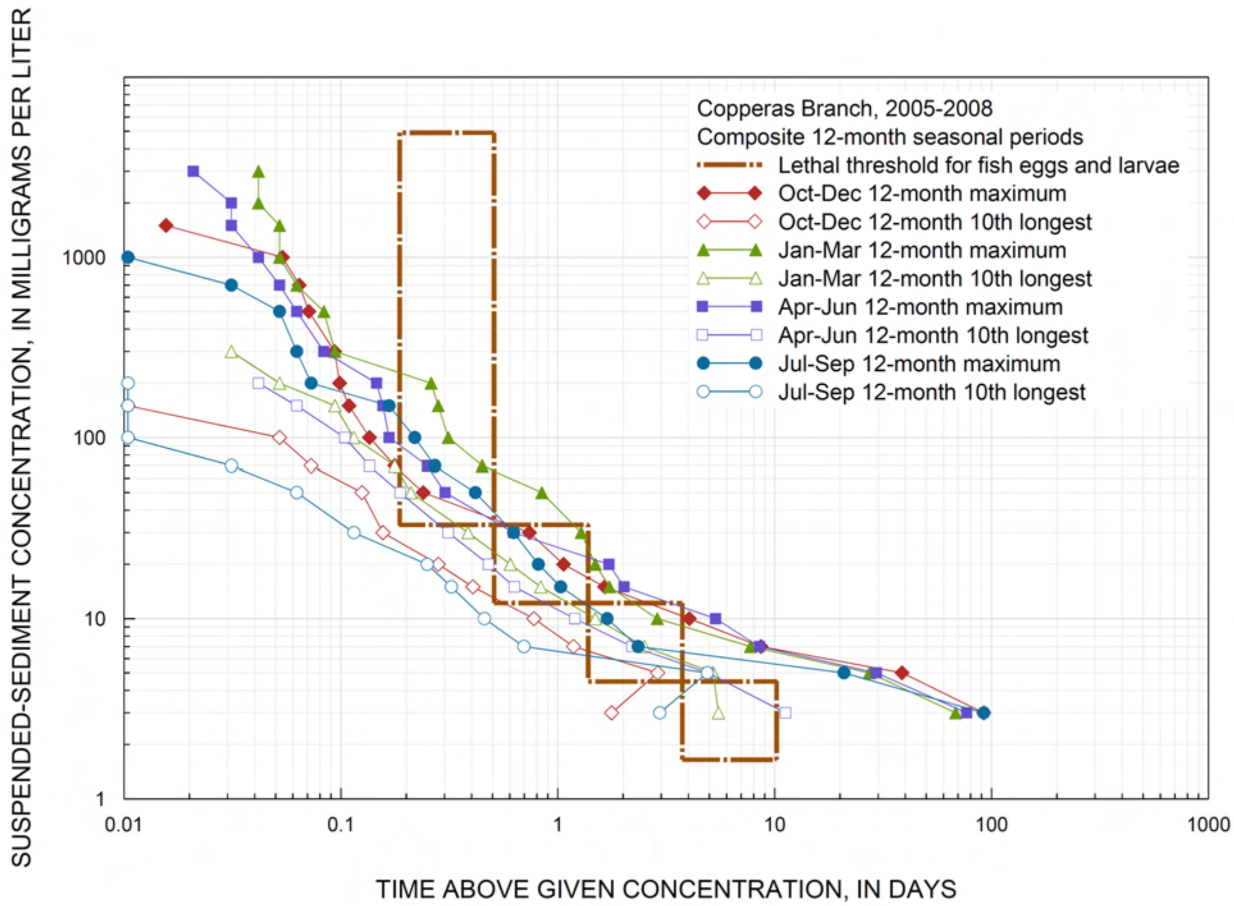

Figure 4 Plots of maximum and tenth-longest SSC-regime curves for 4 composite seasonal periods of 12 months each for water years 2005-2008 in Copperas Branch, and comparisons of these SSC-regime curves to a published threshold for lethal effects on fish eggs and larvae (Newcombe, 1997).

RESULTS AND DISCUSSION

SSC regimes for Copperas Branch and Kelley Creek routinely reached the experiment-based threshold of lethal effects on fish eggs and larvae (Figure 3). Maximum durations each year reached the threshold at concentrations of less than 100 mg/L, and tenth-longest durations reached the threshold at lower concentrations (Figure 3). Differences between years with higher (2005, 2008) and lower (2006, 2007) mean discharge are apparent in tenth-longest durations of 0.1 day or less at Copperas Branch. The threshold was reached during all seasons at Copperas Branch (Figure 4). The seasonal tenth-longest curves for winter and spring reached the threshold over the range of durations covered by the threshold, while the seasonal tenth-longest curves for summer and fall reached it only at relatively long durations.

