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# Correlating Suspended Sediment and Biological Metrics in East Tennessee Streams

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To the Graduate Council:

I am submitting herewith a thesis written by Jeremy Robert Mefford entitled "Correlating Suspended Sediment and Biological Metrics in East Tennessee Streams." 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 Environmental Engineering.

John S. Schwartz, Major Professor

We have read this thesis and recommend its acceptance:

Glenn A. Tootle, Qiang He

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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# Correlating Suspended Sediment and Biological Metrics in East Tennessee Streams

A Thesis Presented for
the Masters of Science
Degree
The University of Tennessee, Knoxville

Jeremy Robert Mefford
December 2011

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much to be desired. Finally I thank my God and Father through Jesus Christ, by whom everything that I have previously mentioned has been graciously given to me without desert.

**“**Every good gift and every perfect gift is from above, coming down from the Father of lights…”

James 1:17

# Abstract

Excessive suspended sediment is a major cause of pollution in US streams, as reported by the United States Environmental Protection Agency. Also known as siltation, having excessive sediment in a stream harms the biology of a stream through directly affecting living organisms, but also through harming natural habitats. Too much excessive sediment leads to a stream being declared impaired. Testing for suspended sediment levels is difficult and time consuming, so indirect methods of testing for total suspended solids (TSS) are desirable. While turbidity has been an often used TSS surrogate in the past, this study takes the next step of looking at potential relationships between biological metrics and turbidity, to see if turbidity can be used to directly test for biological impairment, since turbidimeters can be installed in situ in streams. For this study we installed turbidimeters and depth samplers in 10 streams in East Tennessee that recorded data over a nine month period. The streams selected had pre-existing biological data available from the Tennessee Department of Environmental Conservation (TDEC). This allowed information from the turbidity probes to be compared to the biological integrity of the stream. This study first successfully correlates turbidity and TSS for our study sites through stream samples analyzed in the lab. We then statistically compared the turbidity data to the habitat scores and index scores (specifically the Tennessee Macroinvertebrate Index) of the streams. The main turbidity metric used was turbidity threshold exceedance, but unfortunately we were unable to include a duration factor. Changes in turbidity compared to changes in flow were also examined. The results showed reinforced the relationship between TSS and turbidity, while showing that while there is a correlation between turbidity threshold exceedance and

index/habitat scores, it would be inappropriate to use them for stream impairment predictions at this time. More investigation with both a wider range and number of streams in a single dataset, along with the ability to include turbidity duration may yield more valuable results.

# Table of Contents

# List of Tables

# List of Figures

## 1.0 INTRODUCTION

Excessive suspended sediment is one of the most problematic pollutants in the waterways of the United States (USEPA, 2009; USEPA, 2000). Having sediment that is excess above natural conditions is referred to as "siltation," and waters that are impaired by it are identified by examination of the biological state of the specific water conveyance. This is done through state biomonitoring programs that use biotic integrity scores to define whether a stream is impaired (USEPA, 1996). The causes of biological impairment are pervasive throughout the entire food chain of a stream. The problems start with primary production, where siltation can scour producers such as algae from stream surfaces as well as preventing their initial attachment to stream surfaces (Brookes, 1986). The turbidity caused will also obscure the light needed for photosynthesis for all plants in the affected stream (Van Nieuwenhuyse and LaPerriere, 1986; Wood, 1997). Siltation then affects small invertebrates by hurting their available habitats through substrate change (Culp et al., 1985; Wood, 1997), affects their respiratory processes through silt deposit in and on their respiration mechanisms (Lemly, 1982), and impedes invertebrates that feed through filters (Aldridge et al., 1987). Fish are also affected through several means, including respiratory impairment (Bruton, 1985), lowering the availability of appropriate spawning habitats, harming the development of fish eggs and young fish and reducing growth rates (Chapman, 1988; Moring, 1982), changing the usual migration patterns of fish (Alabaster and Lloyd, 1982), and by creating preferential conditions for non-visual feeders over visual ones (Ryan, 1991). The problem of excess sediment has led to the monitoring of sediment levels and the setting of numeric criteria for turbidity, suspended sediment, or both in the majority of US states (USEPA, 2006). These are usually set as a certain exceedance above background, or “natural” levels, but these levels are not well defined.

One of the most common laboratory methods of quantifying the amount of sediment present in surface waters in the USA is the total suspended solids (TSS) method (Gray et al., 2000). TSS values describe the concentration of sediment in a surface water body at the time the sample is collected. TSS samples do not discriminate between organic and inorganic sediment, and are collected either through in situ passive samplers or through “grab samples” taken by someone present in the stream. TSS concentrations samples are limited by the fact that they are only instantaneous measurements of suspended sediment and cannot give a continuous picture of sediment behavior in a body of water. This inhibits attempts to calculate bed loads and quantify erosion (Finlayson, 1985).

Turbidity sampling as a TSS surrogate presents an appealing alternative to direct measurement due to its lower cost and the ability of turbidimeters to be placed in-situ in streams and take continuous measurements (Finlayson, 1985; Gippel, 1989). Turbidity is the measure of the amount of light that is able to pass through water, and the light in surface water is primarily interfered with by suspended sediment. To use turbidity as a surrogate for TSS, there has to be a significant and reliable relationship between turbidity and suspended sediment concentration (Gippel, 1989; Minella, 2007), and recent research has shown this to be the case (Minella, 2007; Packman, 1999; Lewis, 1996; Hoffman and Dominik, 1995; Clifford et al., 1995; Jansson, 1992; Gippel, 1989). The challenges faced when using turbidimeters, and then to obtain sediment concentrations from the turbidity readings are numerous and well documented. These include electronic drift, algae or biofilm fouling of the lenses, sensitivity to particle size variation, background water color (Gippel, 1995), and even water temperature (Packman 1999). All of these factors can confound both the turbidity readings themselves, and thus any relationship between turbidity and TSS. While turbidity is the most commonly cited surrogate measurement for TSS, other possibilities include discharge (Webb and Walling, 1982) and water density (FISP, 1982).

This study examines the next step in using TSS surrogates. The ultimate goal is to be able to determine biological impairment through use of obtainable surrogates, as opposed to more strenuous and often impractical examination methods. The way to do this is to establish viable TSS surrogates, such as turbidity, and compare them to biological metrics in an attempt to find significant correlations between them. If a strong, reliable relationship exists between a TSS surrogate and a measure of biological health, then that surrogate can be used to test directly for biological impairment. For this study, the biological metric being used is the Tennessee Macroinvertebrate Index (TMI), which is based off of the Benthic Rapid Bioassessment Protocol III (RBP III) that was established in 1989 as a way of assessing the diversity of benthic macroinvertebrates present in a stream (Plafkin et al, 1989). TMI scores are currently taken in streams throughout East Tennessee by the Tennessee Department of Environmental Conservation (TDEC) as a way of gauging stream impairment. This thesis will specifically attempt to find correlations between TSS surrogate measurements and these TMI scores in several streams in East Tennessee.

## 2.0 SITE DESCRIPTIONS

For the purpose of obtaining well rounded data, the stream sites selected for this study varied in location, surrounding environment, and current levels of biological integrity. The streams were located in the following watersheds in East Tennessee: Fort Loudon Lake (5), Lower Clinch River (3), and Holston River (2). One stream was located in a suburban area, one in a rural town, six in rural farmlands, and two in higher elevation rural environments meant to serve as reference streams. Figure 1 shows the locations of the sites in East Tennessee, and Tables 1 & 2 give more detailed information about each site.

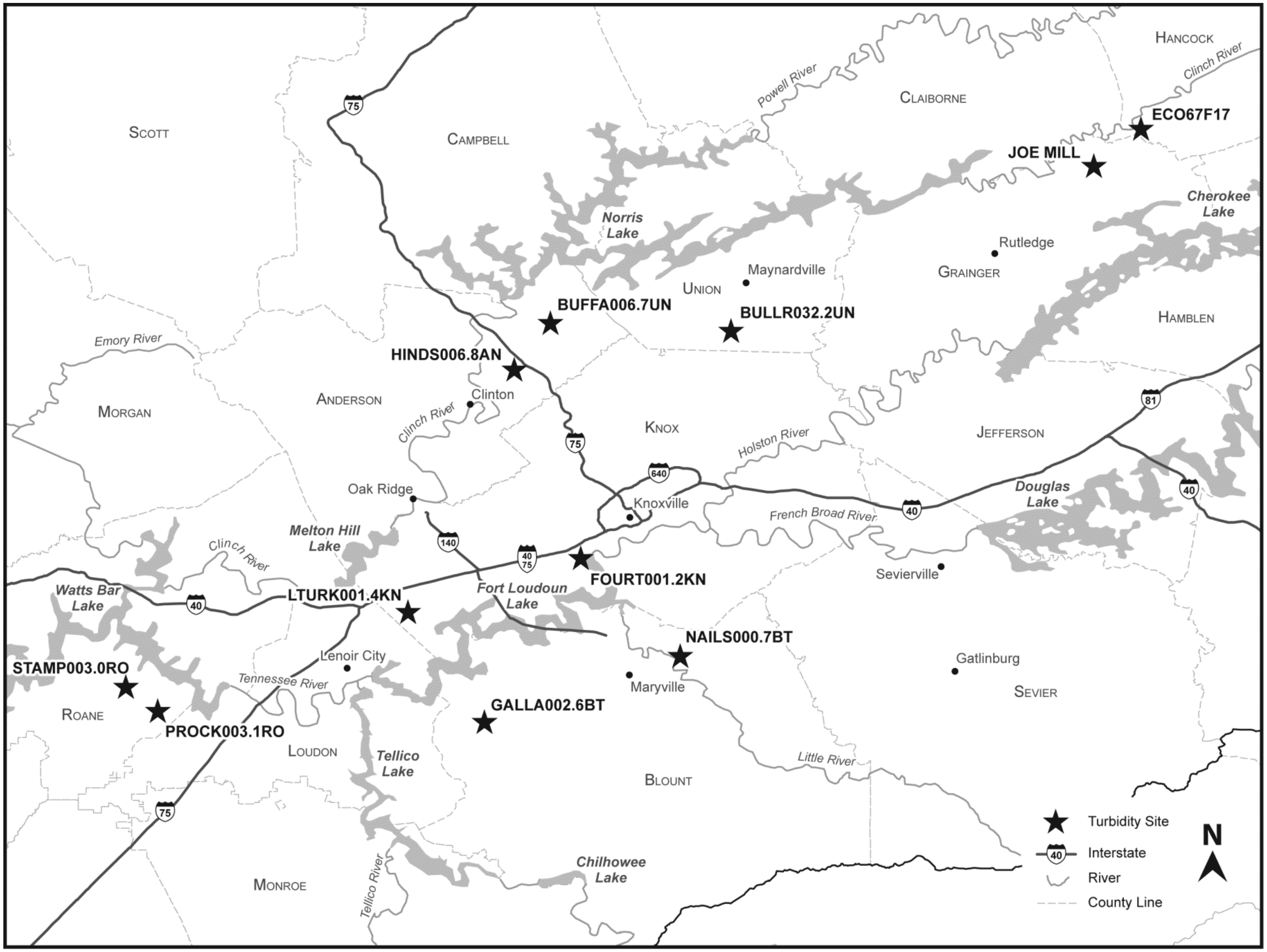


Figure 1: Site locations map (figure created by Matthew Kookogey)

Table 1: This table lists the stream sites used, along with the TDEC identification numbers, the latitude and longitude of each stream site, and a description of the location of the sensors used for this study.

| Site Name | Project ID | Station ID | Nearest City | Latitude | Longitude | Site Location Description |
|---|---|---|---|---|---|---|
| Big War | 21TNECO | ECO67F17 | Morristown | 36.42681 | -83.3474 | North of Clinch Mountain. Head a few miles east on a long backroad (Papaw Rd.) until you reach the bridge over the stream. Site is north of the bridge (downstream) on the north/east side of the bank. |
| Buffalo | 21TNTMDL | BUFFA006.7UN | Andersonville | 36.1996 | -84.0355 | Site is on the property of an old bait and tackle shop. It is north of the road (downstream). |
| Bullrun | 21TNTMDL | BULLR032.2UN | Maynardville | 36.1992 | -83.8144 | Site is east of the bridge (upstream) over the stream. It is located on the south fork. |
| Fourth | 21TNTMDL | FOUR001.2KN | Knoxville | 35.9341 | -84.003 | Site is located in front of the Catholic School on Northshore Dr. The stream is west of the school and east of the school. |
| Gallagher | 21TNTMDL | GALLA002.6BT | Maryville | 35.7355 | -84.1131 | Site is located east of the bridge (upstream) that crosses the stream on a backroad off of HWY 321. |
| Hinds | 21TNTMDL | HINDS006.8AN | Clinton | 36.14605 | -84.0765 | Site is located south of the bridge (upstream) that crosses the stream on Mountain Rd. |
| Joe Mill | 21TNECO | JMILL000.1GR | Morristown | 36.3765 | -83.3993 | Located down Dave Jackson Road. |
| Nails | 21TNTMDL | NAILS000.7BT | Maryville | 35.8136 | -83.88261 | Site is located south of the bridge (downstream) that crosses the stream. |
| Paintrock | 21TNTMDL | PAINT003.1RO | Loudon | 35.7495 | -84.4922 | Site is located upstream of the bridge that crosses the stream. |
| Stamp | 21TNWMS | STAMP003.0RO | Loudon | 35.777 | -84.5277 | Site is located across the field in the stream that the small conveyance the road crosses flows into. |

Table 2: A summary of the basic information about each stream sites' surrounding geography, and includes a photo of each of the streams.

| **Site Name** | **Site Description** | **Site Photo** |
|---|---|---|
| Big War | Very rural, but the stream being tested is fed by other streams that carry runoff from roads and farms. |  |
| Buffalo | Fairly rural area. Not very developed and farms are located not far from the small town the testing area is located in. |  |

Table 2: A summary of the basic information about each stream sites' surrounding geography, and includes a photo of each of the streams.

| | | |
|---|---|---|
| Bull Run | Rural farmlands. |  |
| Fourth | Suburban environment that is less than five miles away from a major city. |  |

Table 2: A summary of the basic information about each stream sites' surrounding geography, and includes a photo of each of the streams.

| | | |
|---|---|---|
| Gallagher | Rural farmland area that quickly transitions into a small city 7-8 miles down the road. |  |
| Hinds | Rural farmlands that are near only to not very developed town centers. |  |

Table 2: A summary of the basic information about each stream sites' surrounding geography, and includes a photo of each of the streams.

| | | |
|---|---|---|
| Joe Mill | Very rural mountainous area. |  |
| Nails | Rural farmlands 5-6 miles from a small city area. |  |

Table 2: A summary of the basic information about each stream sites' surrounding geography, and includes a photo of each of the streams.

| | | |
|---|---|---|
| Paintrock | Rural farmlands. |  |
| Stamp | Rural Farmlands. |  |

## 3.0 METHODS

### 3.1 Turbidity Probes

Because this particular research required both depth measurement and turbidity measurement, a data logger with connections for both sensors was installed at each stream site, and the sensors were installed in the stream itself. The data logger used was a GL500-2-1

Data Logger from Global Water, and the instruments were a WL400 Water Level Sensor and a WQ730 Turbidity Sensor from the same company.  The range of the water level sensor is 0-15 feet, and the range of the turbidity sensor 0-1000 NTU. The WQ730 is a 90 degree scatter nephelometer which uses infrared light to detect turbidity. The particles in the water reflect the light from the IR source, which is protected by a lens, and the amount of reflection is picked up by a sensor at 90 degrees from the light behind another lens. A third sensor is directly across from the light source, which has the purpose of correcting for low levels of lens fouling, water color changes, and light intensity variations. Figures 2 and 3 have images of the equipment that was used at each site.

