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Characterizing the Concentration, Duration, and Frequency of Turbid Events in Tennessee Streams: Potential for Macroinvertebrate Impairment

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To the Graduate Council:

I am submitting herewith a thesis written by Robert Ryan Woockman entitled "Characterizing the Concentration, Duration, and Frequency of Turbid Events in Tennessee Streams: Potential for Macroinvertebrate Impairment." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

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Characterizing the Concentration, Duration, and Frequency of Turbid Events in Tennessee Streams: Potential for Macroinvertebrate Impairment

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Abstract

The impairment of lotic systems due to siltation is one of the most common factors leading to a stream being placed on the 303d list. Once a stream reach is placed on the 303d list, a state's environmental regulatory agency must then develop sediment total maximum daily loads (TMDLs). However, a deficiency exists in available methods for assessing biotic response to siltation, creating the inability to set TMDLs functionally related to cause of impairment. Water quality sondes can collect voluminous amounts of turbidity data and stage data at intervals that can be used to characterize concentration, duration, and frequency (CDF) of flows with elevated turbidities. Data were collected from 10 streams located in both the Interior Plateau (ER 71) and the Ridge and Valley (ER 67) ecoregions of Tennessee. Utilizing a Poisson arrival approach, sediment transport flux was analyzed stochastically by observing the frequency and duration of recorded turbid events over designated threshold levels for a 6-month period. Turbidity measurements converted into concentrations of suspended sediment and characterized through CDF curves allowed comparison between biotic community structure and episodic fluxes of suspended sediment transport. CDF curves identified a strong influence on the duration of turbid events due to contributing basin scale. The significant results of a combination of bivariate regressions and a Welch's test of means suggested that the frequency of elevated sediment concentrations explained the most variance in macroinvertebrate response to siltation. The CDF methodology appears to be a practical means for distinguishing suspended sediment flux behavior resulting in biological impairment.

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1. Introduction

Tennessee, like most U.S. states, relies on biotic indicators to determine whether a stream is meeting the designated use of supporting fish and aquatic life (TDEC, 2010). If a stream has been evaluated as not fully supporting, it is necessary to determine cause by pollutant or other stressor. Silt is one of the most frequently cited pollutants in Tennessee, impacting almost 6,000 miles of streams and rivers (TDEC, 2010). Impaired river and stream segments are then listed in accordance with §303(d) of the Clean Water Act, and total maximum daily loads (TMDLs) for sediment targets must be generated that meet state water quality criteria (USEPA, 1999). TMDL's should represent reference conditions and be functionally related to a healthy biological condition; however, defining reference conditions is problematic considering suspended sediment flux and related turbidity levels are a function of channel morphological conditions, biogeographical location, precipitation intensity, and a host of other variables (Asmus *et al.*, 2009; Lenhart et al., 2009). In addition, limited scientific data exist on relationships between fine sediment exposure and biotic response (Cormier *et al.*, 2000; Magner and Brooks, 2008).

Identifying a relationship between fine sediment flux and biological response is difficult because lotic system ecological function is the result of gradients of multiple stressors (Tong, 2001; Kilgour *et al.*, 2007). To confound matters, simplifications of response are problematic because biological response to suspended sediment differs between species and sediment properties (Berry *et al.*, 2003). Species responses are dependent on: 1) both direct and indirect ecological effects, 2) species life histories, 3) species traits and differential tolerances, and 4) availability of habitat patch refugia. Therefore, in order to understand these time-dependent responses, suspended sediment flux must be characterized in terms of concentration, duration,

and frequency (USEPA, 2000; Schwartz *et al*., 2008; Schwartz *et al*., 2010). Newcombe (2003) spent a great deal of time researching biotic response to suspended sediment dose, where dose represented the product of concentration and duration (Newcombe and MacDonald, 1991; Newcombe, 1994, 1997, 2001), confirming that the duration of exposure to suspended sediments does in fact have a negative impact on aquatic communities in experimental settings. The frequency of turbid events and resulting effects on biota has been less studied, resulting in minimal evidence of potential stressor relationship (Waters, 1995; Henley *et al*., 2000).

Identifying thresholds of impairment in the environment is difficult, as organisms in different habitats have evolved to survive in the resuspension and deposition regimes native to their habitat (Berry *et al.*, 2003). Yet, an approximation of what is natural resuspension and deposition is critical to developing thresholds that will eventually lead to scientifically supported TMDL's that support the return of systems to their designated aquatic life use. Simons and Klimetz (2008) were able to clearly define a difference between stable and unstable streams in both the Interior Plateau (ER71) and Blue Ridge (ER66) ecoregions with regard to both the frequency and duration of specific suspended sediment concentrations. Although, a promising method of suspended sediment transport characterization, how variations in the frequency and duration of suspended sediment might impact biotic communities remains to be determined.

The impact of biogeographic location on sediment flux events is further confirmed by Bilotta (2012), who found, using one-way ANOVA, a significant difference in mean background suspended particulate matter (SPM) for reference conditions (minimal anthropogenic disturbance) in contrasting ecosystems. Diehl and Wolfe (2010) characterized suspended sediment transport as Suspended Sediment Concentration (SSC) regimes in terms of concentration, frequency, and duration of actual observed events for two unimpaired Tennessee

streams in the Interior Plateau ecoregion (ER71). Both SSC regimes exceeded experiment-based thresholds of impairment (Newcombe, 1997), confirming the need for threshold values developed in ecologically relevant settings.

The best method for characterizing concentration, duration, and frequency (CDF) in one powerful and convenient summary is yet to be determined. Questions must first be answered about the degree of influence that both individual effects and the interaction of effects have on biological degradation. Robinson and Roby (2006) suggested the use of CDF curves, much like intensity-duration-frequency (IDF curves), to capture the variability in pH events in a systematic way. Expanding on this concept, Schwartz et al. (2008) applied this method to two sites in the Blue Ridge ecoregion (ER66), demonstrating how concentration, duration, and frequency of sediment flux events can be characterized in one relationship and examined for any thresholds perceived to be ecologically relevant.

Our study objective was to first identify whether the CDF curve method could be used to characterize individual-basin sediment-flux response to precipitation runoff events, on a broad scale and across biogeographical boundaries. If characterization in the format of CDF curves was adequate, our next objective would be to compare CDF curves in order to identify the degree of influence basin scale and spatial location (stream order) imposes on CDF of suspended sediment flux. The final objective was to attempt to identify whether a relationship exists between the estimated parameters from the CDF curves and indicator measures of macroinvertebrate assemblages.

2. Methods

2.1 Study Design

2.1.1 Region Specifics

Sonde turbidity data, TSS samples, and stage data were collected from seven sites located in the Ridge and Valley ecoregion (ER67) and within the subregion Southern/Dolomite Valleys and Low Rolling Hills (ER67f). The Ridge and Valley ecoregion is a relatively low elevation region bordered by the Blue Ridge Mountains to the east and the Cumberland Plateau to the west. The ecoregion has abundant aquatic habitat diversity and supports a diverse fish fauna rivaled only by the Highland Rim ecoregion. ER67f is composed predominately of limestone and cherty dolomite. Typical landforms consist of rolling ridges and valleys. Land cover includes intensive agriculture, urban and industrial, or areas of thick forest. White oak forests, bottomland oak forests, and sycamore-ash-elm riparian forests are the common forest types (Griffith *et al*., 1997).

Data were also utilized from three additional sites with ongoing turbidity monitoring, hosted by the United States Geological Survey (USGS) and affiliates. These three sites are located in the Interior Plateau Ecoregion (ER71), a very diverse ecoregion extending from Southern Indiana and Ohio to the northern portion of Alabama. Landforms include open hills, irregular plains, and tablelands. ER71 possesses the greatest diversity in fish fauna in Tennessee. The Harpeth River site (USGS #03432100) is located in the Inner Nashville Basin (ER71i) subregion. ER71i has a unique vegetation mix of grassland/forest cedar glades with many endemic species and is located mostly on limestone beds. The other two sites, Copperas Creek (USGS #03433640) and Locke Branch Creek (USGS #3601630), are located in the subregion

referred to as Western Highland Rim (ER71f). The landscape is characterized by a dissected rolling terrain of open hills, and the geologic base consists of limestone, chert, and shale (Griffith *et al.*, 1997).

All 10 total site locations were located within the state of Tennessee (Figure 1). Tennessee typically receives over 127 centimeters of precipitation annually. Most of this rainfall is received during the months between November and May (TDEC, 2010).

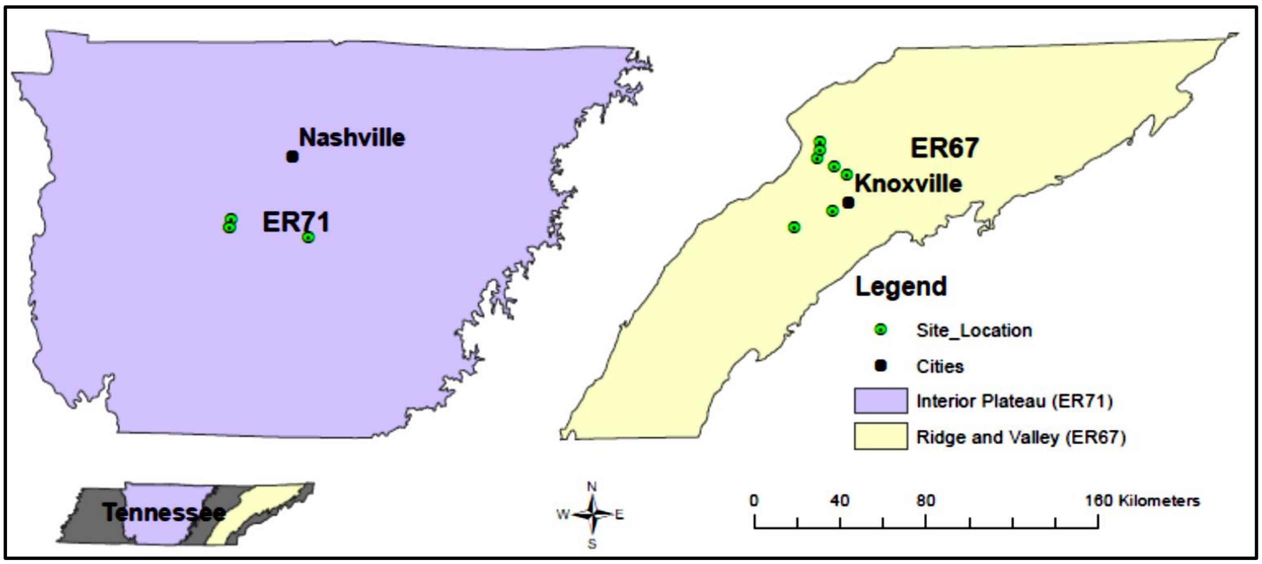

Figure 1. Map of site locations within Level III ecoregion and ecoregion location within Tennessee.

2.1.2 Site Selection

Site selection involved identifying TDEC biological monitoring sites with recent assessments of both macroinvertebrate assemblages and habitat quality that were either unimpaired or impaired due to siltation and/or habitat alteration, and not impacted by sewage point sources or regulated by upstream reservoirs (Table 1). For the ER67 sites, consideration

was also given to the requirements of sonde maintenance and access feasibility. USGS site locations are maintained by USGS and affiliates and the real-time data are made available to the public, an incredible resource for researchers now and in the future.

Table 1. Site Location Characteristics, TMI represents Tennessee Macroinvertebrate Index values, Habitat represents Habitat Index values

Site Name	Level IV EPA Ecoregion	Drainage Area (km)	Stream Order	TMI	Habitat	% Developed	Latitude	Longitude
Beaver Creek	67f	38.9	3	28[b]	118[b]	26	36° 4'48.73"N	83°55'22.27"W
Fourth Creek	67f	16.7	3	16[a]	114[a]	91	35°55'35.73"N	83°59'59.27"W
Buffalo Creek	67f	24.4	4	34[a]	151[a]	11	36°10'59.12"N	84° 3'42.22"W
Little Turkey Creek	67f	11.6	3	28[a]	154[a]	78	35°51'44.59"N	84°11'58.15"W
Hinds Creek	67f	103.3	4	30[a]	152[a]	9	36° 8'44.99"N	84° 4'32.98"W
BullRun Creek	67f	177.6	5	36[b]	115[b]	10	36° 6'51.44"N	83°59'19.77"W
Clear Creek	67f	7.2	3	34[a]	177[a]	5	36°12'49.45"N	84° 3'31.21"W
Harpeth River	71i	174.9	4	34[a]	119[a]	4	35°49'57.00"N	86°41'56.04"W
Copperas Creek	71f	4.2	2	40[c]	*	3	35°54'19.00"N	87° 5'56.00"W
Locke Branch Creek	71f	2.1	2	28[c]	*	1	35°52'19.00"N	87° 6'14.00"W

a. *Provided by Tennessee Department of Environmental Conservation*
b. *Provided by Knox County Stormwater*
c. *Provided by Tennessee Department of Transportation*
*. *No Data available*

2.1.3 Equipment

Two different sonde models were used to measure turbidity at ER67 site locations: a Global Water GL500-2-1 Data Logger with a WQ730 turbidity sensor, and a Yellow Springs Instruments (YSI) sonde, Model 6920 with a Model 6136 turbidity probe. Both devices recorded turbidity in 15-min increments during a period from December 20, 2011 through June 19, 2012. Calibration and cleaning were routine for both devices and based on recommendations by manufacturer. No gaps in data were experienced in excess of 120 minutes during the recording

period of the project. In situ sampling was also performed at each site using siphon samplers to collect passive samples during elevated stage events.