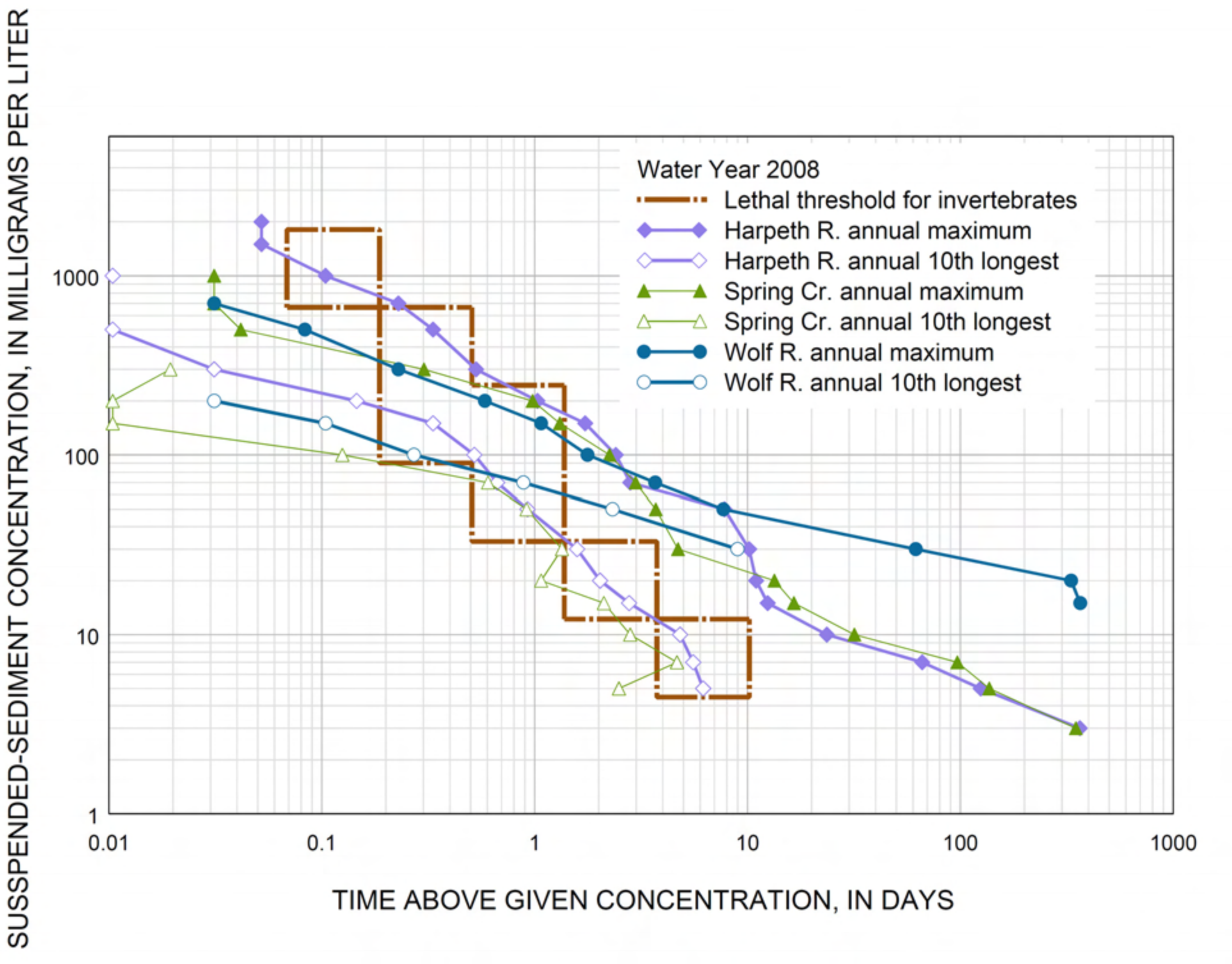

Figure 5 Plot of annual maximum and tenth-longest SSC-regime curves and cumulative-duration distributions for Spring Creek, Harpeth River and Wolf River, water year 2008, and comparisons of Spring Creek, Harpeth River and Wolf River annual SSC-regime curves to a published threshold for lethal effects on aquatic invertebrates (Newcombe, 1997).

Annual-maximum curves and tenth-longest curves for Spring Creek, the Harpeth River, and the Wolf River in 2008 reached the experiment-based threshold for lethal effects on aquatic invertebrates (Figure 5). The Wolf River had SSC greater than 15 mg/L throughout the year, but its SSC regime was similar to that of Spring Creek above 100 mg/L. The Harpeth River regime resembled that of Spring Creek at low concentrations, but included longer durations than the other streams at high concentrations (Figure 5).

Experiment-based thresholds of lethal effects were reached in these five Tennessee reference streams, apparently without compromising biological diversity. Although summer and fall had relatively few high-SSC events, SSC regime curves for these seasons still reached the lethal threshold. Routine exceedance of experimentally-based thresholds suggests that they may not apply to aquatic communities of warm-water streams in Tennessee and arguably in the southeastern United States in general; most studies of the effects of suspended sediment on fish and invertebrates, including most of those cited by Newcombe, have focused on salmonids in the Pacific Northwest rather than warm-water aquatic communities (Waters, 1995).

CONCLUSION

An appropriately detailed description of SSC regimes in biological reference streams can provide a benchmark for acceptable SSC. SSC regimes in biological reference streams in Tennessee exceed thresholds of concentration and continuous duration that have been defined as sublethal or lethal based on laboratory experiments, even though biological diversity indicates these regimes are benign. Consequently, existing experiment-based thresholds do not provide such a benchmark. A useful description of SSC regime needs to include the features that biological diversity depends on, including concentration and continuous duration of exceedance. The SSC regime can be more simply characterized by the cumulative duration curve for SSC, and as such it can be estimated with sparse sampling. However, it remains to be shown whether cumulative duration curves adequately capture biologically significant differences in SSC regime among different sites and periods of analysis.

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