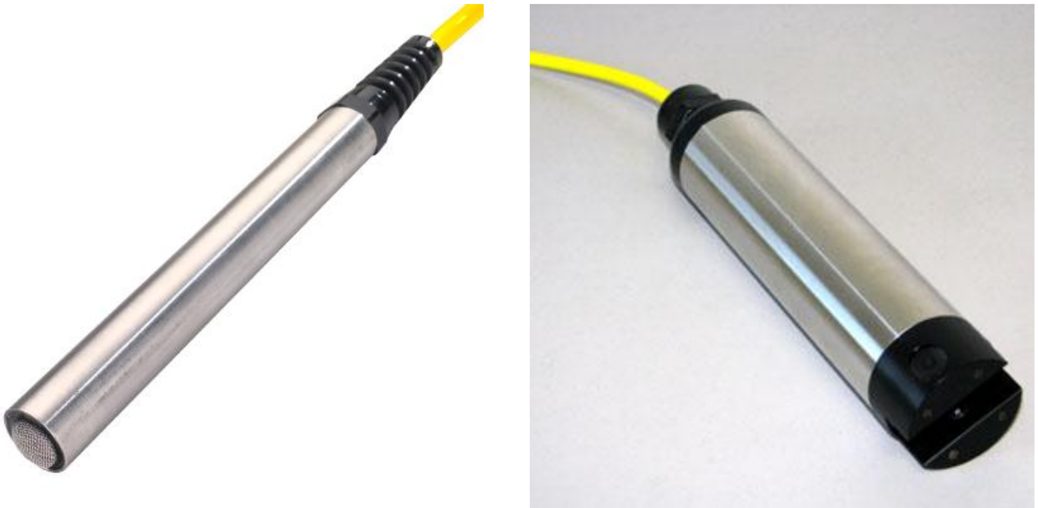


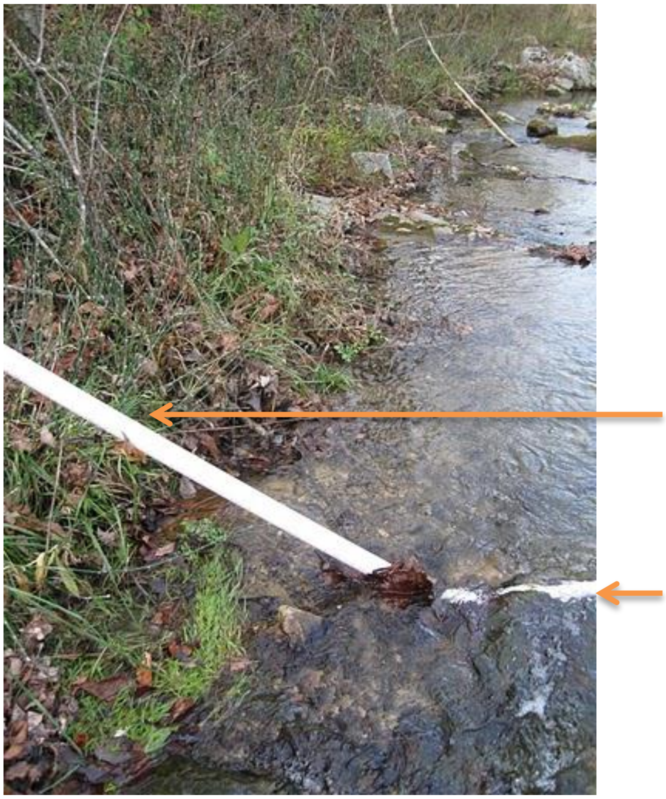
Figure 2: The water depth sensor (left) and turbidity probe (right) used in this study (photos from Globalw.com)

Figure 3: The Data logger (left) and container (right) used in this study (photos from Globalw.com)

The data logger was contained in a water tight box and was attached to a tree or other anchored location at an elevation above that of the observable flood plain. The connecting cables from the sensors to the data logger were insulated to protect them from the elements. The sensors were placed into PVC pipe connected to a tree or other grounded object on the bank of the stream that the data logger was also attached to. The PVC pipe extended down into the stream and had holes drilled in the submerged section (Figure 2). This allowed for the passage of both water and sediment around the sensors contained in the pipe, and protected the sensors from debris or other hazards in the stream. The last piece of PVC that contained the actual instruments was designed to be easily detached from the rest of the PVC housing to allow for ease of maintenance and cleaning of the sensors.

Early on in the data collection process, it was discovered that the actual turbidity measurements were confounded in two different ways. The first problem, as had been recorded in previous papers (Gippel, 1989), was that of biological fouling on the turbidity lenses. The probes were designed to handle low levels of this expected fouling, but beyond a certain amount the fouling inflated the recorded turbidity. The second problem was that of sediment being retained in the probe PVC housings. The PVC pipes that contained and protected the probes were perforated with 0.25” holes to allow water to flow around the probe and achieve as accurate a reading as possible. Unfortunately sediment still tended to settle on surfaces within the PVC pipe, even when the pipe was set at a sharp downward angle. This problem was at its worst during and after storm events. During a storm event, large amounts of sediment would be in the stream and would get into the sensor housing. As the storm flow receded, there was not enough flow velocity to clean out the sediment that was left behind.

These problems resulted in attempts to clean every probe and pipe housing one to two times per week. This helped prevent the fouling from getting out of hand (measured turbidity levels would steadily rise and show abnormally high values in as little as 2-3 days) and regularly removed sediment buildup. Another problem we encountered was that of batteries dying before we had a chance to change them. This led to there being gaps in the data that were filled in to the best of our ability using the information from nearby site data.



Wires travel up the PVC and connect to the data logger.

Sensors are contained in the perforated PVC pipe placed beneath the water surface.

Figure 4: The basic setup of the turbidity probe and depth sensor in the water.

**3.2 Passive Sampling**

In order to get total suspended solid (TSS) data from the stream during storm events, a way of capturing a water sample at the time of a storm event was needed. The method of in situ sampling we chose is called a siphon-sampler (Figure 5). It is a simple setup designed to take TSS samples from a specific water depth during a rain event. The apparatus consists of a 1000 mL bottle, two ¼” plastic tubes inserted into the lid of the bottle, and a fence post firmly placed into the stream bed and also wired to a nearby tree truck. The end of one of the plastic tubes is responsible for allowing the stream water into the bottle, and is placed at an elevation higher than the top of the collection bottle. The other plastic tube allows the air already in the bottle to be displaced by the incoming water, and is placed at a height above the bottle and first tube entrance. The water bottle is attached to the fence post with hose clamps, and the tubes are attached with zip ties.

During regular flows, the passive sampler is installed and the end of the first plastic tube is attached to the fence post at a height above the stream so that the sampler will only fill during a significant rain event. When the stream reaches the level of the tube opening, the bottle will begin to fill with water. If the tube opening is placed facing upstream, both the water pressure and the velocity head will contribute to the filling of the bottle, but the tube opening could also be blocked by organic debris. We pointed the tubes downstream to avoid this problem. After the steam reaches the level of the higher tube opening, the bottle should already be filled with water, preventing water from flowing into the bottle through the upper tube as the remaining air cannot be displaced.

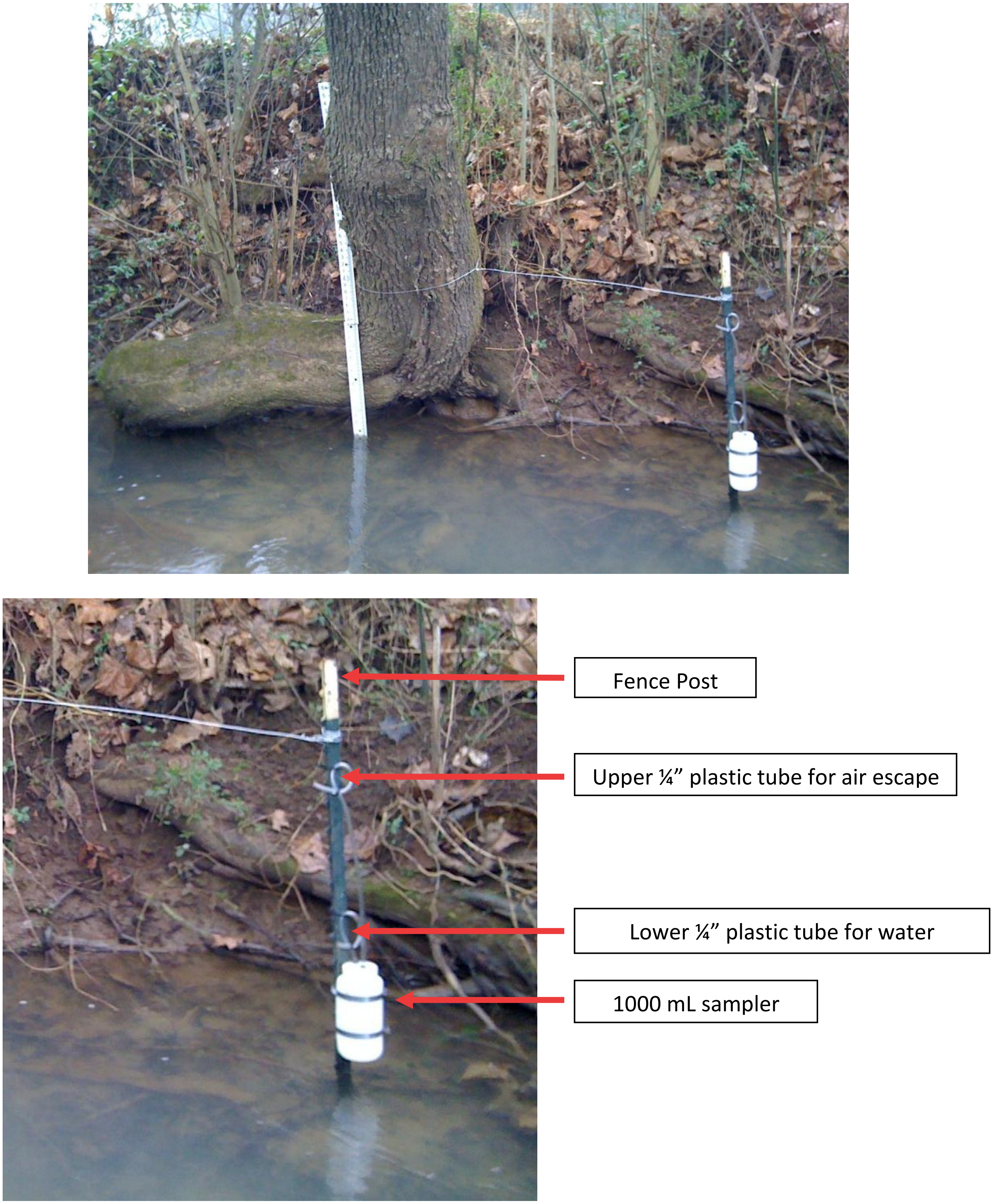


Figure 5: The typical passive sampler setup. The only time this setup was changed was if the stream bedrock prevented the installation of a fence post.

### 3.3 TSS Concentration

Once the passive samplers had been filled with water from a storm event, water samples were returned to the lab and tested for TSS concentration. TSS analysis was completed following Standard Methods (Eaton et al, 2005). Premeasured volumes of the samples were run through 0.45 µm filters of known mass, and the filters were then heated to 103$^{o}$C – 105$^{o}$C for one hour to remove all moisture. The filters were then weighed again on a scale accurate to 0.0001 grams, and the difference in weights gave the mass of suspended solids present in a given volume of that water sample. This value was then converted to give a final TSS concentration in mg/L.

### 3.4 Discharge Methods

The discharge of the various streams being tested was determined using three different methods. The first method was a use a simple cross-sectional area and velocity analysis to determine the flow, and the second was more high tech with the use of a SonTek/YSI RiverSurveyor™. Given this information, it was then possible to implement a third method of creating a good hydraulic model of water flow through a stream reach. This was accomplished by surveying several cross sections at each stream and inputting that data into HEC-RAS v.4.0 (Hydrologic Engineering Centers River Analysis System) (USACOE 2008). The previous flow measurements helped in the fine tuning of each model to describe the flow in each stream as accurately as possible.

The first method of cross-sectional area and velocity was done using the following steps:

1) A convenient cross-section of the stream was selected, and a tape measure was pulled taut across that section of the stream between two grounded objects such as tree trunks.

2) Once the actual width of the stream was determined, it was divided into an appropriate number of sections. At each section, depth and velocity measurements would be taken

3) Starting at the very edge of one of the banks, a portable velocity meter, specifically the Flo-Mate 2000™ by Marsh-McBirney was used to measure first the depth of the water, followed by the velocity. The depth was measured first because we were using the 0.6 rule of thumb that states that the average velocity at a particular point in the stream generally occurs around 60% of the way down the total depth of that point in the stream. The velocity meter was adjusted at each point along the tape measure in order to find the average velocity at that point. The person operating the velocity meter stood downstream of the meter in order to not disturb the flow.

4) At each point the depth, velocity, and distance from the bank was recorded.

5) This process is repeated multiple times to get several flow measurements that are then averaged to get the most accurate flow possible.

6) After all the data for a stream was collected, the measurements were used to calculate the flow over the entire cross-section.

The second method was done using the SonTec/YSI River Surveyor™ M9 model. This device is essentially a large kickboard with surveying equipment attached to it to survey rivers and streams and measure the flow as well. It utilizes multiple acoustic frequencies, a vertical acoustic beam, a GPS, and other instruments to get as accurate a picture as possible how a stream looks and how it behaves. The River Surveyor™ was run multiple times across the cross-section of a stream, and the flow values obtained were averaged to give the most accurate flow reading possible.

Once these "real world" values were obtained, the flow in each stream could be accurately modeled using HEC-RAS, and the information there was used in some statistical analyses.