2.2 Data Analysis

2.2.1 Suspended Sediment vs. Turbidity

Turbidity is a surrogate measure for the concentration of suspended sediment within a water column. However, this relationship varies both spatially and temporally due to variations in particle size, particle composition, and water color (Gippel, 1995). As well, turbidity meters are prone to fouling by biofilm growth, siltation, and entangled debris (Minella *et al*., 2008; Sloto and Olson, 2011). Yet, even with these potential sources of error, precision of the turbidity meters typically outperforms that of alternative methods of estimation using streamflow-based approaches (Gippel, 1995; Jastram *et al*., 2009).

Spatial and temporal variance in estimated concentrations of suspended sediment from turbidity measurements make it necessary for the scientific community to determine where and when these relationships can be extrapolated for speed and convenience. Within the context of this study an attempt was made to explain relationships at the Level IV ecoregion scale and within the Level IV ecoregion scale relationships were developed by percentage of existing urban development within the contributing basin.

Field samples collected by in situ siphon samplers placed in a range from 10 inches to 20 inches, based on cross sectional characteristics, above base flow level and grab samples taken during elevated flow events were analyzed in the lab through standard TSS method (AWWA,

1999). Sites were then categorized by Level IV ecoregion and percentage of land developed within the contributing basin. If urban development within the basin exceeded 50%, the basin was considered to have a potentially altered sediment supply within the context of its ecoregion classification. A linear regression was then performed, where turbidity was represented as the dependent variable and concentration the independent variable, to establish the necessary transformation from turbidity to concentration of suspended sediments.

$$Log_{10}(Concentration) = aLog_{10}(Turbidity) + b \qquad (1)$$

For the USGS sites, relationships between turbidity and suspended sediment concentration were established in the same manner. It is important to note that USGS uses the SSC method to estimate the concentration of suspended sediments in streams. Research has shown variations in the reported concentrations of suspended sediments resulting from the use of SSC methods, as opposed to standard TSS methods; this variance is relative to particle size distribution (Clark and Siu, 2008). For the purpose of this research, variance between the two methods has been deemed a practical oversight due to the limited amount of turbidity data available for comparison. These observable differences do speak of the need for homogeneity between measurement methods among agencies.

2.2.2 CDF Curves

Preparation of Sonde Data

As with any turbidity investigation, there are associated characteristic issues with data collection and data analysis. Sondes measure the scattering of light in a water column of interest and, based on the degree of scatter, a value is assigned, typically in FNU or NTU. The degree of scatter is susceptible to errors because of drift and other calibration problems, and interference from debris, algae, bugs, bed load, the water surface, nearby objects, bubbles, and sunlight (Lewis *et al*., 2009). Scatter can also be altered by variations in water column chemical properties and by the size, composition, and distribution of particles (Gippel, 1995).

Preparation of the sonde data required an assessment of possible issues resulting from formerly mentioned events and where appropriate a correction was made. The method for applied corrections was derived from Lewis *et al*. (2009). Applied corrections were expected to be consistent with trends in correlated stage event, turbidity values, and suspended sediment samples.

Building the CDF Curves

A Visual Basic macro was used to tally the number and the duration of events that exceeded sediment flux intensities of interest. Events that exceeded cutoff values were then ranked by magnitude of duration. Nine cutoff values (thresholds) were arbitrarily selected as 50 mg/L, 100 mg/L, 150 mg/L, 250 mg/L, 350 mg/L, 450 mg/L, 550 mg/L, 650 mg/L, and 750 mg/L for the purpose of this study (Table 2). Arbitrary selection was deemed appropriate as it

has already been suggested that streams exceeded proposed thresholds of impairment by Newcombe (1997) outside of a lab setting in Tennessee (Diehl and Wolfe, 2010).

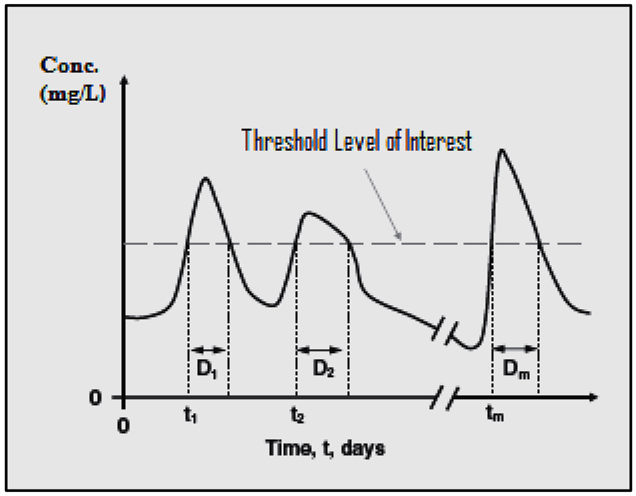

Figure 2. Example of threshold level of interest being crossed for a hypothetical plot of suspended sediment concentration vs. time. Modified from Schwartz et al., 2008.

Sediment flux pulses can be analyzed as a Poisson distribution. Episodic turbidity pulses during storm flows are stochastic in nature. This stochastic type of problem is supported by a substantial theoretical development history (Cramer and Leadbetter, 1967; Todorovic, 1978). Therefore, observation of both the frequency and duration of hydrologic events, above a given level of interest and for a given time period (Figure 2), provides the necessary data to characterize site-specific curves for concentration, duration, and frequency of events (Schwartz et al., 2008). Following these assumptions ranked sediment flux pulses can be characterized by the following equation:

$$N_t = N_{t,p} \cdot e^{\left(-\frac{d}{\mu}\right)} \qquad (2)$$

Where N_t is the expected number (frequency) of events exceeding a specified level of interest with a duration $\geq d$ and $N_{t,p}$ is total number of events in a given time period. The variable μ represents mean duration.

Table 2. Ranked duration of sediment pulse events for nine different concentrations of suspended sediment at Little Turkey Creek site.

	Duration of Events (days)								
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Ranked Events	≥ 50	≥ 100	≥ 150	≥ 250	≥ 350	≥ 450	≥ 550	≥ 650	≥ 750
1	0.6042	0.3646	0.2396	0.1563	0.1042	0.0729	0.0729	0.0625	0.0521
2	0.5313	0.2917	0.2188	0.1250	0.0938	0.0729	0.0625	0.0520	0.0417
3	0.5208	0.2813	0.2188	0.1250	0.0833	0.0625	0.0521	0.0417	0.0314
4	0.4479	0.2708	0.2083	0.1146	0.0833	0.0625	0.0520	0.0417	0.0312
5	0.4375	0.2604	0.1979	0.1146	0.0729	0.0521	0.0417	0.0313	0.0210
6	0.4271	0.2604	0.1875	0.1042	0.0626	0.0520	0.0313	0.0208	0.0104
7	0.4167	0.2604	0.1771	0.1041	0.0625	0.0418	0.0313	0.0208	
8	0.3854	0.2604	0.1667	0.0937	0.0624	0.0417	0.0209	0.0104	
9	0.3854	0.2500	0.1667	0.0833	0.0521	0.0416	0.0208		
10	0.3854	0.2188	0.1667	0.0833	0.0521	0.0416	0.0208		
11	0.3854	0.2083	0.1563	0.0833	0.0521	0.0312	0.0104		
12	0.3021	0.1979	0.1458	0.0729	0.0313	0.0104	0.0104		
13	0.3021	0.1771	0.1250	0.0729	0.0208	0.0104			
14	0.2917	0.1771	0.1146	0.0625	0.0208				
15	0.2604	0.1667	0.0938	0.0104	0.0104				
16	0.2604	0.1667	0.0833						
17	0.2500	0.1563	0.0729						
18	0.2500	0.1354	0.0521						
19	0.2500	0.1250	0.0521						
20	0.2396	0.1042	0.0313						
21	0.2188	0.1042	0.0312						
22	0.2188	0.0938	0.0208						
23	0.2187	0.0938	0.0104						
24	0.2187	0.0833	0.0104						
25	0.2083	0.0729	0.0104						
26	0.1563	0.0313	0.0104						
27	0.1562	0.0312	0.0104						
28	0.1458	0.0208							
29	0.1354	0.0104							
30	0.1042								
31	0.0937								
32	0.0208								
33	0.0208								
34	0.0104								
35	0.0104								
36	0.0104								
37	0.0104								

2.2.3 Drainage Area and Land-Use Characteristics

Drainage area was calculated through available tools on USGS Streamstats (http://streamstats.usgs.gov/). USGS Streamstats was also used to produce a shape file for each specific contributing drainage basin. The basin shape file from USGS Streamstats was then used in combination with the National Land Cover Database (NLCD) 2006 map produced from USGS National Map Viewer (http://viewer.nationalmap.gov/viewer/) managed by USGS National Geospatial Program (NGP) to determine the percentage of land developed within the watershed basin. The following NLCD land definitions: developed (open space), developed (low intensity), developed (medium intensity), and developed (high intensity) were all included in the cumulative estimate of developed area.

2.2.4 TMI Scores and Habitat Assessments

Tennessee, like most U.S. states, relies on biotic indicators to determine whether a stream is impaired or not. The level of impairment is based on benthic macroinvertebrate samples (TDEC, 2011). The Tennessee Macroinvertebrate Index (TMI) utilizes semi-quantitative single habitat surveys (SQKICK or SQBANK) to determine biocriteria by ecoregion. The SQKICK method is a qualitative measure based on quantitative analysis of community structure at sampling sites, giving consideration to both tolerant and intolerant species. The quantitative analysis of taxa richness (TR), Ephemeroptera Plecoptera Trichoptera richness (EPT), EPT abundance excluding Cheumatopsyche (%EPT-Cheum), percent Oligochaetes and Chironomids (%OC), North Carolina Biotic Index (NCBI), percent contribution of organisms that build fixed retreats or have adaptations to attach to surfaces in flowing waters (% Clingers), and % TN

nutrient tolerant organisms (%TNutol) leads to a final semi-qualitative numerical summation referred to as the TMI index score. Biometrics expected to decrease with increased pollution include: TR, EPT, % EPT-Cheum, and %Clingers. Biometrics expected to increase with increased pollution include: %OC, NCBI and %TNUTOL (TDEC, 2011). A score of 32 or higher is considered to pass biocriteria guidelines in all ecoregions except ER73 (TDEC, 2011). Only sampling efforts that followed the TDEC SQKICK or Modified SQKICK methods were used for direct comparison to relevant biocriteria guidelines for the purpose of this research.

Habitat assessments were conducted by TDEC personnel in conjunction with SQKICK sampling efforts at all but two sites, Copperas and Locke Branch. Habitat assessments are a modified version of the Rapid Bioassessment Protocols for Use in Wadeable Streams and Rivers provided in Barbour et al. (1999) (TDEC, 2011). Scoring is based on a qualitative analysis of the following characteristics: epifaunal substrate, embeddedness of riffles, velocity/depth regime, sediment deposition, channel flow status, channel alterations, frequency of riffles/bends/re-oxygenation zones, bank stability, bank vegetative protection, and riparian vegetative zone width. A site is considered to be habitat impaired if scoring is determined to be less than 75% of established qualitative reference level for the relevant ecoregion.