### 3.5 Rapid Bioassessment Scores

Benthic macroinvertebrates are used by TDEC as indicator organisms for whether or not a stream supports diverse aquatic life maintaining adequate biotic integrity (Barbour et al, 1999). Other aquatic organisms such as fish and periphyton can also be examined to determine stream health if there is a diverse and dense enough populations to examine. Bioassessment of stream reaches can be done in a quick and efficient manner if macroinvertebrates are used as indicators. Rapid bioassessment got its start when Plafkin et al. (1989) laid down protocols (called Rapid Bioassessment Protocols- RBP) for macroinvertebrate and fish testing. For the benthic macroinvertebrates, an area of a stream bed is disturbed in order to kick up the small creatures resting on the streambed. The test specifically looks at the diversity of macroinvertebrates found, as well as the population densities of different species. These observations are ranked in several categories and scores added up to create the "Tennessee Macroinvertebrate Index" (TMI) value, which will be the primary biological score examined in the statistical analysis section. It is also known as the "Index Score" for short.

The advantages to using macroinvertebrates are many. Besides how quickly an examination can take place, these benthic macroinvertebrates have limited migration, so they are particularly well suited to look at site specific impacts. Since macroinvertebrates have a short life cycle of a year or so, differing organisms will show varying effects of pollution based on how sensitive their stage in life is. Finally, macroinvertebrate populations are made up of a wide range of species that vary in pollution tolerance, which provides strong information for determining cumulative effects (Barbour et al, 1999).

To fully assess the health of a stream, this bioassessment method looks not only at macroinvertebrate density and variance, but also at the availability of natural habitat structures (roots, boulders, rock overhangs, etc.) and other stream characteristics. These include embeddedness, availability of various flow regimes, sediment deposition, artificial channel alteration, re-oxygenation zones (such as riffles and bends), bank stability, bank vegetative protection, riparian vegetative zone width,  pool variability, channel sinuosity, and other factors that may be noticed only upon stream examination. Which parameters are examined may vary depending on the stream in question. After all the parameters are examined, each stream is given a habitat score that indicates whether the stream is impaired or unimpaired. If impaired, the impairment is clarified as either being from natural or artificial factors. The Habitat Score and the TMI are separate, which allows for impairment of habitats to be observed separate from general biological impairment.

### 3.6 Statistical Analysis

The attempt to find statistically significant relationships in the data obtained was guided by previous research that pointed to certain turbidity or TSS measurements (such as frequency of events above a turbidity threshold) as being significant indicators as to whether or not a stream would be biologically impaired. The stats were run using correlation and linear regression to examine the direct relationship between biological integrity and potential indicators.

### *3.6.1 Turbidity vs. TSS*

The initial stats analysis was a correlation between the actual TSS concentrations obtained from our passive and grab samples with their turbidity values. Before testing for TSS, each stream sample was run through a calibrated turbidimeter in a lab setting. Once we had both the TSS and turbidity of each sample, we were able to look at the strength of the relationship between the TSS and turbidity. Although from many past experiments there is a strong consensus about the relationship that exists between TSS and turbidity, it was important to establish the strength of that relationship for the streams being used in this study. While Packman et al. (1999) found a relationship in their streams of $R^2 = 0.96$ between TSS and turbidity, another study by Suk et al. (1998) found a lower correlation of $R^2 = 0.827$ between the two measurements when they examined the relationship between turbidity and TSS in a tidal saltmarsh creek. Other studies have been done which attempted to specifically relate TSS and turbidity measurements (Minella et al., 2007; Lewis, 1996; Hoffman and Dominik, 1995; Clifford et al., 1995; Gippel, 1995; Jansson, 1992), all with successful results and varying correlation strengths. These findings from others are consistent over a variety of surface water types, and taken as a whole they leave little doubt as to the existence of a strong relationship between the two measurements. However the differences between the resulting correlation coefficients and regression equations show that there can be plenty of “noise” in the relationship. For instance, the study by Packman et al. (1999) showed that the best relationship between TSS and turbidity was with both sets of data natural-log transformed, while most other studies preferred a linear relationship without any adjustment. The data from this research will add to the conversation.

The results of this analysis have a large effect in the rest of the research. Without a reliable, strong relationship between recorded turbidity values and TSS of a water sample, there is no reason to think that turbidity is going to provide an adequate surrogate measurement for the suspended sediment content of surface water. Based on the experiments previously referenced, the eventual statistical result from correlating TSS and turbidity seems to hinge on several large factors and potentially countless smaller ones. The main confounding factors include the type of water body being tested, the type of turbidimeter used, whether the turbidity is taken from an instrument in the stream itself or in a laboratory setting, the geography surrounding the body of water, the land use of the watershed, etc. Because of this, we needed to specifically look at the relationship between TSS and Turbidity in the streams we were testing.

### *3.6.2 Number of events above a turbidity threshold*

Each time a large sediment event happens in a stream, the biota must survive the initial wave of high SSC but then also must recover from said event. Repeated exposure to adverse conditions for breeding, feeding, migrating, etc., as well as repeated habitat damaging events, may wear down a population of fish or invertebrates over time, assuming that the events themselves are non-lethal (Schwartz et al., 2008). Knowing this, we decided to look at the number of events per year above a certain turbidity threshold which a stream experiences, and compare that to the biological health of the stream. We chose several turbidity levels (100, 200, 300, 500, and 1000 NTU) to get a picture of where in the different NTU ranges there may be a significant threshold of either number of events or NTU levels. We then counted up the number of events that exceeded those thresholds over the time-frame of the testing and did correlation tests with biological indices. The specific biological indicators we used were the TMI scores, Habitat scores, and %EPT scores from the RBP testing methods. %EPT was chosen because this particular metric contributes to the TMI, but looks specifically at three more sediment intolerant orders of macroinvertebrate; Ephemeroptera, Plecoptera and Trichoptera.

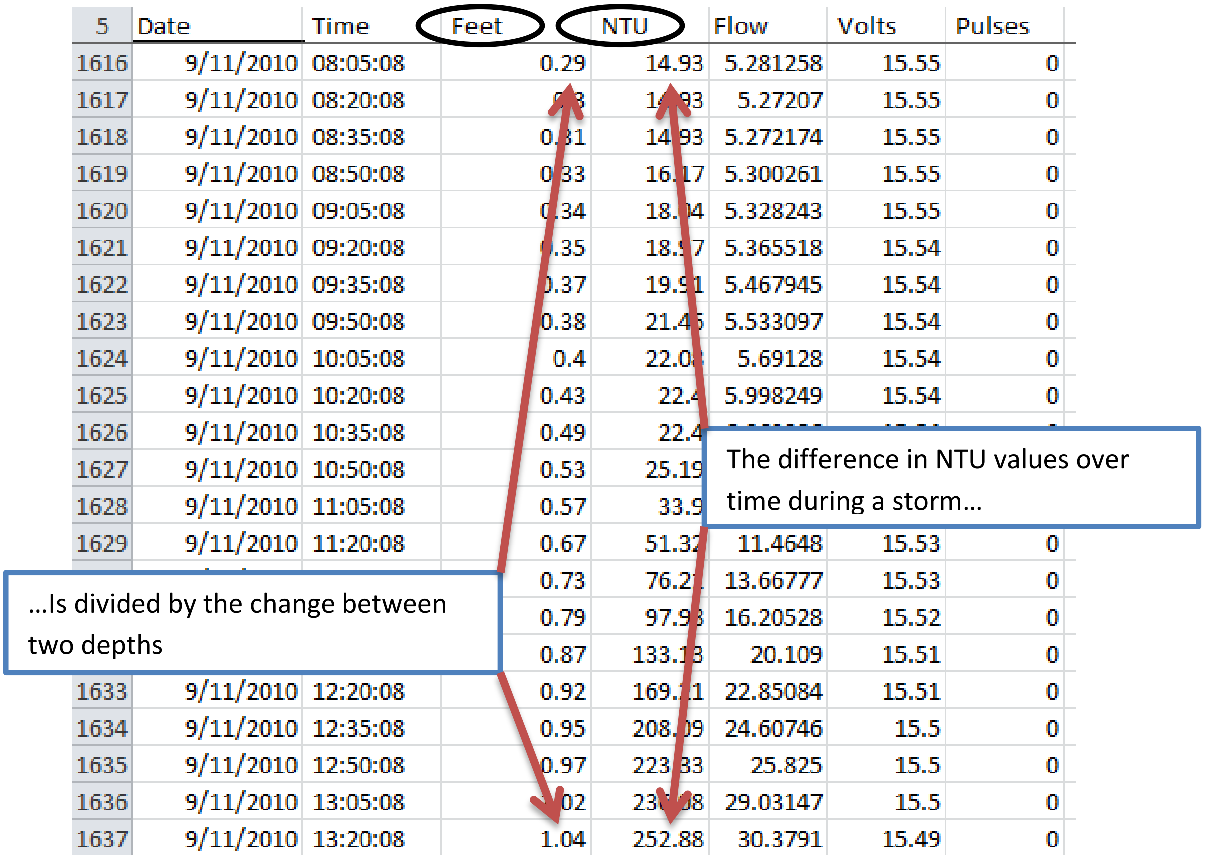
One problem with the entire data set is the lack of even distribution of the TMI scores. The single stream (Fourth Creek) located in a suburban area has an Index Score of 16, another stream has a score of 26, while all others range from 30-40 and are located in very rural geography. Because of this, we felt it important to also run a correlation between turbidity thresholds and TMI scores without Fourth Creek's data, because it exerts a large influence over the correlation when it is present. This secondary correlation will help show the strength of the relationship between TMI and turbidity thresholds over a smaller range. To possibly find a stronger relationship between turbidity threshold and biological health or habitat impairment, the testing sites would need to be selected over a wider range of index scores, likely with more suburban and urban environment streams selected. However, these stream sites are likely to have far more problems than just siltation affecting the stream's health. For instance, the

Fourth Creek site is likely feeling the effects of street runoff, and possible leaky sewer pipelines and other man made pollutants far more than the effects of the sediment. So in a more urbanized setting, determining the real cause of biological impairment may be far more complicated.

It is important to note that while Fourth Creek differs greatly from the other sites, it is not an anomaly that should be removed from the dataset because it does in fact reflect real conditions for many streams in East Tennessee. It just happens to be the only one in this dataset.

### *3.6.3 Change in turbidity over change in stage*

The rate of increase of SSC in a stream during a storm event may indicate how easily a stream is receiving excess sediment. If a small change in water depth results in a large change in SSC, then the stream is likely located near some areas that have poor erosion control. Being so susceptible to receiving sediment means that the organisms in the stream must deal with quick, sudden changes in their environment, and deal with them more often than other streams may if even small rain events cause SSC levels to spike. So to look at this statistically, we took several storm events from each site and measured how quickly the turbidity changed with respect to the rise of the water level. We then took the average of this ratio from each site, and compared it to the TMI score and Habitat Score for that stream, and graphed the resulting points to look for relationships within the data.



| 5 | Date | Time | Feet | NTU | Flow | Volts | Pulses |
|---|---|---|---|---|---|---|---|
| 1616 | 9/11/2010 | 08:05:08 | 0.29 | 14.93 | 5.281258 | 15.55 | 0 |
| 1617 | 9/11/2010 | 08:20:08 | 0.3 | 14.93 | 5.27207 | 15.55 | 0 |
| 1618 | 9/11/2010 | 08:35:08 | 0.31 | 14.93 | 5.272174 | 15.55 | 0 |
| 1619 | 9/11/2010 | 08:50:08 | 0.33 | 16.17 | 5.300261 | 15.55 | 0 |
| 1620 | 9/11/2010 | 09:05:08 | 0.34 | 18.04 | 5.328243 | 15.55 | 0 |
| 1621 | 9/11/2010 | 09:20:08 | 0.35 | 18.97 | 5.365518 | 15.54 | 0 |
| 1622 | 9/11/2010 | 09:35:08 | 0.37 | 19.91 | 5.467945 | 15.54 | 0 |
| 1623 | 9/11/2010 | 09:50:08 | 0.38 | 21.45 | 5.533097 | 15.54 | 0 |
| 1624 | 9/11/2010 | 10:05:08 | 0.4 | 22.08 | 5.69128 | 15.54 | 0 |
| 1625 | 9/11/2010 | 10:20:08 | 0.43 | 22.4 | 5.998249 | 15.54 | 0 |
| 1626 | 9/11/2010 | 10:35:08 | 0.49 | 22.4 | [illegible] | [illegible] | [illegible] |
| 1627 | 9/11/2010 | 10:50:08 | 0.53 | 25.19 | [illegible] | [illegible] | [illegible] |
| 1628 | 9/11/2010 | 11:05:08 | 0.57 | 33.9 | [illegible] | [illegible] | [illegible] |
| 1629 | 9/11/2010 | 11:20:08 | 0.67 | 51.32 | 11.4648 | 15.53 | 0 |
| [illegible] | [illegible] | [illegible] | 0.73 | 76.21 | 13.66777 | 15.53 | 0 |
| [illegible] | [illegible] | [illegible] | 0.79 | 97.93 | 16.20528 | 15.52 | 0 |
| [illegible] | [illegible] | [illegible] | 0.87 | 133.13 | 20.109 | 15.51 | 0 |
| 1633 | 9/11/2010 | 12:20:08 | 0.92 | 169.21 | 22.85084 | 15.51 | 0 |
| 1634 | 9/11/2010 | 12:35:08 | 0.95 | 208.09 | 24.60746 | 15.5 | 0 |
| 1635 | 9/11/2010 | 12:50:08 | 0.97 | 223.33 | 25.825 | 15.5 | 0 |
| 1636 | 9/11/2010 | 13:05:08 | 1.02 | 236.08 | 29.03147 | 15.5 | 0 |
| 1637 | 9/11/2010 | 13:20:08 | 1.04 | 252.88 | 30.3791 | 15.49 | 0 |

The difference in NTU values over time during a storm…

…Is divided by the change between two depths

Figure 6: Output example showing how the change in turbidity per change in stage is calculated. The process is the same for change in turbidity per change in flow.

### *3.6.4 Change in turbidity over change in flow*

The reasoning behind this analysis was essentially the same as for the change in turbidity over change in stage test, but to see if the ratio of change in turbidity to flow rate provided a better independent variable ratio to be used as an indicator of stream health. The HEC-RAS stream models previously mentioned provided flow rates for the streams at different stages, so the flow rate throughout a storm event could be closely estimated. We selected several storms per stream and averaged the flow rates throughout them, and these values were compared to the TMI score and Habitat Score of each stream.

### *3.6.5 Total Suspended Solids*

For each stream, there were a minimum of two TSS samples taken from passive samplers located in situ at the streams, or taken as grab samples during high flow events. We decided to directly compare these TSS values to the biological scores of the stream. As previously mentioned, the weakness of TSS samples is that they only provide information about a moment in time. However they are direct measurements of the sediment present in the stream during the time of a storm event, while the water level is especially high. So the TSS samples we have obtained are not arbitrary. There is a wide range of TSS averages for the streams, so we decided to compare them to the biological surrogates and see what relationships may be present.

## 4.0 RESULTS

### 4.1 Turbidity vs. TSS

Our data showed a positive correlation between turbidity and TSS with $R^2 = 0.975$ ($R^2$ adj. = 0.974, $R^2$ pred. = 0.952) with a p-value of less than 0.01. Figures 7 and 8 show this information graphically, and Figure 9 shows the correlations present if you remove the points of highest influence. The $R^2$ value of this correlation was 0.881 ($R^2$ adj. = 0.874, $R^2$ pred. = 0.852) with $p < 0.001$, showing that the relationship is not due mostly to a few especially high TSS events. Figure 10 shows all of the data points log transformed, and the relationship between them. This is also a good relationship, with $R^2 = 0.937$ ($R^2$ adj. = 0.934, $R^2$ pred. = 0.925).

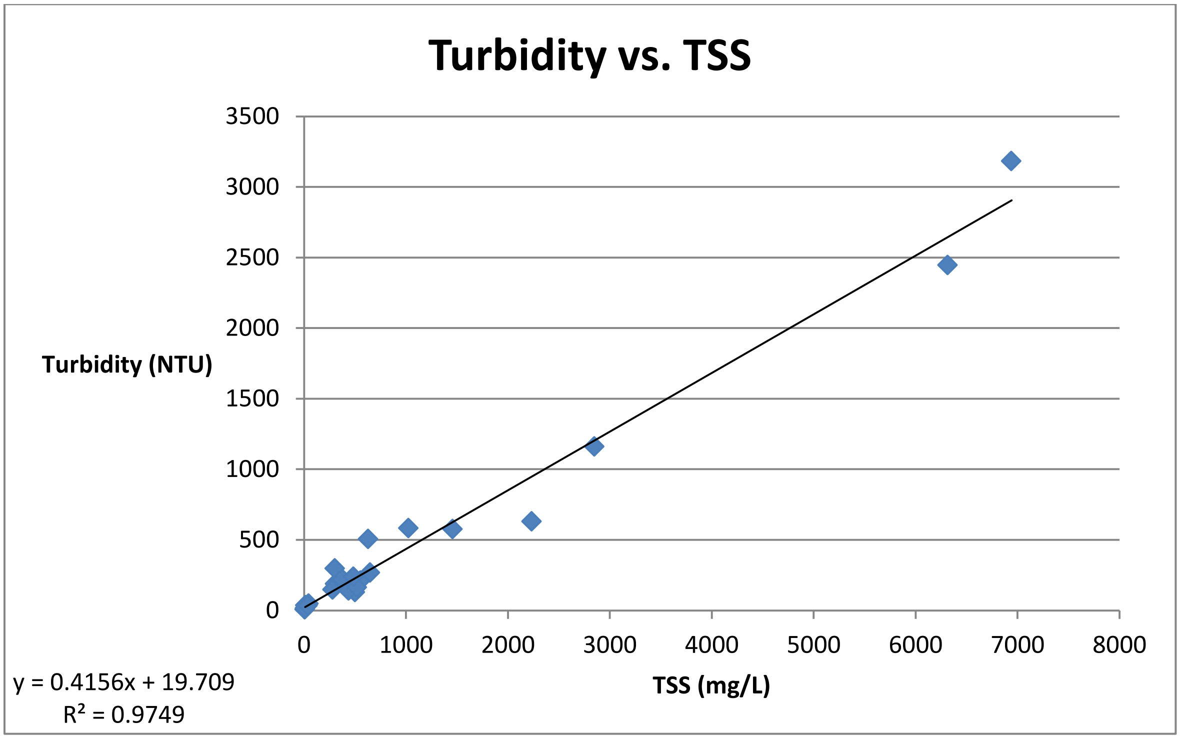


Figure 7: The linear relationship between Turbidity and TSS for all the data points collected in our research

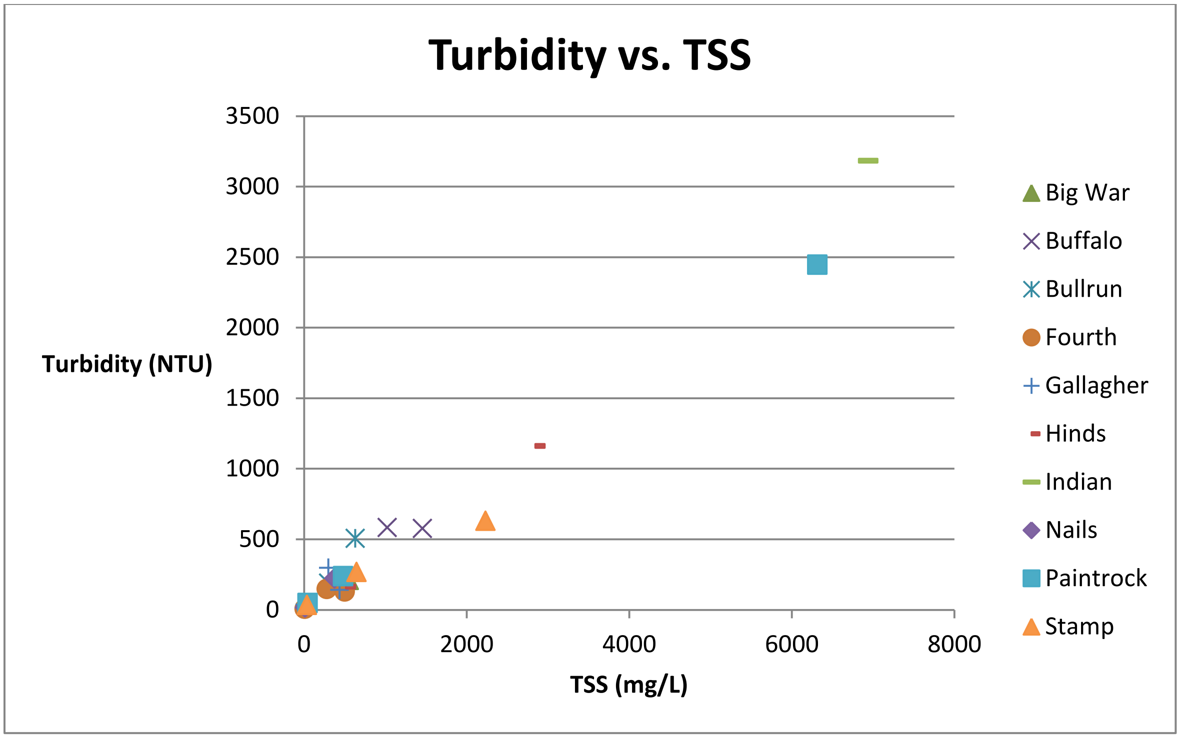


Figure 8: The same plot but showing which data points come from which source. The lack of obvious deviation from the trend shows the consistency of the data from all streams.

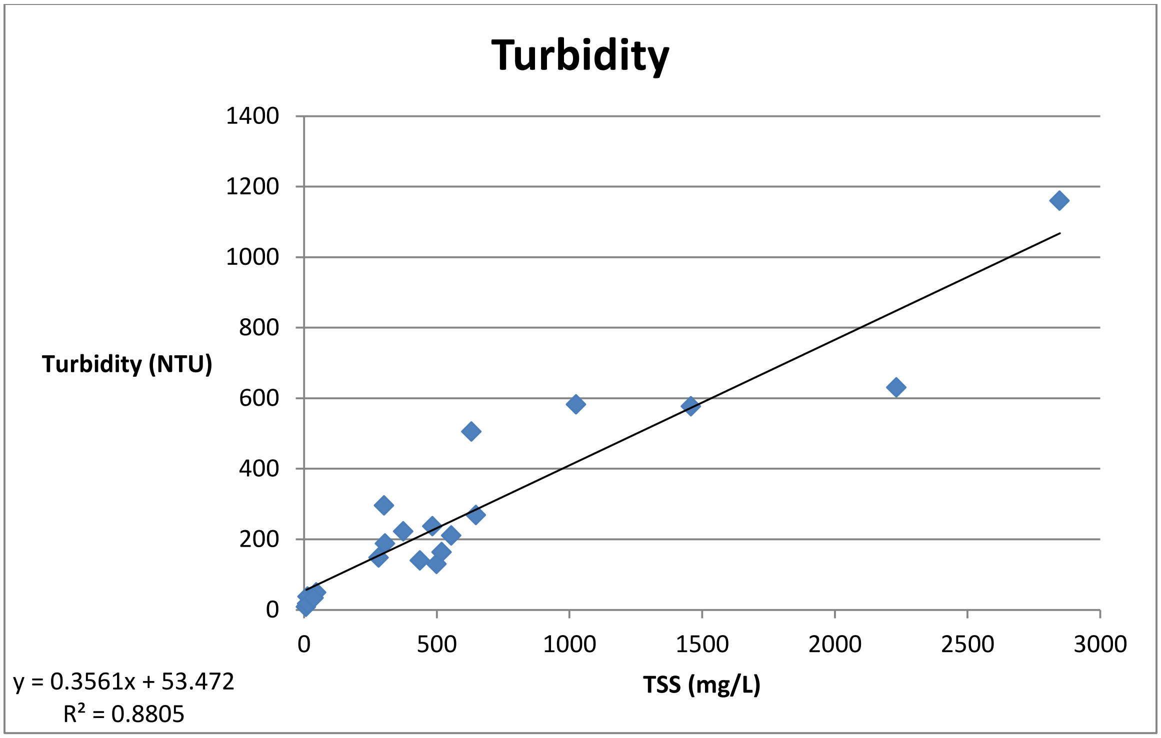


Figure 9: Turbidity vs. TSS with high influence values removed

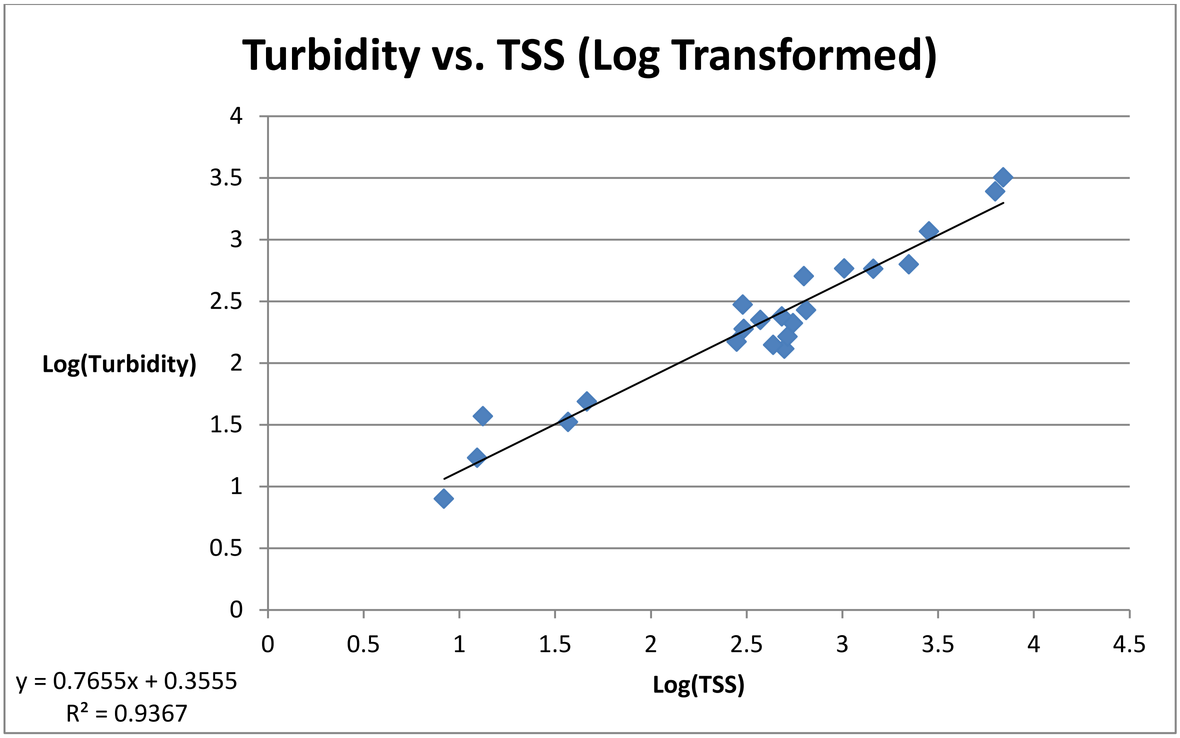


Figure 10: The Turbidity and TSS relationship log transformed

### 4.2 Number of Events above a Turbidity Threshold

The correlation between number of events above a turbidity level and TMI revealed some potentially significant relationships. Figures 11-15 show data plotted by index score verses the 100, 200, 300, 500, and 1000 NTU levels, and Table 3 shows the $R^2$ and p-values for each of these correlations. The $R^2$ values suggest that while very high level events (1000+ NTU in our case) are not good indicators of the biological health of a stream, the number of moderate turbidity events (100-500 NTU) do have a negative relationship with stream health. Figures 11-14 show $R^2$ values from 0.41 to 0.55 for the relationships with 100, 200, 300, and 500 NTU, all of which are significant at the 90% confidence level, and all but one are significant at the 95% level.