3. Results

3.1 Regression of Concentration of Suspended Sediment vs. Turbidity

Regression models for suspended sediment concentrations as a function of turbidity show a positive, significant correlation ($p<0.001$) (Table 3). Models explained a range from 92% to 98% of the variance in concentrations of given turbidity measurements for relevant Level IV

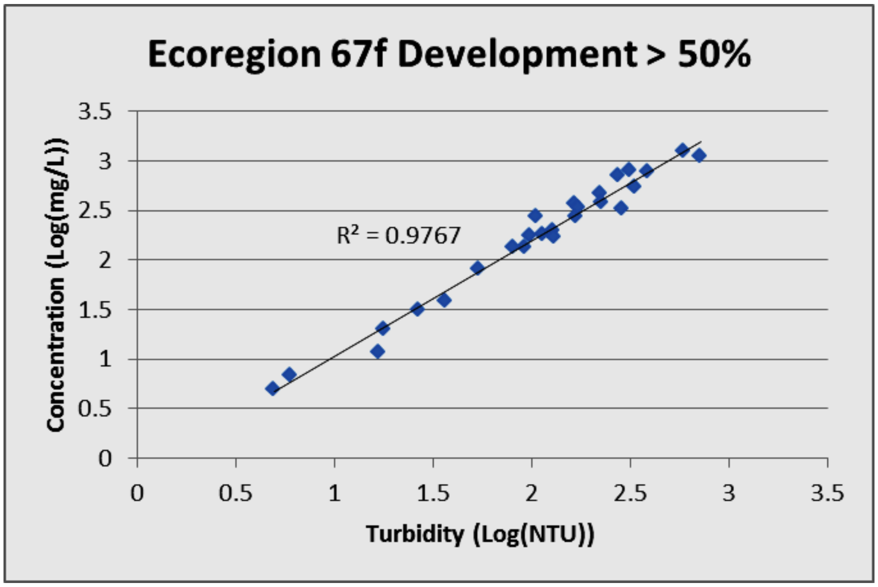

Figure 3. The linear relationship between turbidity and suspended sediment concentration for ER67f basins with development in excess of 50% of the watershed.

Table 3. Table with regression statistics and coefficients for turbidity vs. concentration of suspended sediments.

Turbidity vs. Concentration of Suspended Sediment (Regression Statistics)				
ER	67f	67f	71f	71i
% Developed	≥ 50	≤ 50	≤ 50	≤ 50
R^2	0.98	0.92	0.94	0.97
p	<0.001	<0.001	<0.001	<0.001
n	26	42	35	38
a	1.17	0.89	1.13	1.14
b	-0.15	0.29	-0.01	-0.09

ecoregion and % developed. Figure 3 displays data for ER67f where urban development exceeded 50% across contributing drainage basins.

3.2 Regression of CDF Curves

Analysis of the regressions performed to produce CDF curves confirmed the ability to analyze sediment flux pulses in the manner of a Poisson distribution. There was the possibility to produce 90 different CDF curves based on the 10 site locations and nine cut-off threshold levels. However, regression was only performed for sites with at least four observations that met or exceeded a given turbidity threshold.   However, if a site did not experience at least four observations where it met or exceeded a specific cut-off threshold level, regression was not performed. This resulted in 66 different CDF curves being constructed from the 90 different sample sets. For the 66 curves that were built, 77% were significant at (alpha=0.05) $p<0.001$, and all but one regression was significant at $p<0.05$. The one CDF curve with a statistical significance of $p>0.05$ was from the Clear Creek data set and occurred at the 50 mg/L concentration level ($R^2=0.78$, $p<0.114$). This CDF curve can be seen below in Figure 6.

The mean R^2 value for the 66 curves was 0.91. The maximum R^2 value was 0.99 and the minimum R^2 value was 0.76 (Figures 4 and 5). It is important to note that deviations from the observed data did occur both at the high frequency range and the maximum duration range at some site locations (Figure 5 and 11). These deviations are typically consistent for all threshold levels if observed for a specific site location. As well, it is possible for frequency at higher magnitudes to occur in excess of those at lower magnitudes. Figures 6 and 7 show CDF curves in comparison format and separated based on drainage basin scale. Table 4 shows R^2 values and p values for all CDF curves.

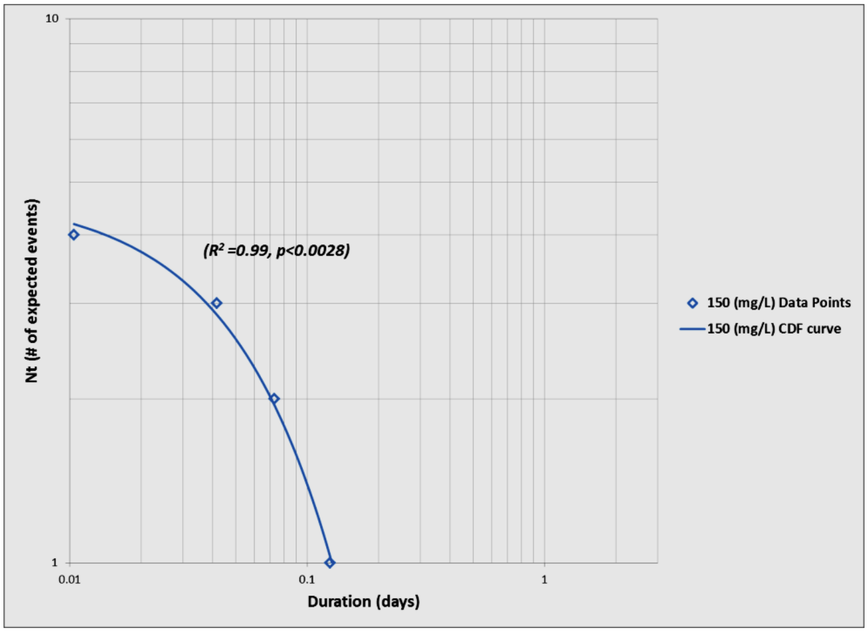

Figure 4. A 150 mg/L CDF curve from the Locke Branch site representing the greatest explanation of variance in frequency of events (R^2=0.99). Points represent observed events for a given duration ≥ to a concentration of 150 mg/L at the Locke Branch site.

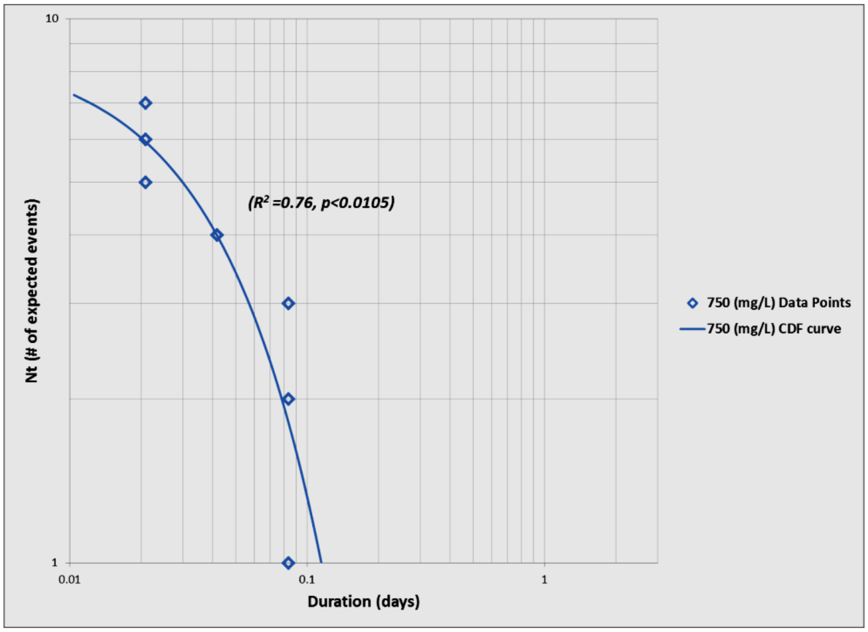

Figure 5. A 750 mg/L CDF curve from the Fourth Creek site representing the weakest explanation of variance in frequency of events (R^2=0.76). Points represent observed events for a given duration ≥ to a concentration of 750 mg/L at the Fourth Creek site.

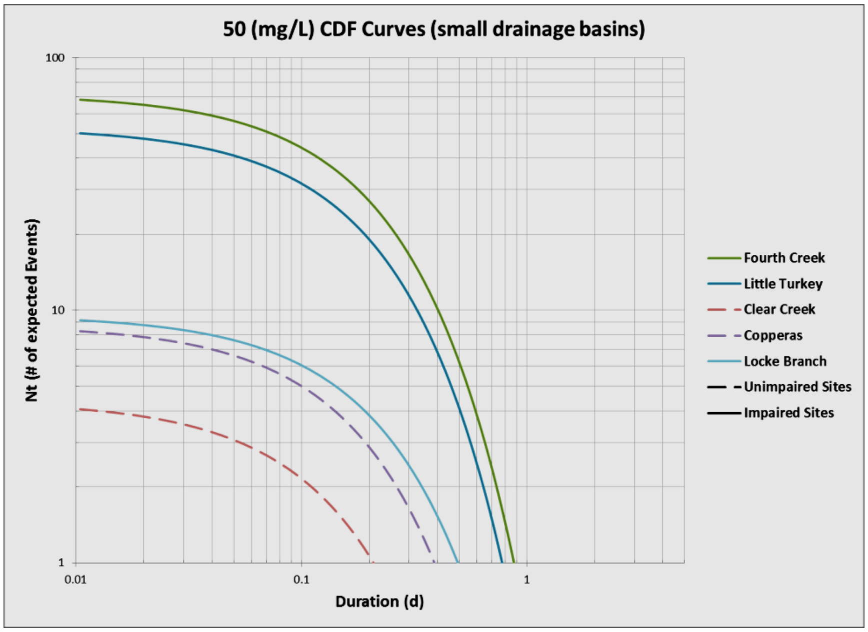

Figure 6. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 50 mg/L concentration. Sites that are represented by dashed lines are unimpaired and those represented by solid lines are considered impaired.

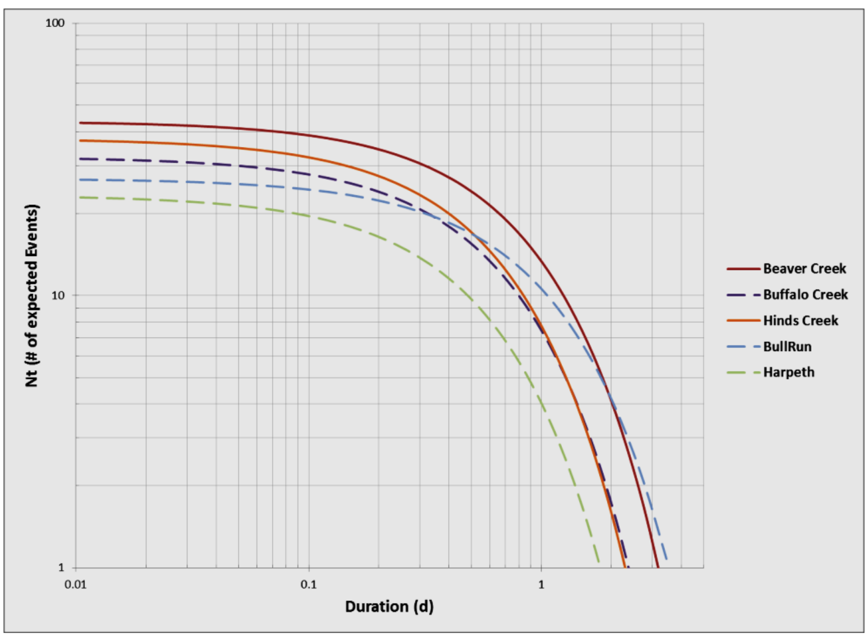

Figure 7. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 50 mg/L concentration. Sites that are represented by dashed lines are unimpaired and those represented by solid lines are considered impaired.

Table 4. Regression output statistics for all CDF curves.

CDF Curve Regression Statistics										
		(mg/L) ≥ 50	(mg/L) ≥ 100	(mg/L) ≥ 150	(mg/L) ≥ 250	(mg/L) ≥ 350	(mg/L) ≥ 450	(mg/L) ≥ 550	(mg/L) ≥ 650	(mg/L) ≥ 750
Beaver Creek	R^2	0.94	0.85	0.88	0.93	0.88	0.89	0.95		
	p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0042		
Fourth Creek	R^2	0.96	0.90	0.97	0.98	0.97	0.92	0.95	0.93	0.76
	p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0105
Buffalo Creek	R^2	0.96	0.77	0.79	0.90	0.84	0.84	0.91	0.89	0.92
	p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0005	0.0025
Little Turkey Creek	R^2	0.89	0.85	0.83	0.78	0.86	0.79	0.95	0.93	0.92
	p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001	0.0024
Hinds Creek	R^2	0.91	0.87	0.91	0.95	0.95	0.98	0.95	0.96	0.97
	p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0198	0.0026
Bullrun Creek	R^2	0.89	0.92	0.88	0.88	0.90	0.87			0.92
	p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0022			0.0095
Clear Creek	R^2	0.78			0.96					
	p	0.1144			0.0210					
Harpeth River	R^2	0.92	0.95	0.96	0.98	0.91	0.89	0.94		
	p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0056		
Copperas Creek	R^2	0.86	0.92	0.96	0.96					
	p	0.0000	0.0025	0.0001	0.0217					
Locke Branch Creek	R^2	0.78	0.97	0.99						
	p	0.0000	0.0138	0.0028						

Blank cells indicate ≤3 observations and regression was not performed.

3.3 Bivariate Regression (μ, $N_{t,p}$, D_{max}, and $N_{t,o}$)

Bivariate regressions were performed at each threshold level of suspended sediment concentration utilizing several possible response variables. The possible response variables included TMI index values, Habitat index values, and each of the sub-categories deemed relevant within TMI and Habitat indexes. The independent variables representing sediment transport characteristics included mean duration (μ), predicted number of total events ($N_{t,p}$), maximum observed duration (D_{max}), and the observed number of total events ($N_{t,o}$). Relationships were deemed significant only if tests resulted in $p<0.05$.

The variables $N_{t,p}$ and μ are estimated parameters from the CDF curve regression models. It was deemed a conservative measure not to run CDF regression models for sites where less than four observations occurred at a specific threshold concentration of interest. This resulted in several scenarios where an observation of both duration and frequency was recorded in the field, but no CDF curve parameters were estimated for the given threshold level. When this situation occurred, the specific site was left out of any bivariate regression models that required those parameters. However, if an observation was not made in the field, then a value of zero was entered as the estimated parameter value for $N_{t,p}$ and μ. This method was used for all bivariate regressions that employed either $N_{t,p}$ or μ as a variable (Table 5 and 9).

Regression using Habitat index values and the subcategories within the Habitat index considered to be related to siltation (embeddedness of riffles, sediment deposition, and epifaunal substrate) as the response variable produced no significant results. Regression using the subcategories of TMI index values, considered to be a measure of tolerant biota (%OC, NCBI, and %TNUTOL), as response values and the variables μ, $N_{t,p}$, and D_{max} as independent variables resulted in no significant relationships observed across multiple levels of concentration (Table 5

and 9). However, six statistically significant relationships were identified between $N_{t,o}$ and NCBI that indicated an increasing NCBI value with increasing frequency of observations.

TMI and several subcategories considered representations of intolerant species produced several statistically significant relationships with μ, $N_{t,p}$, and $N_{t,o}$ (Table 5 and 9). Of these TMI, EPT, and %Clingers produced the greatest number. The variables %EPT-Cheum and TR, however, produced no significant results. EPT had the greatest number of significant relationships and included the only multiple-threshold observation of a duration parameter having impact on biota (Table 9). However, this relationship represented an increasing relationship between μ and EPT, a likely byproduct of covariance with basin scale.

When $N_{t,p}$ was used as the independent variable and TMI, EPT, or %Clingers as the response variable, significant results were observed at six different levels of concentration (Table 5). These six concentrations included 50 mg/L, 100 mg/L, 250 mg/L, 350 mg/L, 450 mg/L, and 550 mg/L. The R^2 values associated with these results explained a range of 0.47% to 0.80% of the variance (Table 5). The median R^2 value was 0.63 and the mean 0.64 for these results (Table 5). Bivariate regressions using $N_{t,o}$ as the independent variable and TMI, EPT, or %Clingers as the response variable produced similar outcomes. It is important to note that several additional results would have become significant at an alpha value of 0.10. The weakest and strongest statistically significant relationships at a 95% confidence interval for this series of bivariate regressions can be seen in Figure 8 and 9, respectively.

Table 5. *Bivariate regression results using different measures of macroinvertebrate assemblages as response variable and $N_{t,p}$ the independent variable.*

Macroinvertebrate Assemblage Metrics vs. $N_{t,p}$ Regression Statistics										
		(mg/L) ≥ 50	(mg/L) ≥ 100	(mg/L) ≥ 150	(mg/L) ≥ 250	(mg/L) ≥ 350	(mg/L) ≥ 450	(mg/L) ≥ 550	(mg/L) ≥ 650	(mg/L) ≥ 750
TMI	R^2	0.60	0.47	0.41	0.61	0.58	0.39	0.24	0.10	0.22
	p	0.0080*	0.0420*	0.0644	0.0136*	0.0456*	0.1312	0.2621	0.5974	0.3524
	n	10	9	9	9	7	7	7	5	6
TR	R^2	0.13	0.08	0.04	0.13	0.27	0.10	0.07	0.03	0.01
	p	0.3749	0.5435	0.6646	0.3841	0.2344	0.4908	0.5667	0.7653	0.8597
	n	8	7	7	8	7	7	7	5	6
EPT	R^2	0.74	0.51	0.24	0.67	0.80	0.74	0.65	0.04	0.52
	p	0.0058*	0.0732	0.2618	0.0126*	0.0062*	0.0131*	0.0278*	0.2654	0.1041
	n	8	7	7	8	7	7	7	5	6
%EPT-Cheum	R^2	0.00	0.05	0.14	0.05	0.01	0.01	0.18	0.07	0.06
	p	0.8692	0.6396	0.4173	0.5954	0.8345	0.8047	0.3490	0.6607	0.6475
	n	8	7	7	8	7	7	7	5	6
%OC	R^2	0.10	0.00	0.02	0.00	0.03	0.01	0.01	0.07	0.10
	p	0.4424	0.9213	0.7890	0.9926	0.6882	0.8654	0.8693	0.6608	0.5395
	n	8	7	7	8	7	7	7	5	6
NCBI	R^2	0.76	0.43	0.47	0.42	0.29	0.20	0.33	0.34	0.50
	p	0.0051*	0.1075	0.0894	0.0835	0.2113	0.3203	0.1738	0.3031	0.1140
	n	8	7	7	8	7	7	7	5	6
%Clingers	R^2	0.66	0.60	0.45	0.57	0.35	0.31	0.43	0.50	0.61
	p	0.0138*	0.0419*	0.1011	0.0306*	0.1611	0.1941	0.1075	0.1796	0.0678
	n	8	7	7	8	7	7	7	5	6
%TNutol	R^2	0.02	0.02	0.07	0.00	0.14	0.19	0.00	0.01	0.05
	p	0.7551	0.2676	0.5639	0.8866	0.4114	0.3288	0.9484	0.8992	0.6691
	n	8	7	7	8	7	7	7	5	6

-Variations in n are due to unavailable data for subcategory TMI values or $N_{t,p}$
** Represents significance at alpha=0.05*

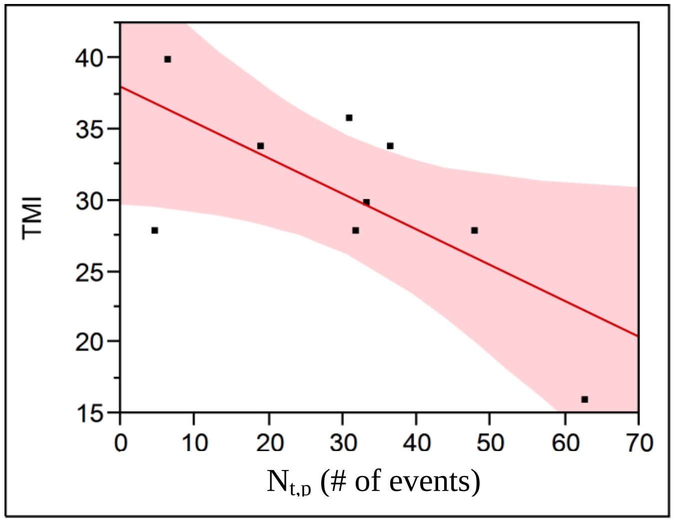

Figure 8. Bivariate regression at a concentration of 100 mg/L with an R^2=0.47 and p<0.042. The x-axis variable is the predicted total number of events and the y-axis is the associated TMI value for relevant study site.

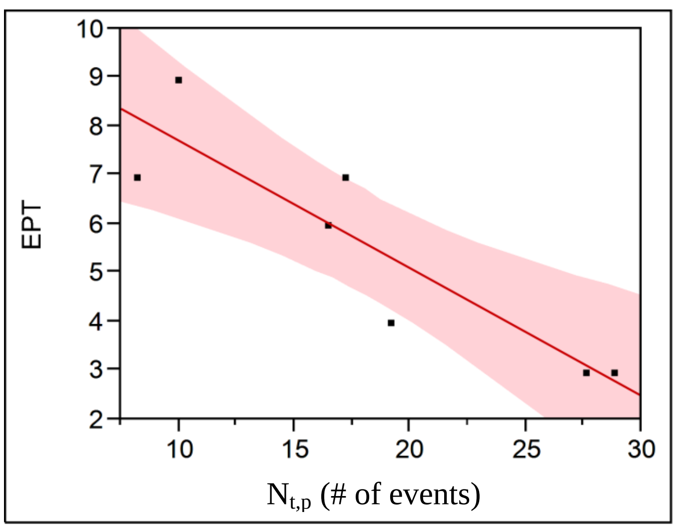

Figure 9. Bivariate regression at a concentration of 350 mg/L with an R^2= 0.80 and p<0.006. The x-axis variable is the predicted total number of events and the y-axis is the associated EPT value for relevant study site.

As a precaution, statistics were reprocessed with consideration for influential observations for the bivariate regressions where $N_{t,p}$ was the independent variable and the response variable was TMI, EPT, or %Clingers. Removal of an observation was governed by a Cook's D value greater than one. The Fourth Creek site produced the greatest number of influential observations among bivariate regressions.

The practice of removing influential observations reduced the number of regressions with $p<0.05$. The most notable reduction occurred at 150 mg/L, where there were no longer any observed statistically significant results for any response variable. However, significant results were still observed for at least one response variable at 50 mg/L, 100 mg/L, 250 mg/L, 350 mg/L, 450 mg/L, and 550 mg/L. EPT again had the greatest number of significant results, with five of nine concentrations producing significant results. The range of R^2 values for all significant regressions that were reassessed was 0.54 to 0.8, with a median value of 0.66 and a mean of 0.66. It is important to note that several additional results would have become significant at an alpha value of 0.10.

3.4 Habitat Impacts on Community Structure

In an attempt to better understand how habitat condition might influence intolerant taxa community structure, bivariate regressions were performed for the response variables TMI, EPT, % EPT-Cheum, and the independent variable Habitat index scores. The regressions were assessed by concentration level. Results from these tests indicated no significant relationships existed in the data sets, with $p>0.10$ for all regressions.

3.5 Regression of Basin Scales

Bivariate Regressions were also performed to determine the effect that drainage area has on μ (Table 6). There were six significant results across nine concentration threshold levels. Significant results were determined by $p<0.05$. Of these six regressions, the mean R^2 value was 0.70, median 0.73, max 0.82, and min 0.50. All relationships indicated a positive correlation between drainage area and μ. Figure 10 is a CDF curve representation of the influence drainage basin appears to have. Table 1 can be referenced for drainage area size.

3.6 Welch's Test for $N_{t,p}$

A Welch's test (unequal variance t-test) was performed to determine whether the estimated frequency of turbid events for impaired TMI sites significantly varied from the estimated frequency of turbid events at impaired sites. Results indicated that the frequency of turbid events differed significantly between TMI impaired and unimpaired sites, ($F(1,67.74)=10.95$, $p=0.0016$). The estimated mean $N_{t,p}$, based on a 95% confidence interval, for impaired sites was 25.53 ±2.44, and the estimated mean $N_{t,p}$ for unimpaired sites was 14.06 ±2.62.

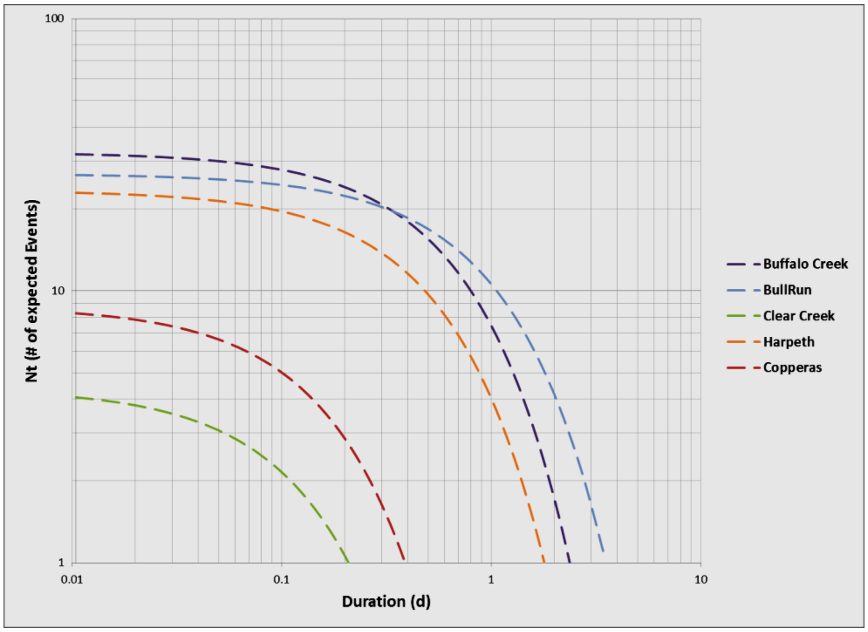

Figure 10. A CDF comparison of all Unimpaired TMI sites at a 50 mg/L concentration.