Table 3: This table tabulates the $R^2$ and P-values for each NTU threshold test
*- indicates significance at the 90% confidence level

| **TMI Correlations** | | | | |
|---|---|---|---|---|
| **NTU Threshold** | **$R^2$** | **P-value** | **$R^2$ Adj.** | **$R^2$ Pred.** |
| 100 NTU | 0.450 | 0.035* | 0.378 | 0.000 |
| 200 NTU | 0.552 | 0.018* | 0.466 | 0.000 |
| 300 NTU | 0.411 | 0.058* | 0.303 | 0.000 |
| 500 NTU | 0.491 | 0.044* | 0.344 | 0.000 |
| 1000 NTU | 0.212 | 0.153 | 0.142 | 0.000 |

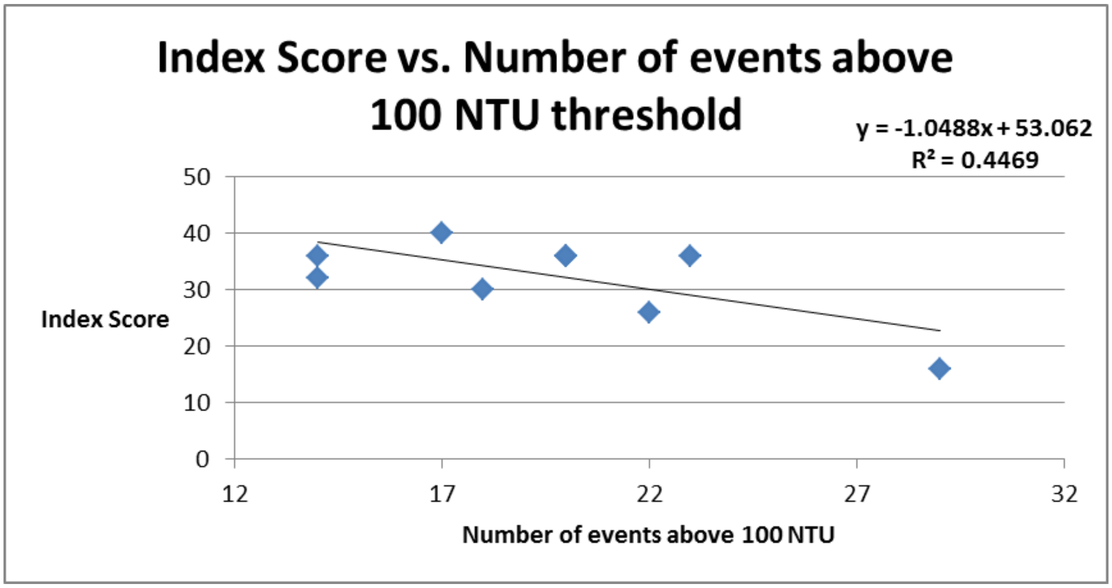


Figure 11: The relationship between the number of events above 100 NTU and the TMI scores

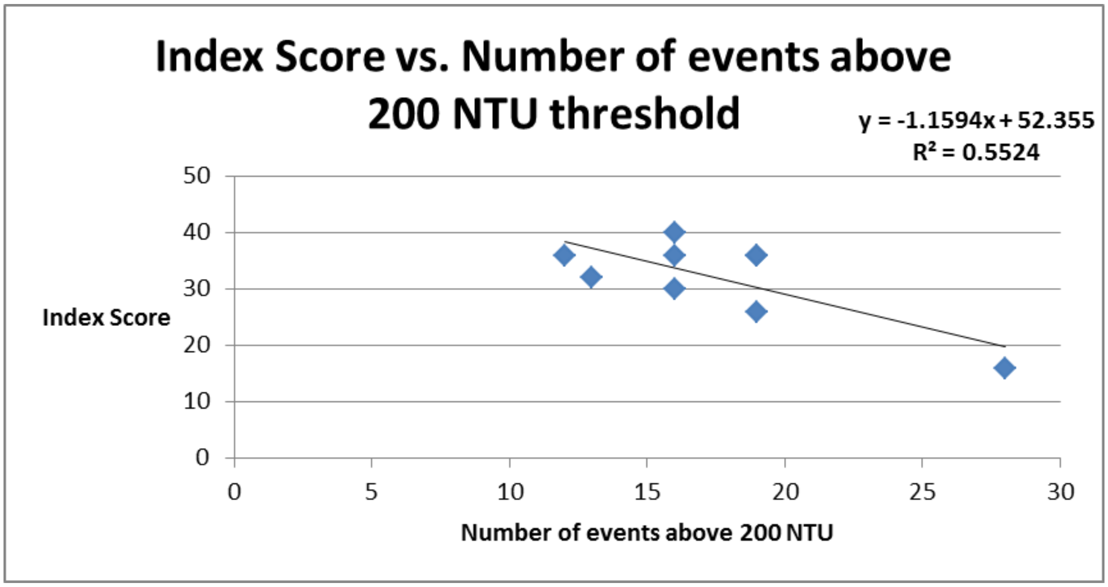


Figure 12: The relationship between the number of events above 200 NTU and the TMI scores

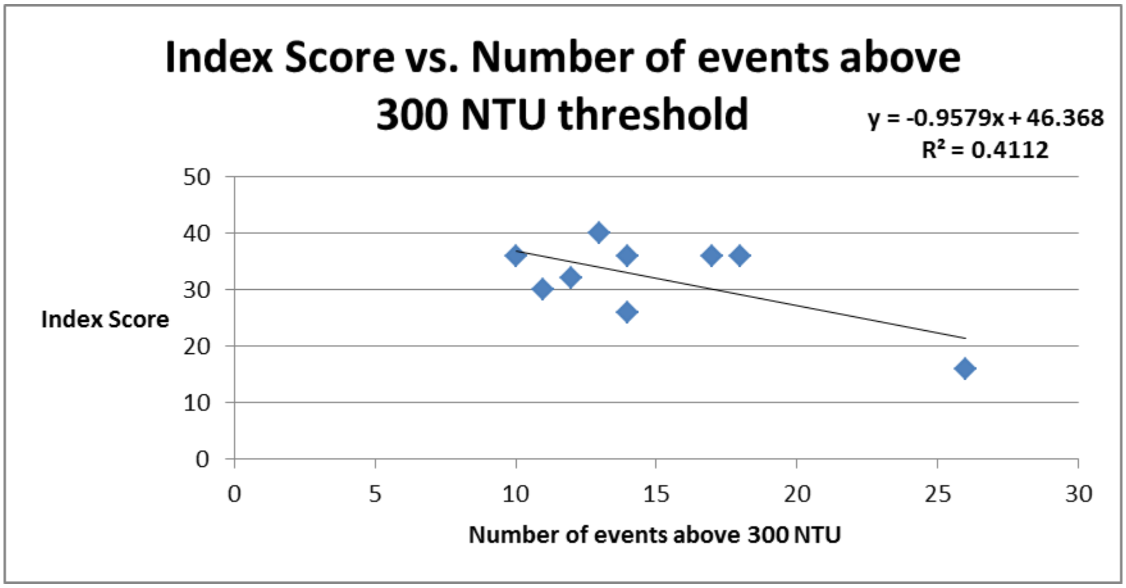


Figure 13: The relationship between the number of events above 300 NTU and the TMI scores

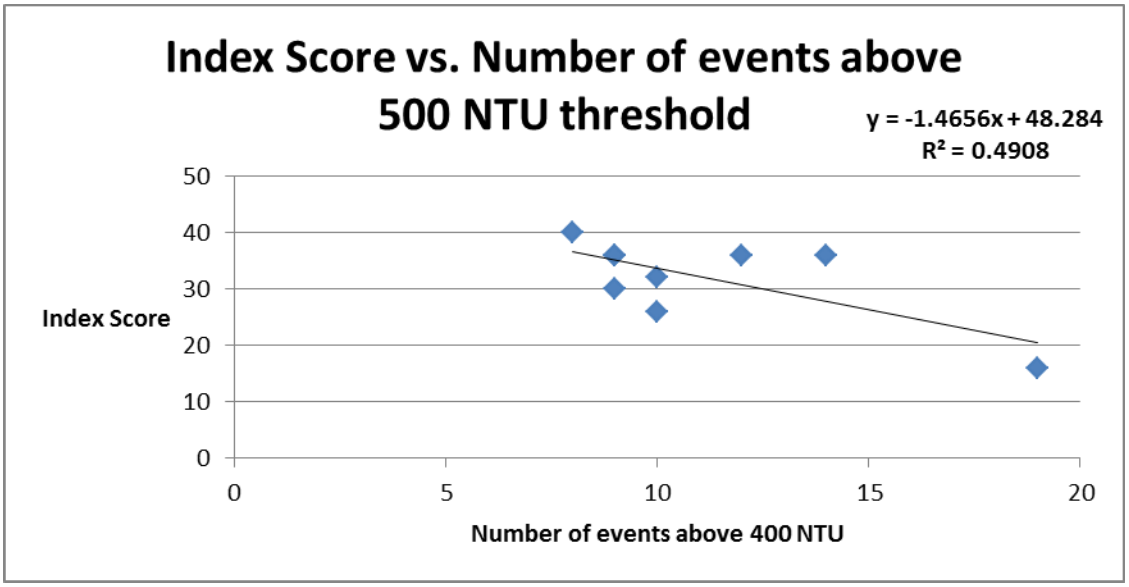


Figure 14: The relationship between the number of events above 500 NTU and the TMI scores

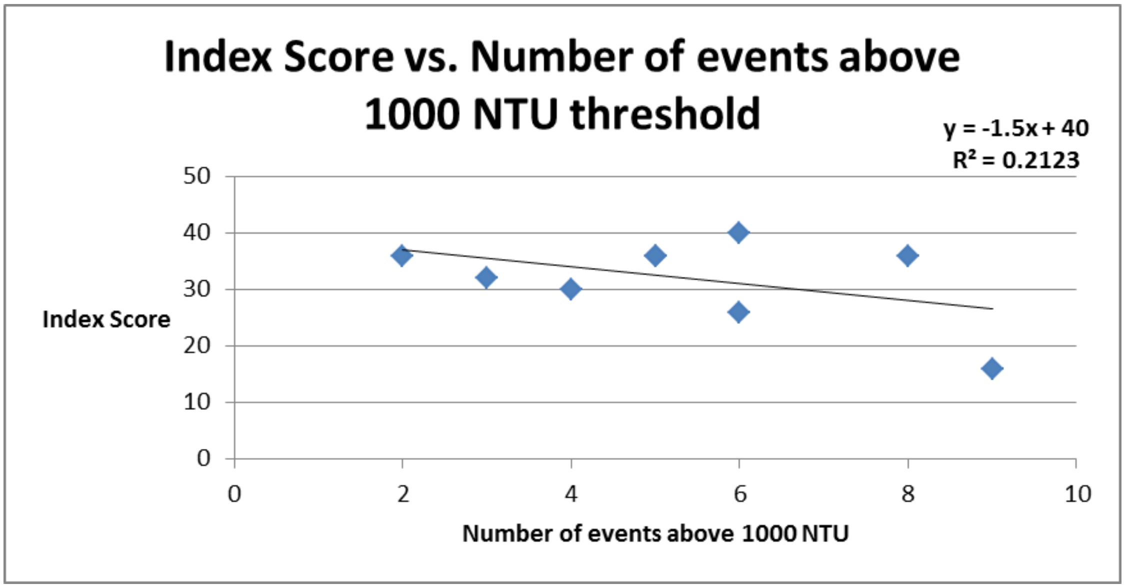


Figure 15: The relationship between the number of events above 1000 NTU and the TMI scores

Further analysis was done to look at what the effect would be on the data if Fourth Creek was removed from the dataset, for the reasons discussed in the Methods section. Figures 17-21 show this information graphically. As you can see, there is not a discernable relationship in the figures without the presence of Fourth Creek's data. The highest $R^2$ value found without Fourth Creek is 0.05; not indicative of any relationship.

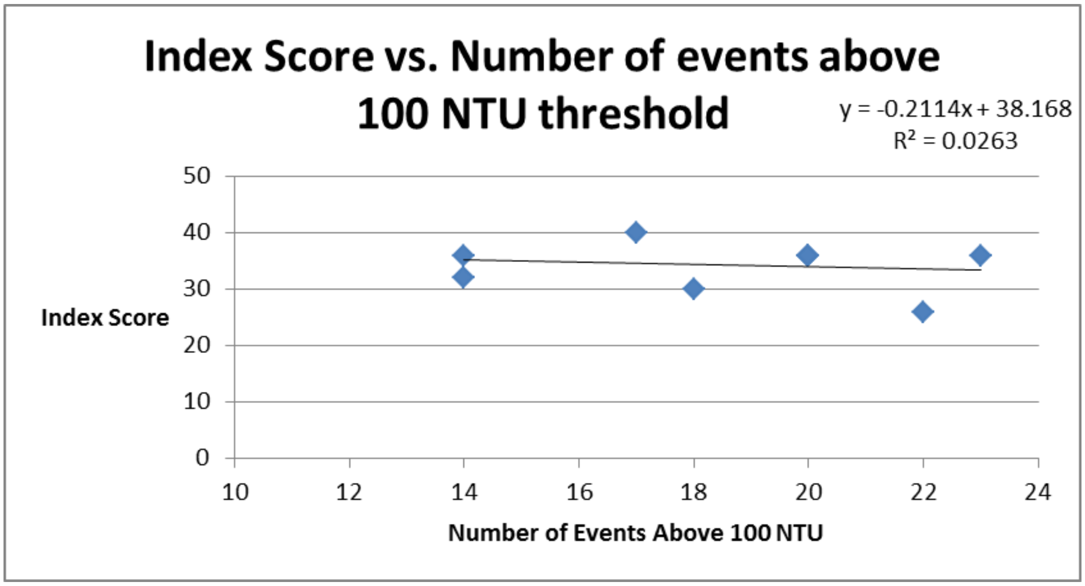


Figure 16: Index Score vs. 100 NTU Threshold without Fourth Creek in the dataset

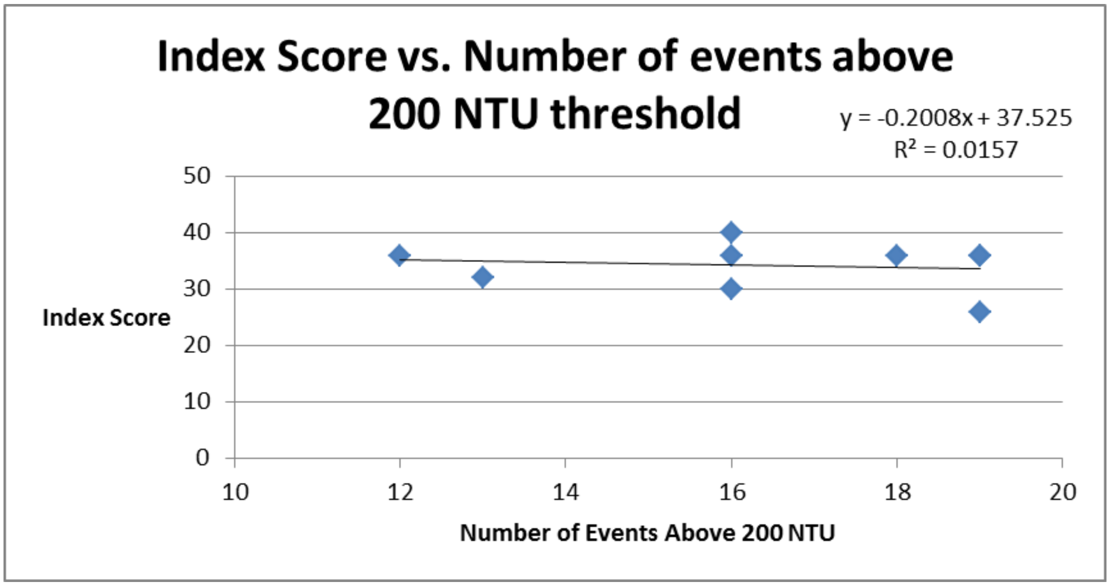


Figure 17: Index Score vs. 200 NTU Threshold without Fourth Creek in the dataset

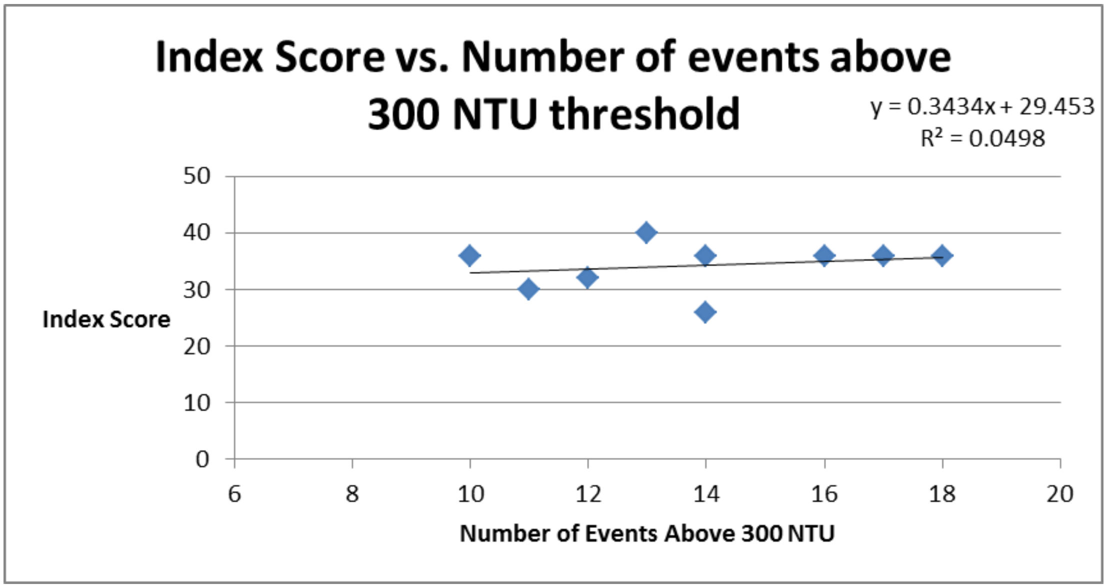


Figure 18: Index Score vs. 300 NTU Threshold without Fourth Creek in the dataset

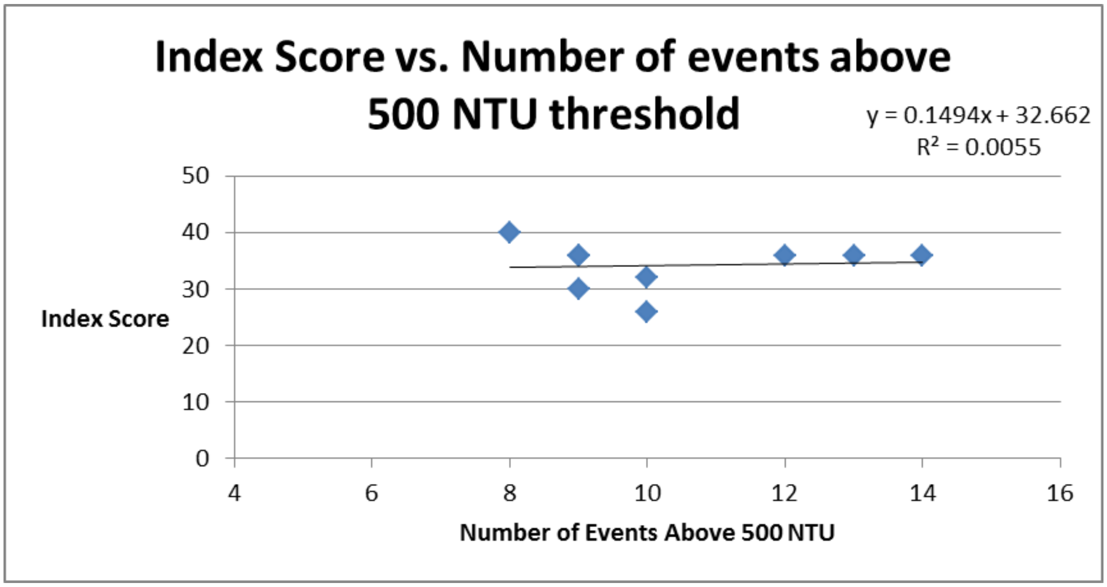


Figure 19: Index Score vs. 500 NTU Threshold without Fourth Creek in the dataset

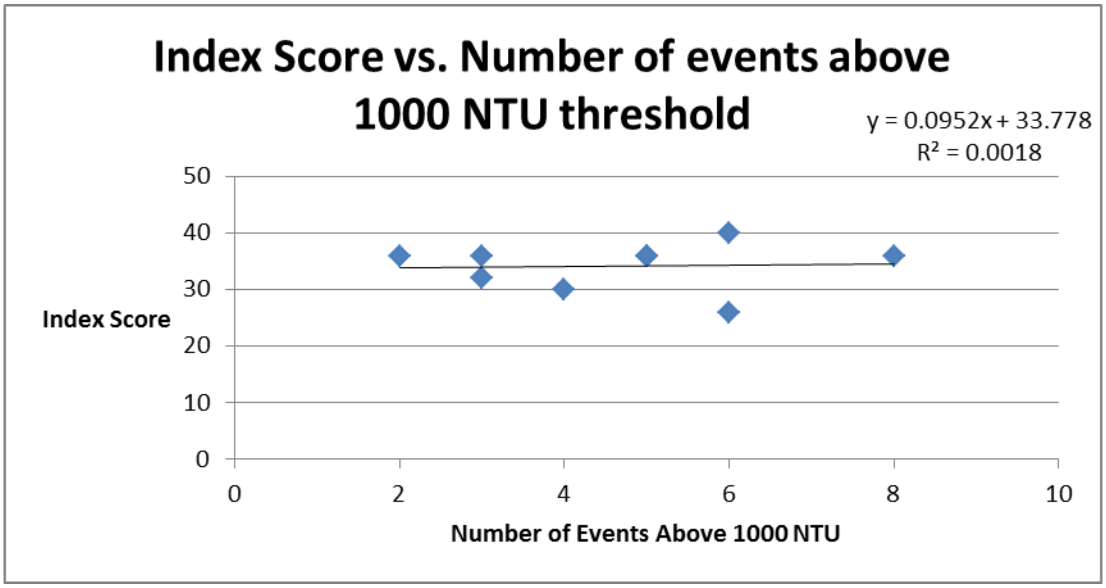


Figure 20: Index Score vs. 1000 NTU Threshold without Fourth Creek in the dataset

The same comparison was done for the Habitat Scores and %EPT scores, comparing the selected NTU thresholds to the scores for the same stream. Tables 4 and 5 show the $R^2$ and p-values for these relationships. Figures 21-25 show the Habitat Score graphs, and Figures 26-30 show the %EPT graphs. The %EPT correlations mirror the TMI correlations with statistically significant results at the 100, 200, 300, and 500 NTU levels, with $R^2$ values ranging from 0.33 to 0.53, all significant at the 90% confidence level, and the three lowest NTU thresholds significant at the 95% confidence level. The Habitat Score correlations only show a significant relationship at the 1000 NTU level.

Table 4: This table tabulates the $R^2$ and P-values for each NTU threshold test
*- indicates significance at the 90% confidence level

| **Habitat Score Correlations** | | | | |
|---|---|---|---|---|
| **NTU Threshold** | **$R^2$** | **P-value** | **$R^2$ Adj.** | **$R^2$ Pred.** |
| 100 NTU | 0.072 | 0.454 | 0.000 | 0.000 |
| 200 NTU | 0.101 | 0.371 | 0.000 | 0.000 |
| 300 NTU | 0.132 | 0.301 | 0.024 | 0.000 |
| 500 NTU | 0.206 | 0.188 | 0.107 | 0.000 |
| 1000 NTU | 0.449 | 0.034* | 0.381 | 0.201 |

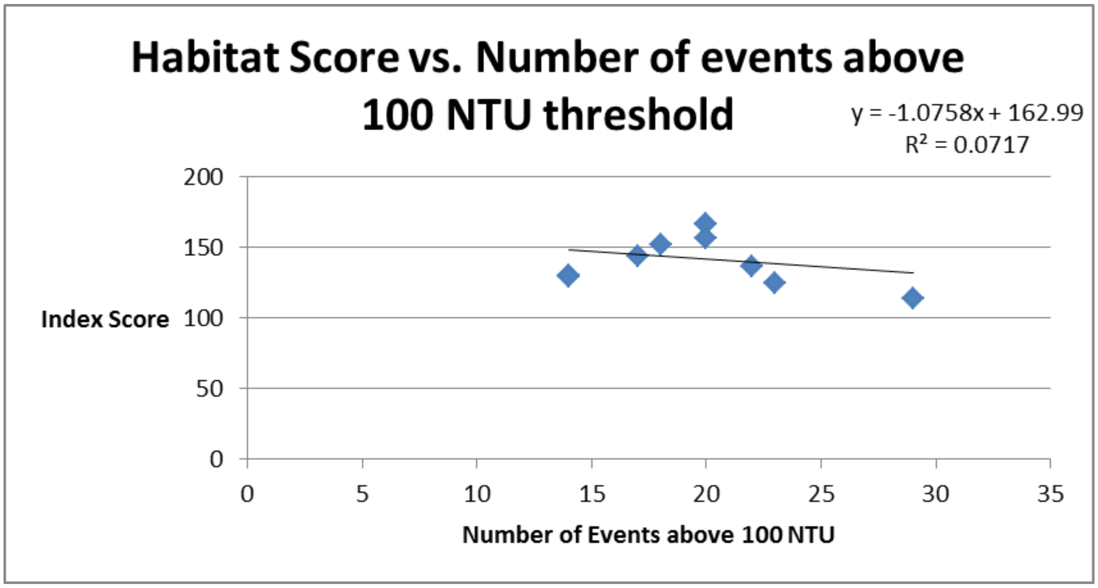


Figure 21: The relationship between the number of events above 100 NTU and the Habitat Scores

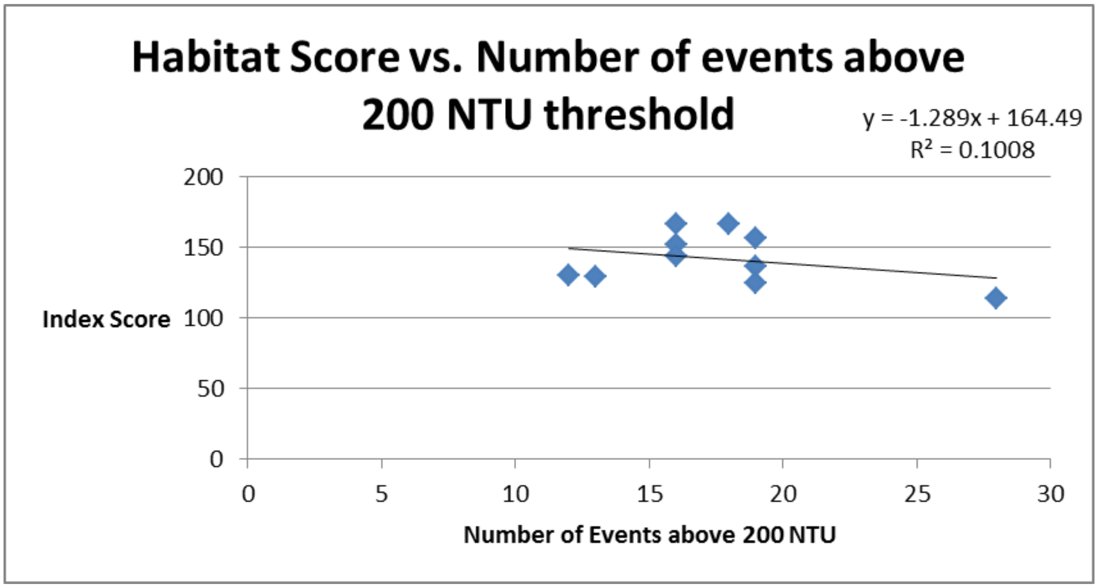


Figure 22: The relationship between the number of events above 200 NTU and the Habitat Scores

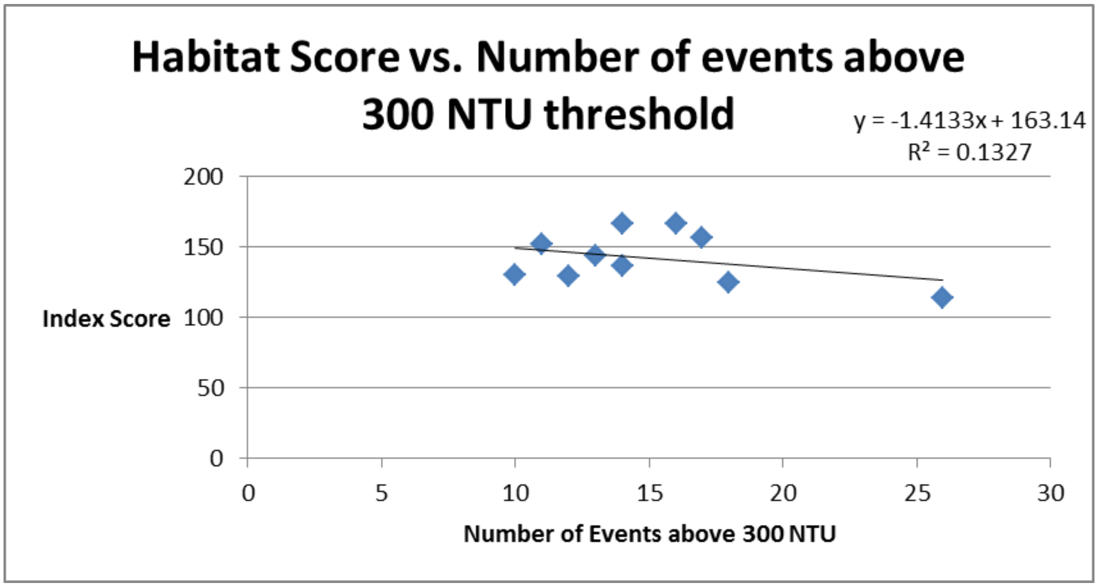


Figure 23: The relationship between the number of events above 300 NTU and the Habitat Scores

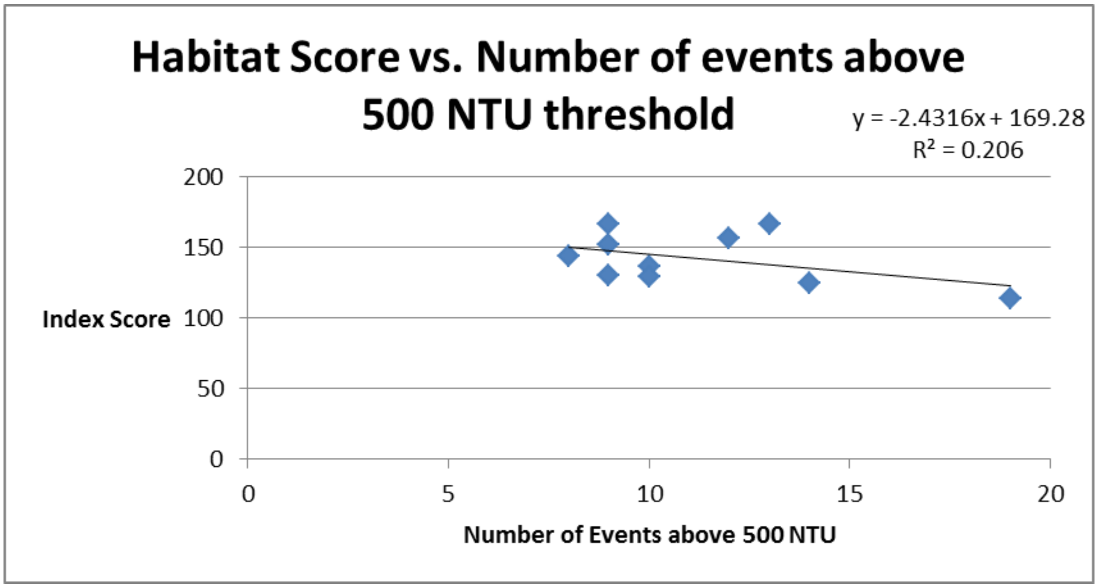


Figure 24: The relationship between the number of events above 500 NTU and the Habitat Scores