Table 6. Table provides regression statistics for mean duration (μ) as the dependent variable and drainage area as the independent variable.

μ vs. Drainage Area (Regression Statistics)									
	(mg/L) ≥ 50	(mg/L) ≥ 100	(mg/L) ≥ 150	(mg/L) ≥ 250	(mg/L) ≥ 350	(mg/L) ≥ 450	(mg/L) ≥ 550	(mg/L) ≥ 650	(mg/L) ≥ 750
R^2	0.50	0.58	0.73	0.73	0.82	0.44	0.53	0.58	0.82
p	0.0227*	0.0170*	0.0034*	0.0032*	0.0051*	0.1044	0.0627	0.1356	0.0129*
n	10	9	9	9	7	7	7	5	6

**. Represents statistical significant at an alpha=0.05*
-*Variations in sample sizes is the result of available estimated μ value for the relevant threshold of interest.*

4. Discussion

4.1 Characteristic Response in CDF Curve format

Concentration, duration, and frequency characterize episodic fine sediment transport during precipitation runoff events. These physical descriptions are necessary to explain turbid episodic behavior because turbid pulses may pass through the stream in a single pulse, in a series of pulses, or in a fairly constant flux; each scenario having differing effects on the ecology (Bilotta et. al., 2012). The time-dependent response to precipitation events will reflect the land-use and channel conditions as well as the spatial and scale properties of the watershed basin. By nature, precipitation events are random and unevenly distributed, making it difficult to compare observed data across sites without potential bias suggesting a need for a systematic approach to characterize basin specific CDF behavior and allow comparisons between basin CDF and biological community structures within those basins.

The CDF curve method provides a statistical approximation of the frequency of various durations of episodic events within a common time scale, identifying a functional relationship for this pulse behavior. This relationship is important when considering biotic response to turbid events. Ideally, by characterizing the pulses of turbid events, the CDF curve method captures effective doses, representing a quantifiable stressor on biota, with one pulse representing one completed dose. These pulses/doses are representations of a watershed response to a hydrological event and characterize sediment flux for that event.

Based on this research the CDF curve methodology appears to sufficiently capture effective dose behavior providing a means to analyze characteristic dose behavior and in appropriate situations compare across spatial, temporal, and basin scales. These qualities, CDF curves appeared to be the best tool to capture the diversity in site specific sediment flux

behavior, putting it in a format for supplementary comparisons. However, it is important to note that some CDF curves described the variance in frequency with respect to duration with mediocrity. For example, at the Beaver Creek site, the 50 mg/L curve estimated $N_{t,p}$ to be 43 events as compared to the observed 61 events. In contrast, the deviation of the 100 mg/L curves from the observed frequency was minimal. The estimated frequency of events was 31 and the actual observed number of events was 33 (Figure 11).

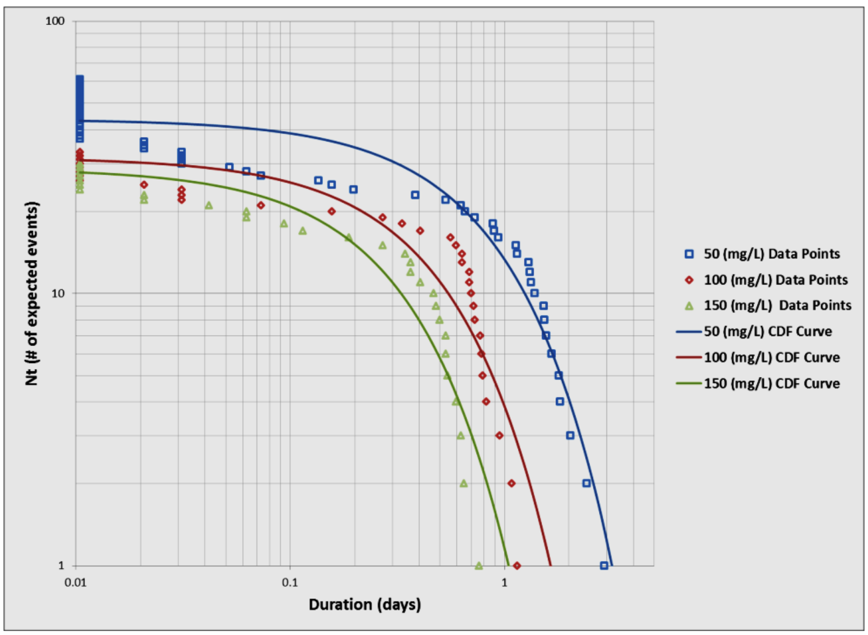

Figure 11. A CDF curve comparison of 50 mg/L, 100 mg/L, and 150 mg/L for the Beaver Creek site. The data points represented in the graph are the ranked durations of observed suspended sediment spikes ≥ relevant threshold concentrations.

These deviations were not uncommon at 50 mg/L. They were likely due to the longer durations that occurred at 50 mg/L after the CDF curve had recently reached inflection point. It is not uncommon for turbidity readings to bounce across a concentration of interest before finally passing it on their way back to base levels. This is a by-product of the resolution of the data. Increasing the turbidity measurement of your probe to 30-minute samples would likely avoid this

issue while still capturing an accurate measure of the rate of change of turbidity over time. These deviations have been observed in other research (Schwartz et al., 2008).

4.2 Duration of Turbid Events

The positive correlations identified through bivariate regression between drainage area and μ, suggest duration of turbid events is significantly influenced by basin characteristics that determine flow patterns as a function of time. These results, in conjunction with the inability to identify significant relationships between biotic response and an increasing μ, suggest that macroinvertebrate response to duration of sediment flux vary based on spatial location within a watershed. Bullrun Creek, the largest of the watersheds in the study, saw some of the longest durations per turbid event. Yet, the creek supports what, based on TMI scores, is considered to be a healthy community of macroinvertebrates, serving as possible evidence that the potential vulnerability of aquatic biota to sediment pulses may vary based on watershed position and relative geomorphic processes (River Continuum Concept) (Vannote et al., 1980).

Varying community response based on spatial location within watershed indicates the need to develop reference thresholds ranked by basin parameters that dominate flow patterns. This may be a difficult task for agencies because reference site opportunities diminish as basin scales increase.

Theoretically, this variation in community response relative to spatial location may suggest that maximum durations of individual, high concentration, turbid events may be closely linked to standard disturbance regimes. Lotic systems are exposed to a natural regime of disturbances, and biota evolved life history characteristics that favor flexibility and adaptability (Yount and Niemi, 1990). This suggests that a sustained turbid event, in and of itself, may be

inducing a standard life history response that encompasses recolonization capabilities and patch dynamics of the contributing watershed. Patch dynamics and recolonization rates are both relative to stream position and suggest vulnerability based on watershed position.

4.3 Frequency of Turbid Events

Data suggest that an increased frequency of turbid events likely leads to a change in community structure and a potential decrease of intolerant macroinvertebrate taxa. A t-test of the central tendencies for $N_{t,p}$ at impaired and unimpaired sites, indicated that sediment flux events are more frequent at impaired sites. A series of bivariate regressions using response values representing community structure also indicated that an increasing number of sediment pulses, of varying concentrations, may lead to both a decrease in intolerant taxa and a change in macroinvertebrate community assemblages.

These statistics offer a convincing explanation of relationship, but concerns do exist about repeatability over larger scales due to the limited number of study sites, possibilities of unknown stressor gradients superimposed on the suspended sediment stressor gradient, and necessary extrapolations of data sets. Yet, when considered in conjunction with other research that has indicated frequency of suspended sediment pulse events as a likely antagonist to biotic communities (Schwartz *et al*., 2011; Berry *et al*., 2003), it seems plausible that an effective dose parameter may be simple, but sufficient to characterize the relationship between suspended sediment pulse events and macroinvertebrate response. If observed from the perspective of effective dose (cumulative doses) as opposed to an individual dose response it is possible consider basin-specific sediment pulse behavior as a press and pulse disturbance regime. Viewing basin-specific sediment pulse behavior as a press and pulse disturbance regime may

offer a greater understanding of recovery times and inherent effects that may occur due to sediment flux (Yount and Niemi, 1990).

Under these assumptions, maximum-duration sediment pulse events may possibly be within the confines of standard flood disturbances, with no discernible difference in response between these low frequency random events. A natural disturbance regime under natural probabilities of occurrence fosters a diverse and healthy community structure (Ward and Stanford, 1983). However, when shifts in the frequency of suspended sediment pulse events occur, response to the variation in disturbance regime results in a ramp response and a shift in community structure. If, in fact, this is the case, $N_{t,p}$ or a predicted frequency gradient may be a reasonable metric for determining the ill effects of turbid pulses on macroinvertebrates. This measure of effective dose also appears to be comparable across basin scales at certain concentrations and to a degree, an almost necessary convenience as agencies would likely face huge difficulty in finding potential reference CDF sites representative of larger basins. However, extrapolating this metric across broad biogeographical scales would not be prudent because shifts in natural disturbance regimes occur.

5. Conclusion

Results of this research suggest that thresholds for “clean” fine sediment are related to alterations in site-specific natural disturbance regimes. These natural disturbance regimes can be characterized, through the use of CDF methodology, sufficiently for multiple geomorphological conditions and scales, representing a quantifiable stressor on biota. Characterizing natural

disturbance regimes is a necessary step to gaining a complete understanding of the ecological resilience of communities (Ward and Stanford, 1983).

Research also suggested that the duration of episodic turbid events is significantly influenced by basin characteristics that determine flow patterns as a function of time, offering evidence that potential vulnerability of aquatic biota to suspended sediment pulses may be unique based on watershed position and relative geomorphic processes. Further, an understanding of frequency gradients may offer agencies the most viable option for predicting macroinvertabrate response to siltation due to the parameters ability distinguish shifts in natural disturbance regimes.

Future research should entail a much larger study sample group, confirming repeatability of results and enhancing statistical power. As the number of CDF datasets increase, characterization of probability distributions should improve. This would, most likely, lead to a greater understanding of natural “clean” suspended sediment disturbance regimes and the alterations to those regimes that will result in a negative biotic response. This functional relationship must be understood in order to set TMDLs that target a restoration of designated use.

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Appendices

Appendix A: CDF Curve Comparisons by Basin Size

Sites that are represented by dashed lines are unimpaired and those represented by solid lines are considered impaired.

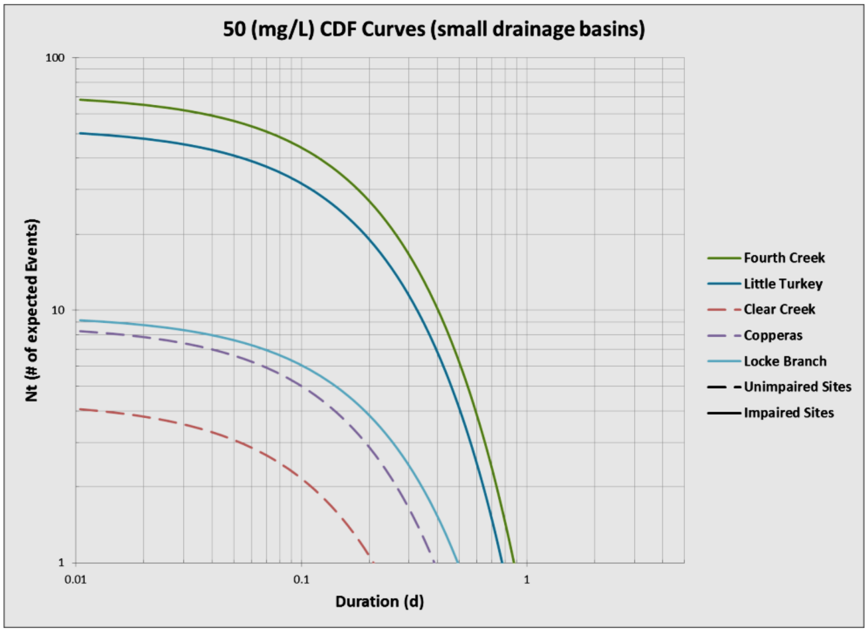

Figure 12. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 50 mg/L concentration.