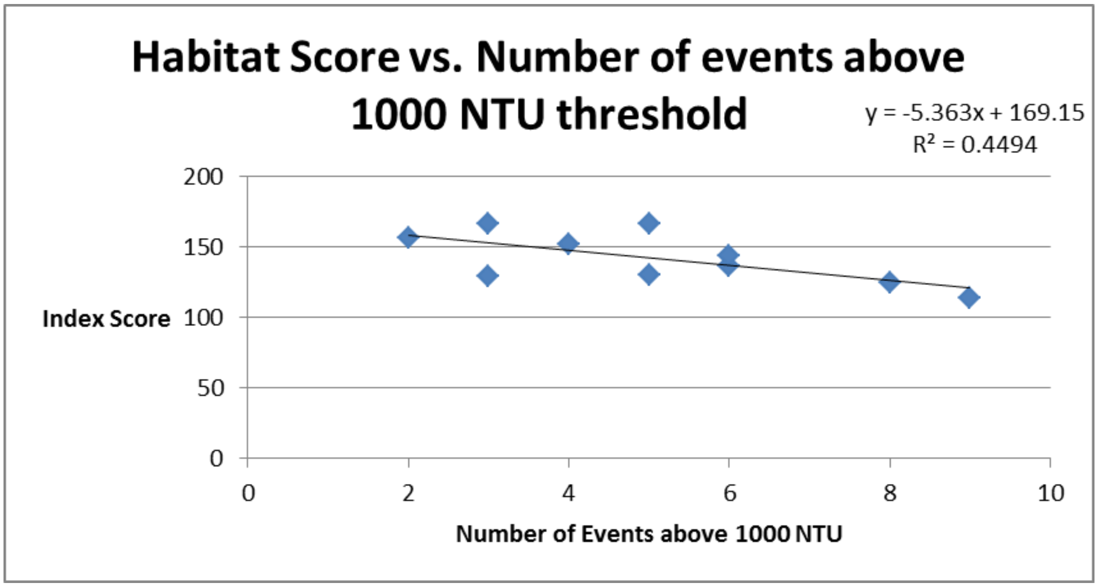


Figure 25: The relationship between the number of events above 1000 NTU and the Habitat Scores

Table 5: This table tabulates the $R^2$ and P-values for each NTU threshold test
*- indicates significance at the 90% confidence level

| **%EPT Correlations** | | | | |
|---|---|---|---|---|
| **NTU Threshold** | **$R^2$** | **P-value** | **$R^2$ Adj.** | **$R^2$ Pred.** |
| 100 NTU | 0.530 | 0.017* | 0.471 | 0.242 |
| 200 NTU | 0.537 | 0.016* | 0.479 | 0.322 |
| 300 NTU | 0.422 | 0.042* | 0.350 | 0.000 |
| 500 NTU | 0.334 | 0.080* | 0.251 | 0.000 |
| 1000 NTU | 0.096 | 0.384 | 0.000 | 0.000 |

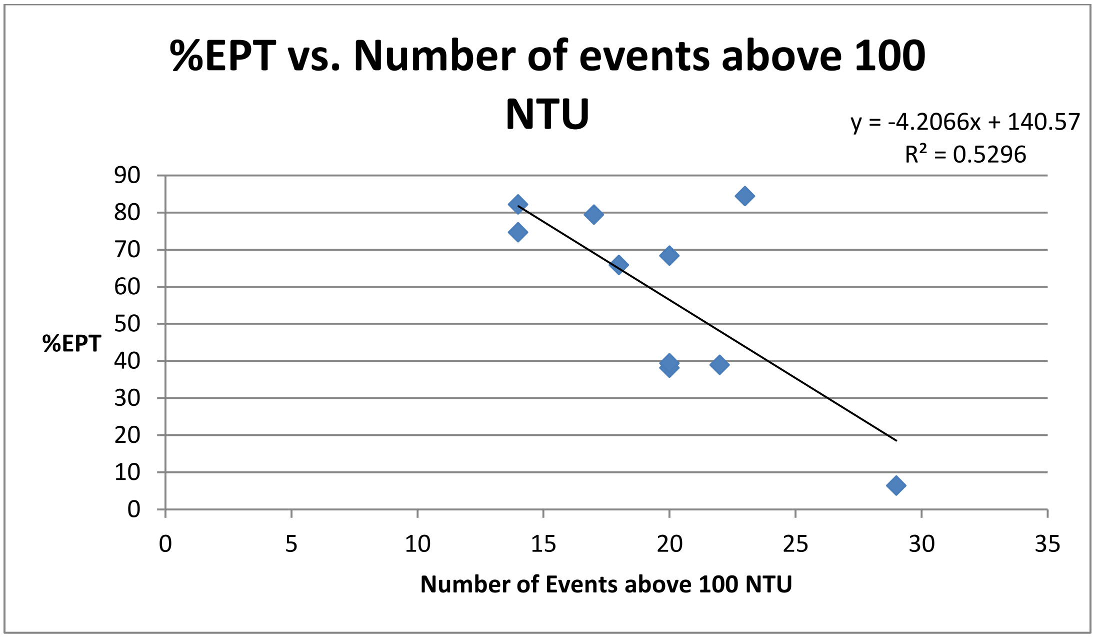


Figure 26: The relationship between the number of events above 100 NTU and the %EPT scores

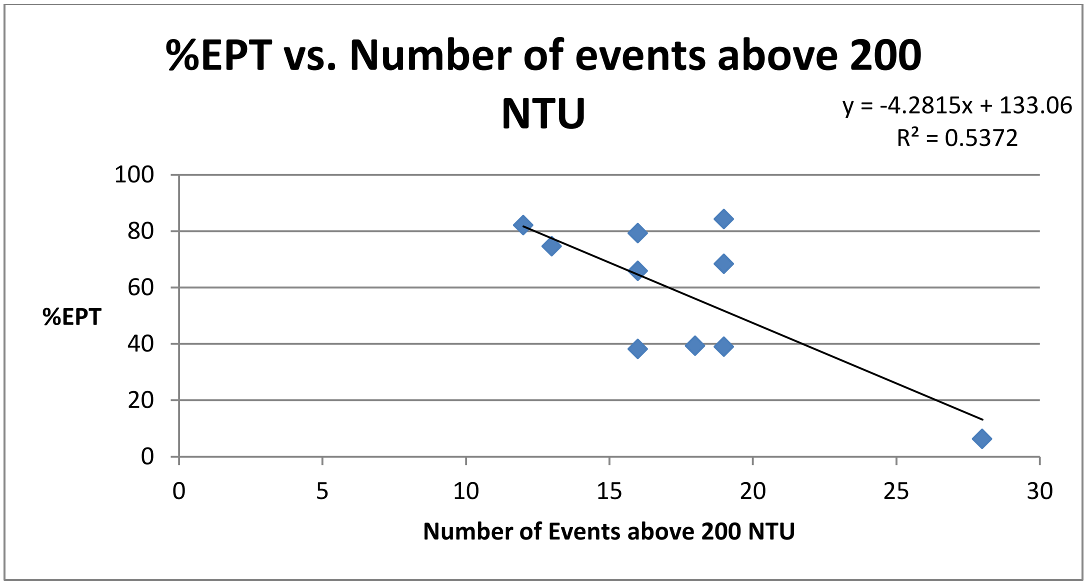


Figure 27: The relationship between the number of events above 200 NTU and the %EPT scores

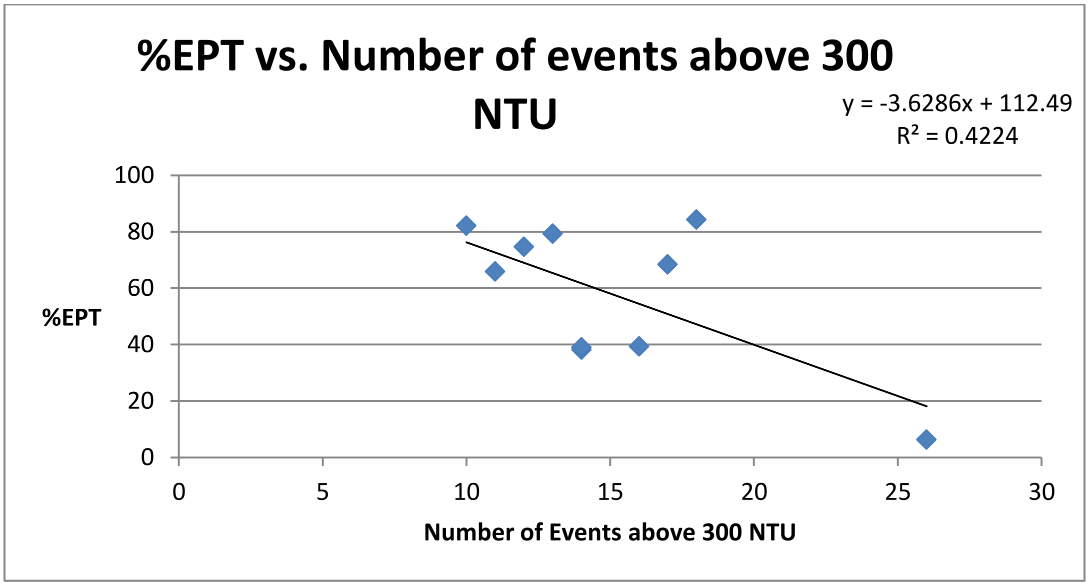


Figure 28: The relationship between the number of events above 300 NTU and the %EPT scores

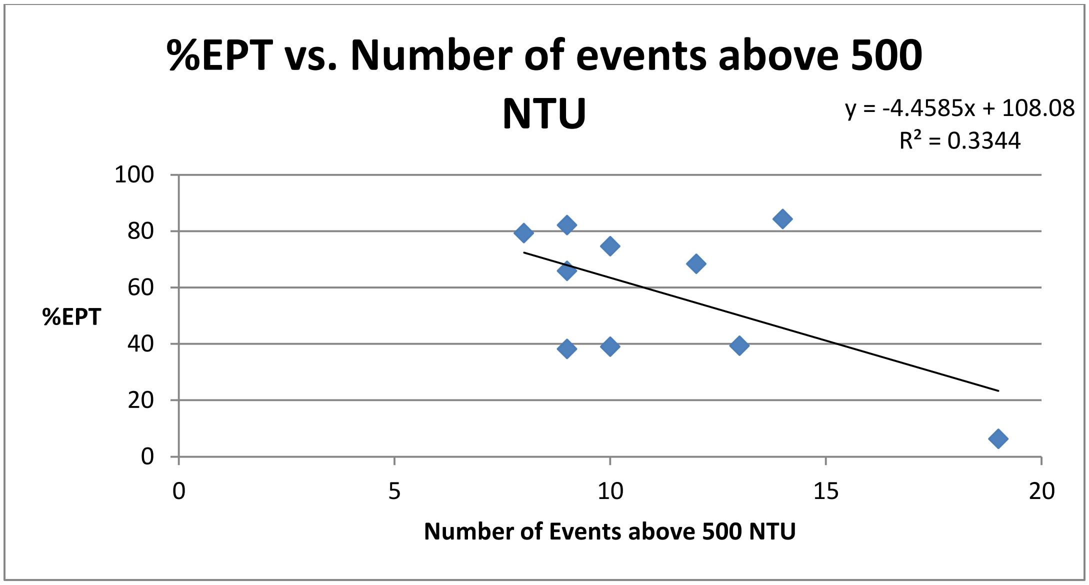


Figure 29: The relationship between the number of events above 500 NTU and the %EPT scores

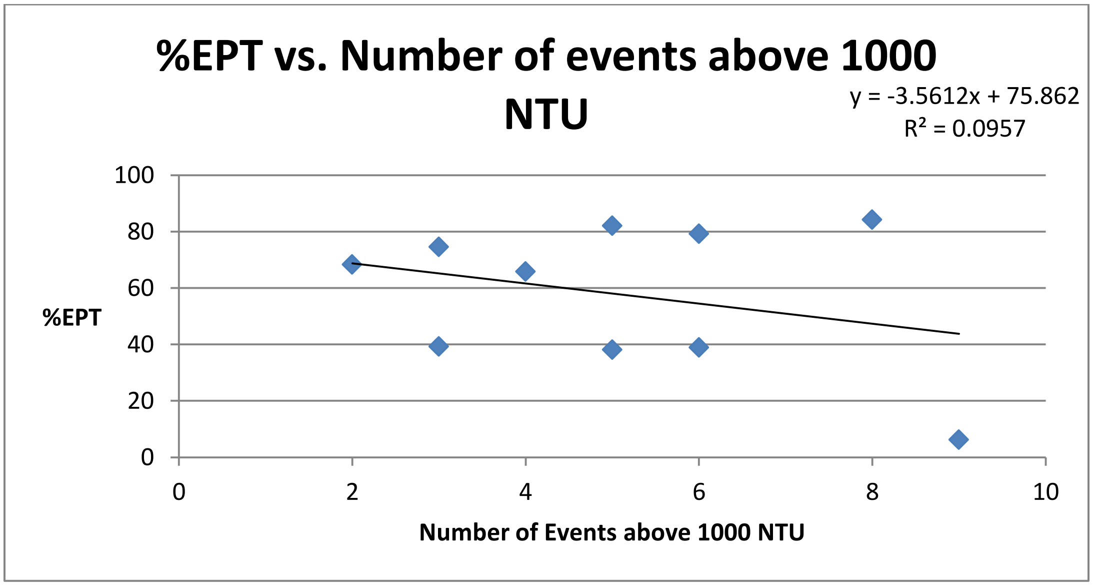


Figure 30: The relationship between the number of events above 1000 NTU and the %EPT scores

### 4.3 Change in Turbidity Over Change in Stage per Storm Event

The correlation between TMI scores and the increase in turbidity per change in stage did not reveal a correlation when the values were averaged per site ($R^2 = 0.0758$, $p = 0.441$) or when the storm events were taken separately ($R^2 = 0.0403$, $p = 0.145$). The correlation between Habitat Scores and the rate of turbidity increase also did not reveal a correlation in either case ($R^2 = 0.0054$, $p = 0.840$ for site average; $R^2 = 0.0076$, $p = 0.530$). While this data is likely impacted quite a bit by the tendency of the instrument housing to retain sediment, the lack of a noticeable difference between the rates of turbidity increase between streams of differing TMI and Habitat Scores indicates that the problem probably does not lie in the confounding variables. See Figures 31-34 below for the graphical information.