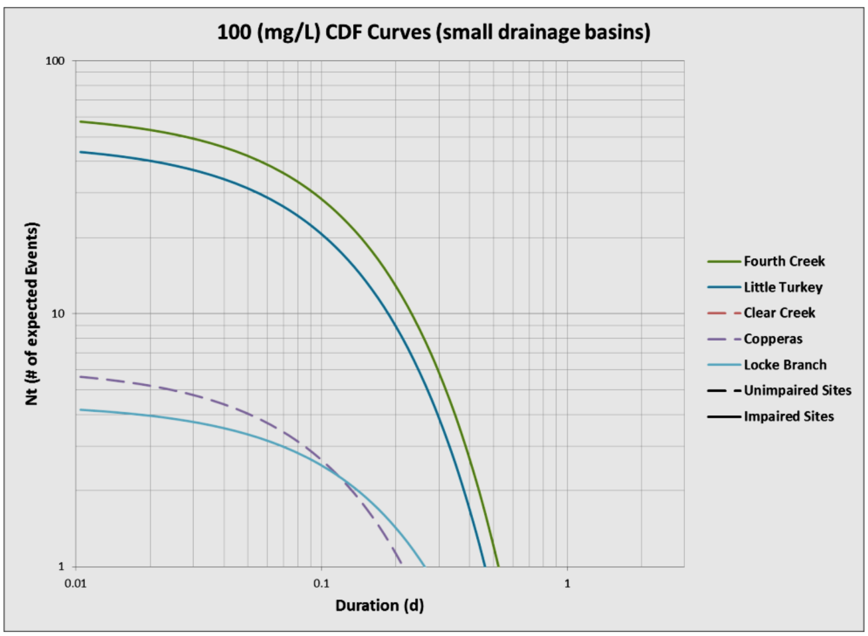

Figure 13. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 100 mg/L concentration.

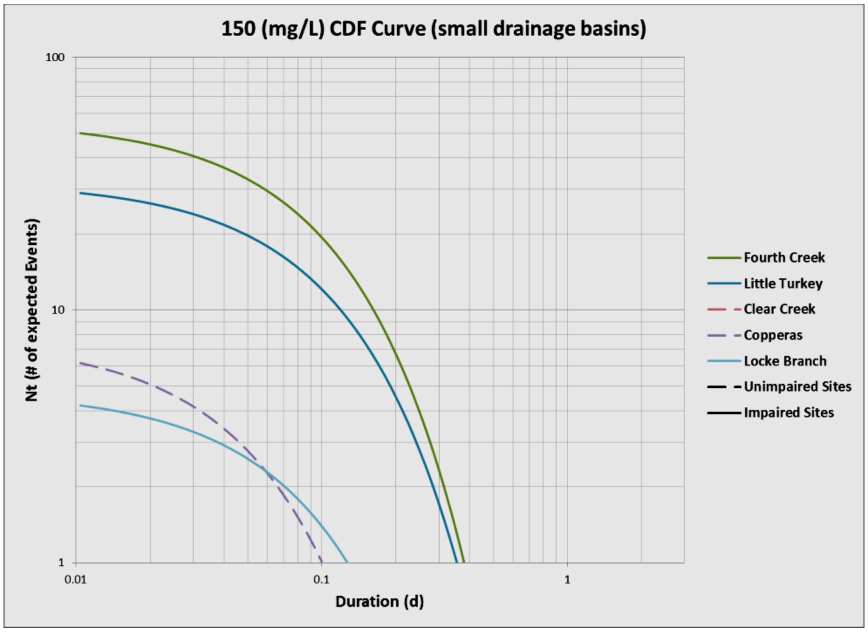

Figure 14. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 150 mg/L concentration.

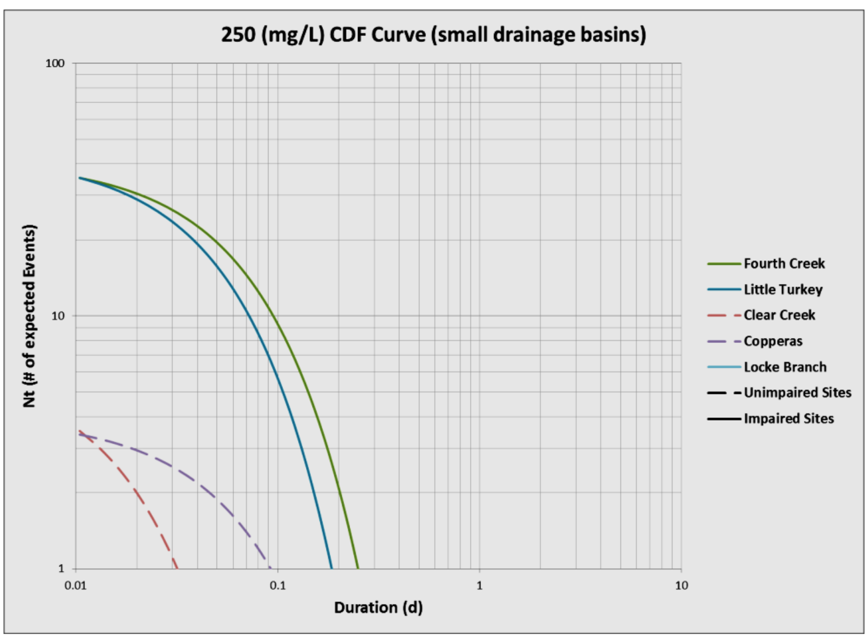

Figure 15. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 250 mg/L concentration.

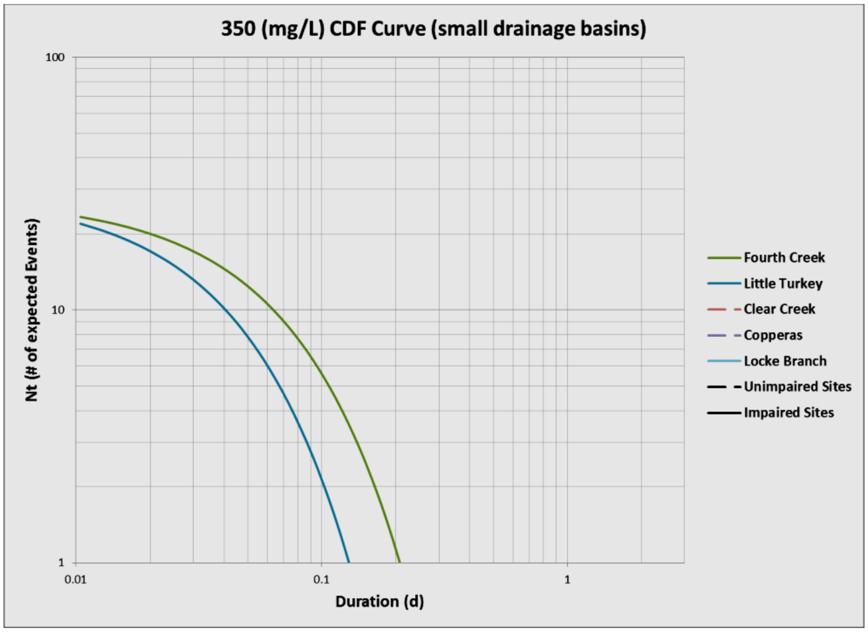

Figure 16. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 350 mg/L concentration.

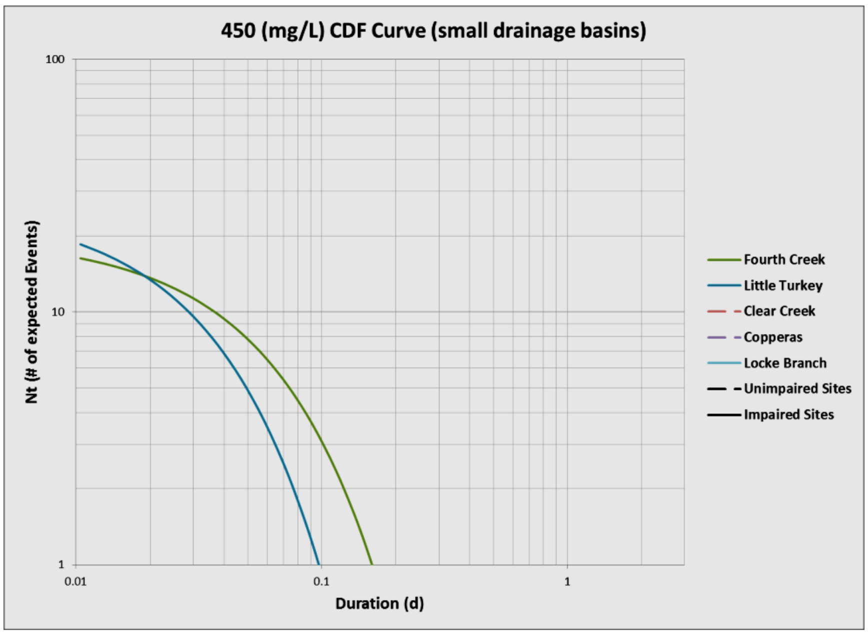

Figure 17. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 450 mg/L concentration.

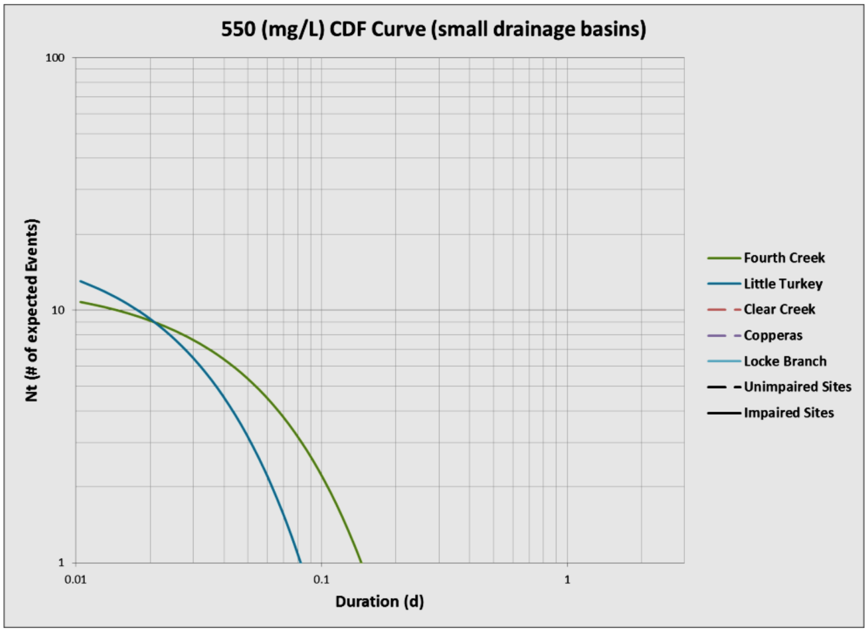

Figure 18. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 550 mg/L concentration.

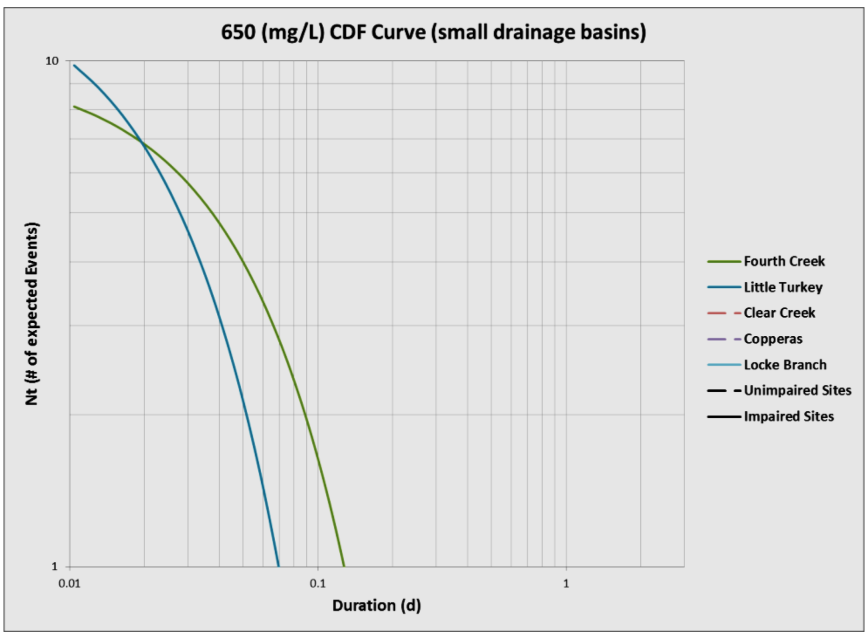

Figure 19. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 650 mg/L concentration.

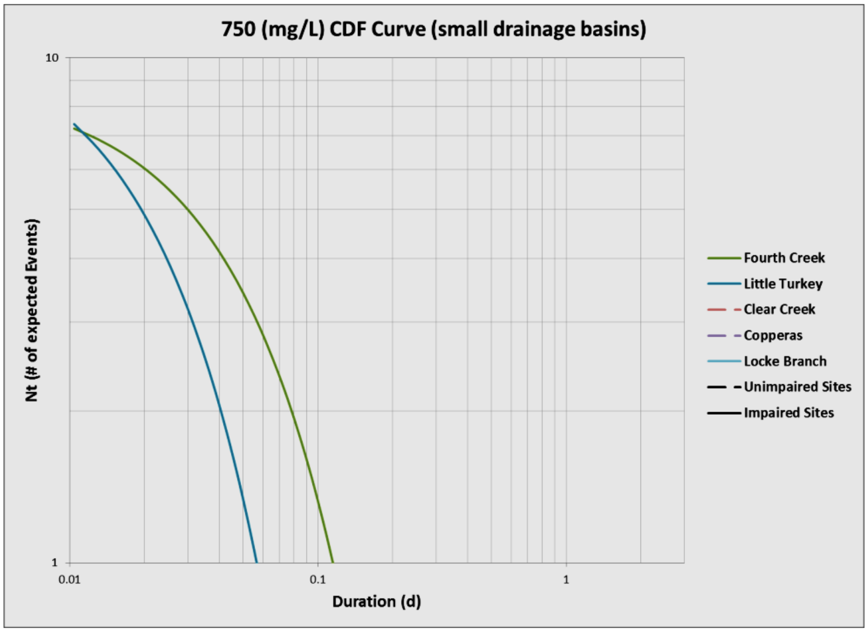

Figure 20. A CDF comparison of lower 50 percentile based on drainage basin scale (<17 km^2) for a 750 mg/L concentration.

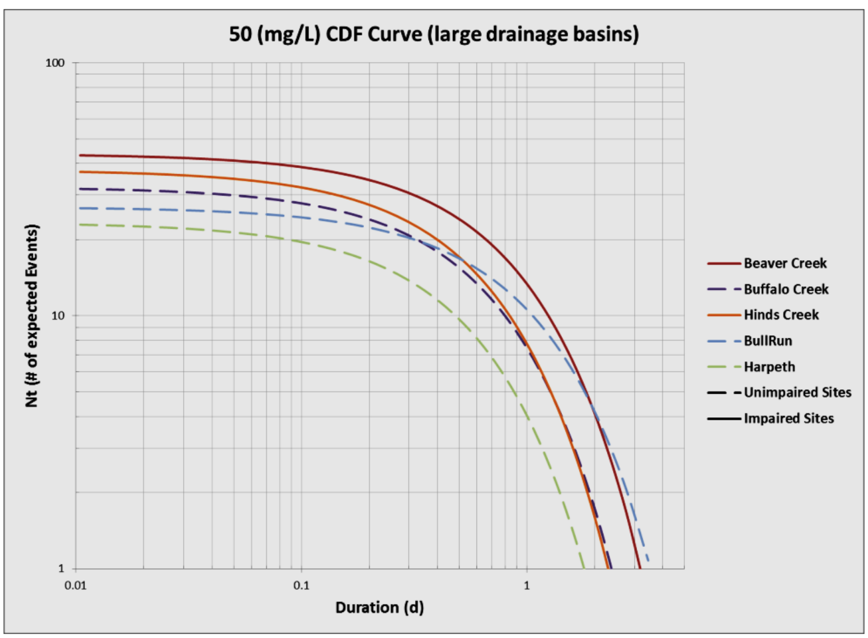

Figure 21. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 50 mg/L concentration.

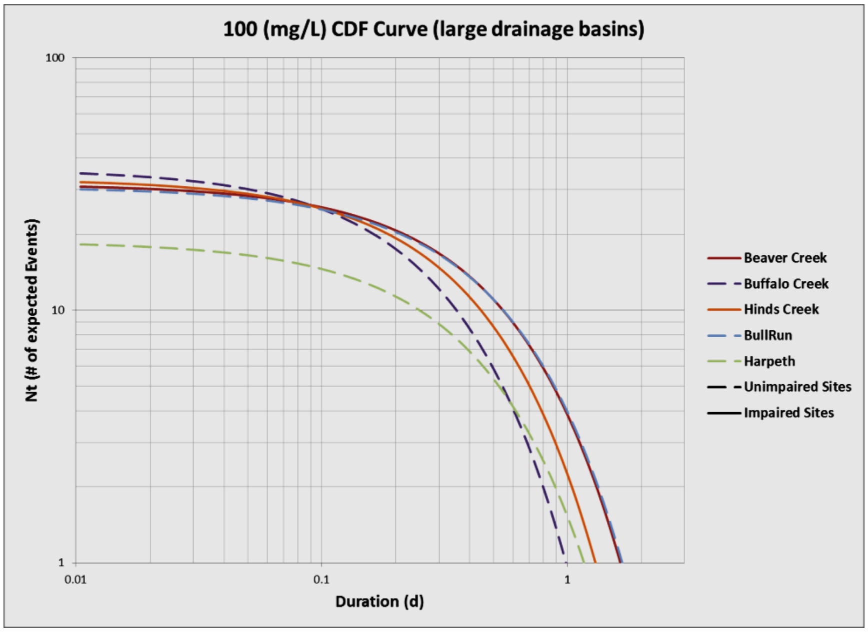

Figure 22. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 100 mg/L concentration.

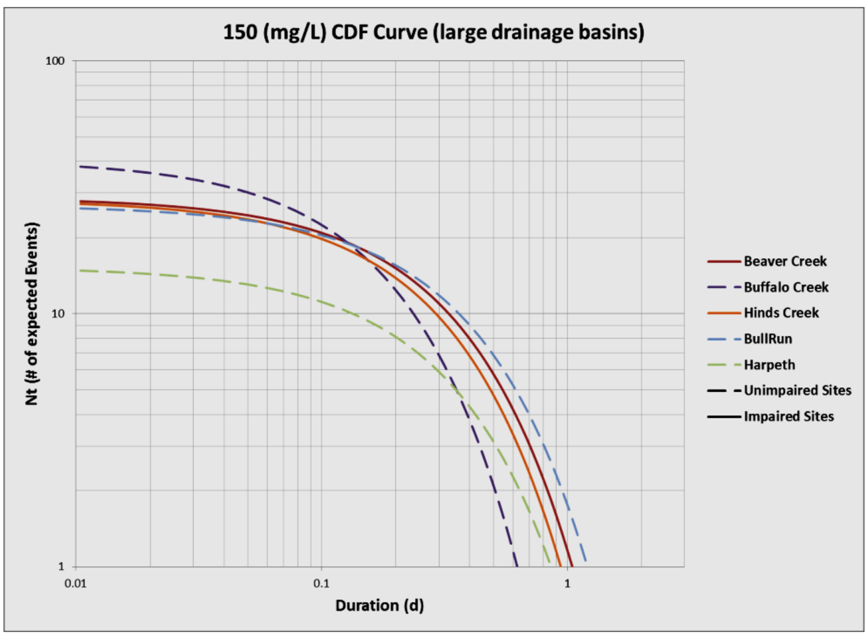

Figure 23. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 150 mg/L concentration.

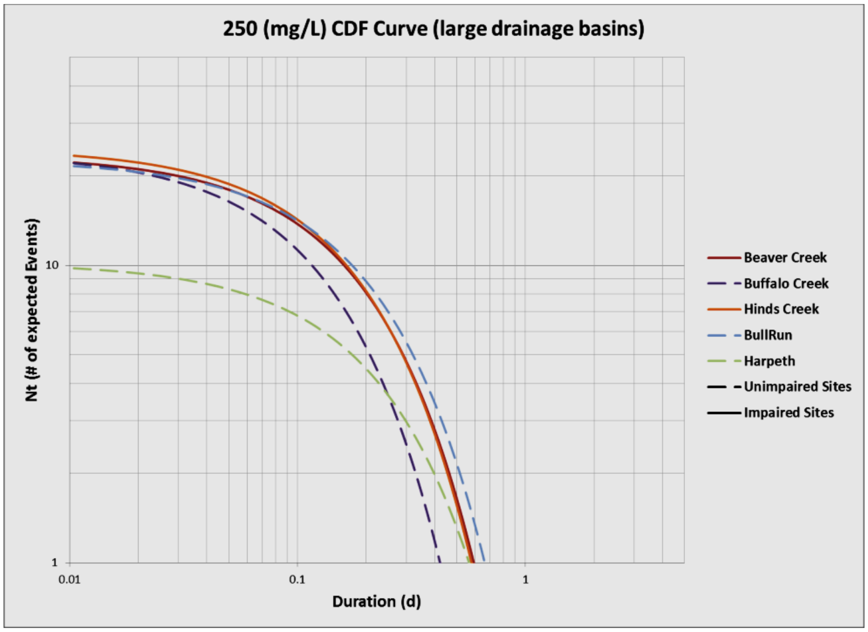

Figure 24. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 250 mg/L concentration.

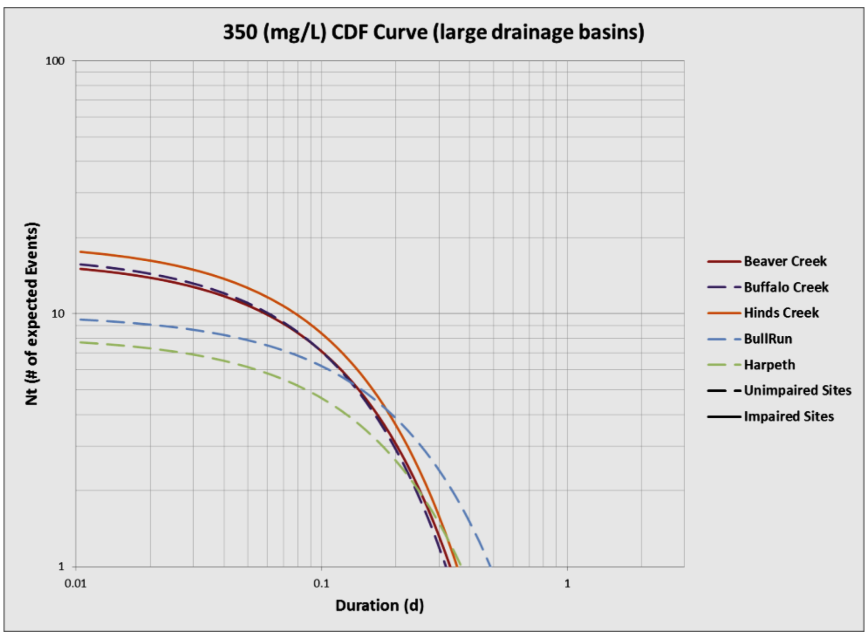

Figure 25. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 350 mg/L concentration.

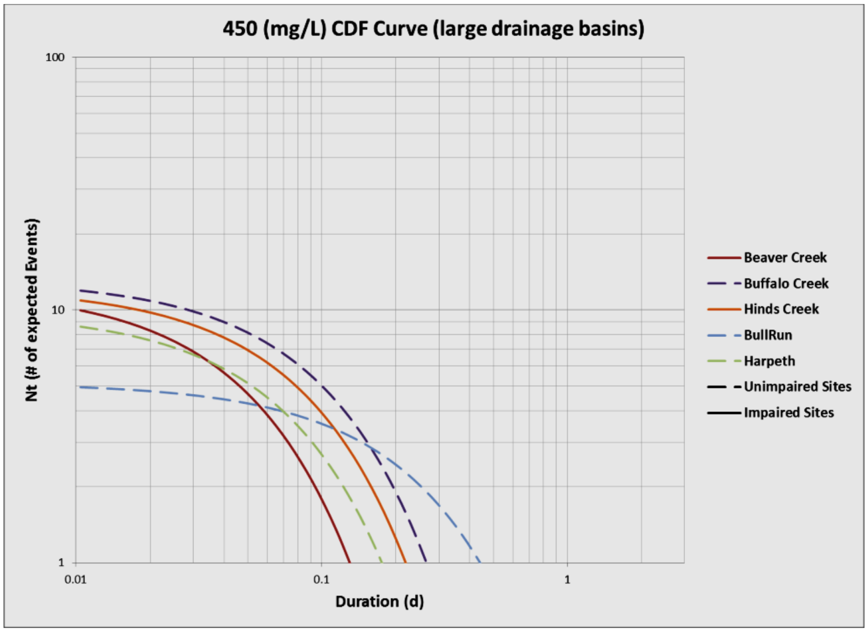

Figure 26. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 450 mg/L concentration.

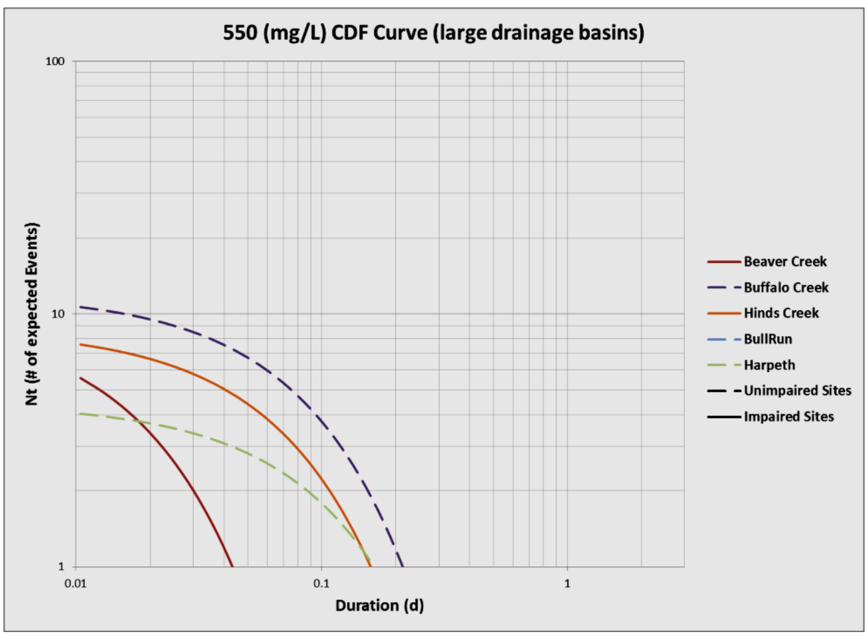

Figure 27. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 550 mg/L concentration.

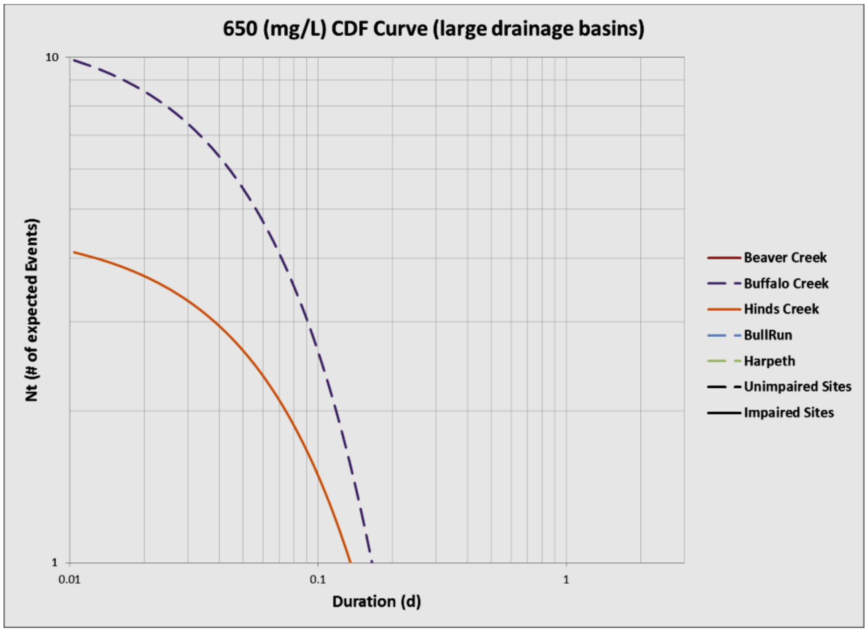

Figure 28. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 650 mg/L concentration.

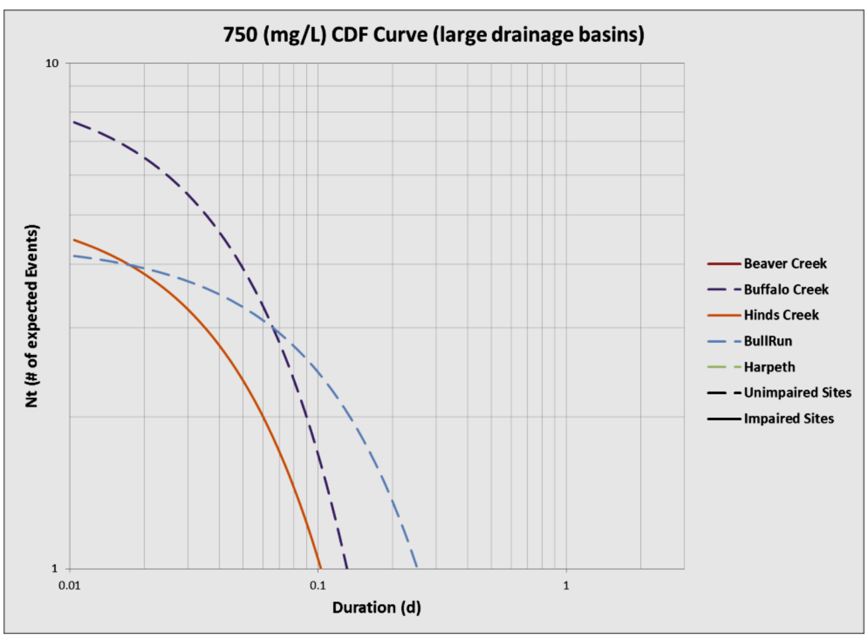

Figure 29. A CDF comparison of the upper 50 percentile based on drainage basin scale (>24 km^2 & <177.7 km^2) for a 750 mg/L concentration.

Appendix B: Process of Regression for CDF Curves

A Visual Basic macro was used to tally the number of events and the duration of events that exceeded sediment flux intensities of interest. Events that exceeded cutoff values were then ranked by magnitude of duration. Nine cutoff values (thresholds) were arbitrarily selected as 50 mg/L, 100 mg/L, 150 mg/L, 250 mg/L, 350 mg/L, 450 mg/L, 550 mg/L, 650 mg/L, and 750 mg/L for the purpose of this study (Table 2).

Sediment flux pulses can be analyzed as a Poisson distribution. Therefore, observation of both the frequency and duration, of episodic turbid events, above a given level of interest, and for a given time period (Figure 2), provide the necessary information to characterize site specific curves for concentration, duration, and frequency of events (Schwartz et al., 2008). Following these assumptions ranked sediment flux pulses can be characterized by the following equation:

$$N_t = N_{t,p} \cdot e^{\left(-\frac{d}{\mu}\right)} \qquad (2)$$

where N_t is the expected number (frequency) of events exceeding a specified level of interest with a duration $\geq d$ and $N_{t,p}$ is total number of events in a given time period. The variable μ represents mean duration.

By utilizing ranked data from Table 2, a linear regression can be performed by taking the natural log of N (Table 7). The corresponding x-axis variable can be seen in Table 2, which is the duration of the event. With these variables, a bivariate linear regression can then be performed to obtain the a linearized version of the characteristic CDF curve and parameters.

$$Ln(N) = md + b \qquad (3)$$

$$\mu = 1/m \qquad (4)$$

$$N_{t,p} = e^b \qquad (5)$$

The output from CDF curve regression models can be seen in Table 3.

Table 7. Natural log of ranked events for the Little Turkey Creek site.

	Y axis Variable								
	(mg/L) ≥ 50	(mg/L) ≥ 100	(mg/L) ≥ 150	(mg/L) ≥ 250	(mg/L) ≥ 350	(mg/L) ≥ 450	(mg/L) ≥ 550	(mg/L) ≥ 650	(mg/L) ≥ 750
	LN(N)	LN(N)	LN(N)	LN(N)	LN(N)	LN(N)	LN(N)	LN(N)	LN(N)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.693	0.693	0.693	0.693	0.693	0.693	0.693	0.693	0.693
3	1.099	1.099	1.099	1.099	1.099	1.099	1.099	1.099	1.099
4	1.386	1.386	1.386	1.386	1.386	1.386	1.386	1.386	1.386
5	1.609	1.609	1.609	1.609	1.609	1.609	1.609	1.609	1.609
6	1.792	1.792	1.792	1.792	1.792	1.792	1.792	1.792	1.792
7	1.946	1.946	1.946	1.946	1.946	1.946	1.946	1.946	
8	2.079	2.079	2.079	2.079	2.079	2.079	2.079	2.079	
9	2.197	2.197	2.197	2.197	2.197	2.197	2.197		
10	2.303	2.303	2.303	2.303	2.303	2.303	2.303		
11	2.398	2.398	2.398	2.398	2.398	2.398	2.398		
12	2.485	2.485	2.485	2.485	2.485	2.485	2.485		
13	2.565	2.565	2.565	2.565	2.565	2.565			
14	2.639	2.639	2.639	2.639	2.639				
15	2.708	2.708	2.708	2.708	2.708				
16	2.773	2.773	2.773						
17	2.833	2.833	2.833						
18	2.890	2.890	2.890						
19	2.944	2.944	2.944						
20	2.996	2.996	2.996						
21	3.045	3.045	3.045						
22	3.091	3.091	3.091						
23	3.135	3.135	3.135						
24	3.178	3.178	3.178						
25	3.219	3.219	3.219						
26	3.258	3.258	3.258						
27	3.296	3.296	3.296						
28	3.332	3.332							
29	3.367	3.367							
30	3.401								
31	3.434								
32	3.466								
33	3.497								
34	3.526								
35	3.555								
36	3.584								
37	3.611								

Appendix C: Additional Regression Statistics

Table 8. Bivariate regression output statistics where TMI and TMI subcategories were used as the response variable and Habitat Index value was used as the independent variable.

Macroinvertebrate Assemblage Metrics vs. Habitat Index value (Regression Statistics)			
	R^2	p	n
TMI	0.10	0.4478	8
TR	0.08	0.4955	8
EPT	0.01	0.8273	8
%0C	0.49	0.0523	8
NCBI	0.38	0.1008	8
%Clinger	0.23	0.2235	8
%EPT-Cheum	0.16	0.3289	8
%TNUTOL	0.06	0.5437	8

Table 9. *Bivariate regression results using different measures of macroinvertebrate assemblages as response variable and μ the independent variable.*

Macroinvertebrate Assemblage Metrics vs. μ (Regression Statistics)										
		(mg/L) ≥ 50	(mg/L) ≥ 100	(mg/L) ≥ 150	(mg/L) ≥ 250	(mg/L) ≥ 350	(mg/L) ≥ 450	(mg/L) ≥ 550	(mg/L) ≥ 650	(mg/L) ≥ 750
TMI	R^2	0.06	0.08	0.05	0.03	0.50	0.31	0.02	0.03	0.08
	p	0.5102	0.468	0.5519	0.6376	0.0735	0.1916	0.7608	0.0980	0.5948
	n	10	9	9	9	7	7	7	5	6
TR	R^2	0.01	0.02	0.03	0.03	0.24	0.17	0.08	0.34	0.12
	p	0.7819	0.7832	0.7201	0.6885	0.2669	0.3598	0.5386	0.3016	0.5004
	n	8	7	7	8	7	7	7	5	6
EPT	R^2	0.18	0.59	0.55	0.06	0.80	0.59	0.01	0.19	0.11
	p	0.3002	0.0441*	0.056	0.553	0.0065*	0.0434*	0.86	0.4600	0.5188
	n	8	7	7	8	7	7	7	5	6
%EPT-Cheum	R^2	0.06	0.00	0.01	0.01	0.01	0.01	0.00	0.06	0.02
	p	0.5608	0.8995	0.8597	0.8206	0.8799	0.8010	0.9480	0.6991	0.8148
	n	8	7	7	8	7	7	7	5	6
%OC	R^2	0.00	0.01	0.00	0.09	0.01	0.04	0.27	0.03	0.01
	p	0.8900	0.8505	0.9036	0.4737	0.8058	0.6723	0.2297	0.7757	0.8384
	n	8	7	7	8	7	7	7	5	6
NCBI	R^2	0.00	0.32	0.34	0.04	0.30	0.34	0.25	0.44	0.01
	p	0.9726	0.1817	0.1721	0.6374	0.2023	0.1708	0.2507	0.2219	0.8525
	n	8	7	7	8	7	7	7	5	6
%Clingers	R^2	0.04	0.64	0.52	0.00	0.24	0.05	0.20	0.18	0.03
	p	0.6273	0.0300*	0.068	0.9321	0.2669	0.6373	0.3080	0.4704	0.7491
	n	8	7	7	8	7	7	7	5	6
%Tnutol	R^2	0.21	0.14	0.12	0.47	0.07	0.01	0.57	0.94	0.05
	p	0.2524	0.4014	0.4381	0.0621	0.5686	0.8054	0.0510	0.0064*	0.6682
	n	8	7	7	8	7	7	7	5	6

-*Variations in n are due to unavailable data for subcategory TMI values or μ*
** Represents significance at alpha=0.05*

Vita

Robert Woockman was born in Anaheim, CA on June 3, 1980. His family later moved to Cumming, GA where he graduated high school from South Forsyth High School in 1998. Following his high school graduation he attended college. He graduated from the University of Georgia, Cum laude, with a Bachelor of Business Administration in finance in December, 2002. He spent the next eight years in various roles within the mortgage industry, including a promotion to management. In 2010, he made the decision to change career paths and began pursuit of the necessary prerequisite coursework to obtain a Master of Science in Engineering. In August of 2011, he was awarded a graduate research assistantship by the Department of Civil and Environmental Engineering at the University of Tennessee. In December 2012, Mr. Woockman will receive a Master of Science degree in Civil Engineering, with a Watershed Minor. In 2013, Mr. Woockman will receive an additional research assistantship from the Department of Civil and Environmental to pursue his Doctor of Philosophy degree.