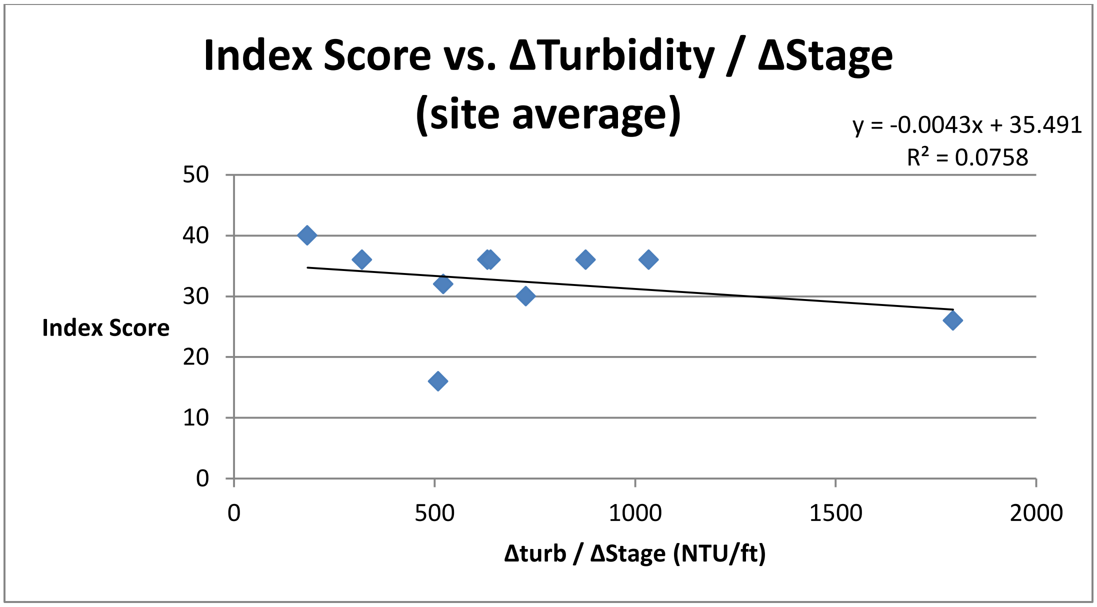


Figure 31: The Index Score vs. the change in turbidity per change in stage average for each stream site

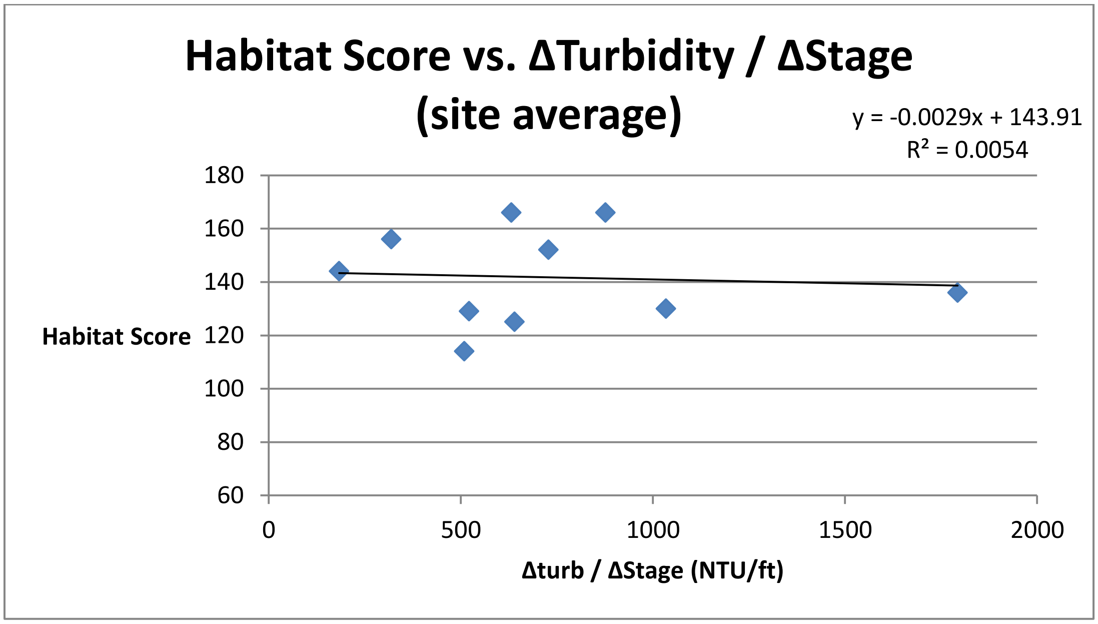


Figure 32: The Habitat Score vs. the change in turbidity per change in stage average for each stream site

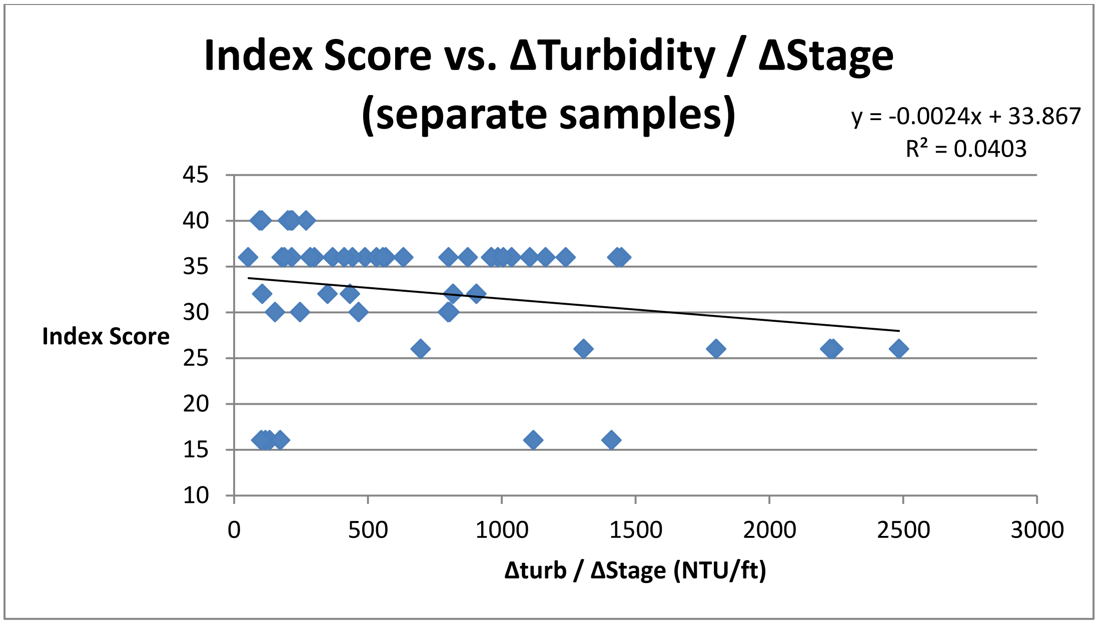


Figure 33: Index Score vs. the change in turbidity per change in stage separated into individual storm events

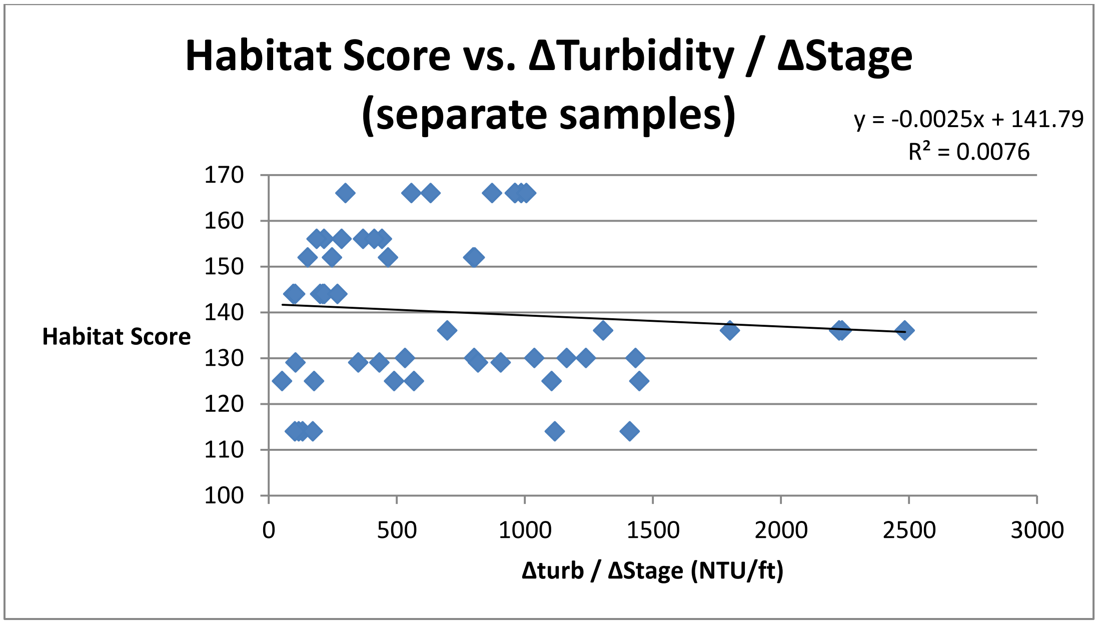


Figure 34: Habitat Score vs. the change in turbidity per change in stage separated into individual storm events

### 4.4 Change in Turbidity Over Change in Flow

The correlation between TMI scores verses the increase in turbidity per change in flow did not reveal a correlation when averaged for each site or when taken as individual storm events ($R^2$ = 0.0098, p = 0.786 and $R^2$ = 0.0052, p =0.605 respectively). The same is true when correlating Habitat Scores verses change in turbidity per change in flow ($R^2$ = 0.0463, p = 0.551 when averaged and $R^2$ = 0.0257, p = 0.247 taken individually). Streams of similar TMI scores have greatly varying rates of turbidity change with flow. Just like the previous correlation, this data is likely impacted by the tendency of the instrument housing to retain sediment, but the lack of a noticeable difference between the rates of turbidity increase between streams indicates that the problem probably does not lie in the confounding variables. Figures 35-38 below show the information graphically.

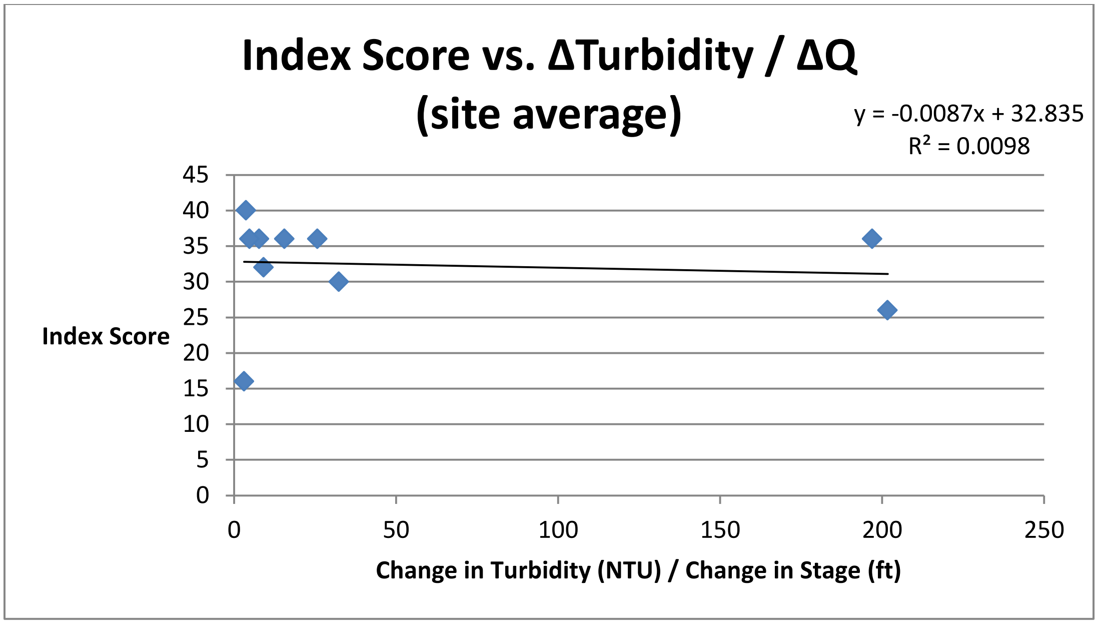


Figure 35: The Index Score vs. the change in turbidity over change in flow average for each stream site

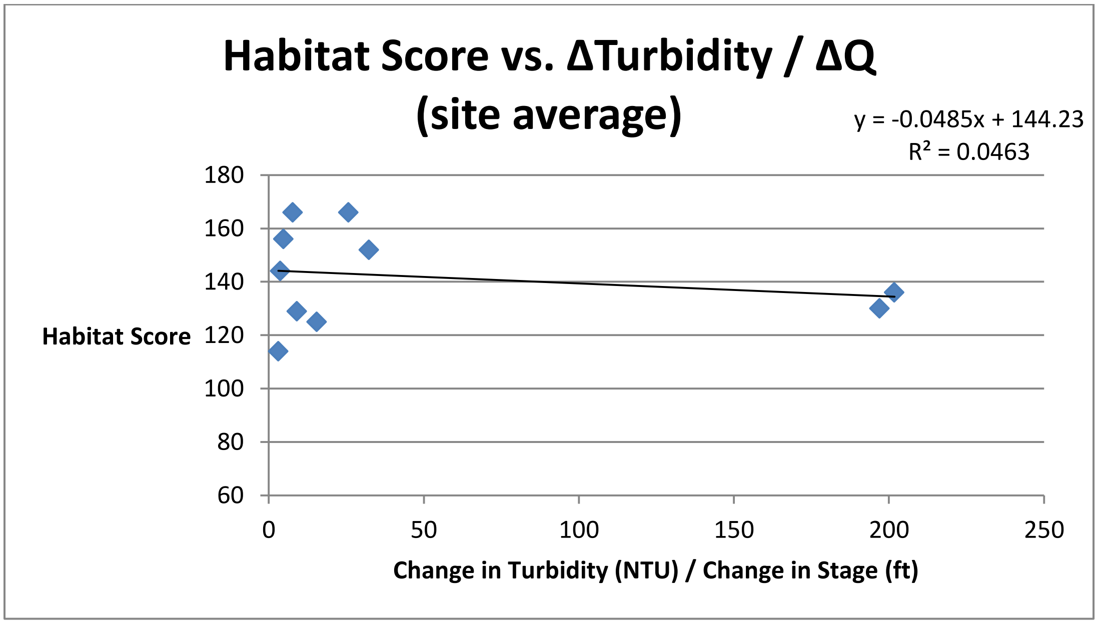


Figure 36: The Habitat score vs. the change in turbidity over change in flow average for each stream site

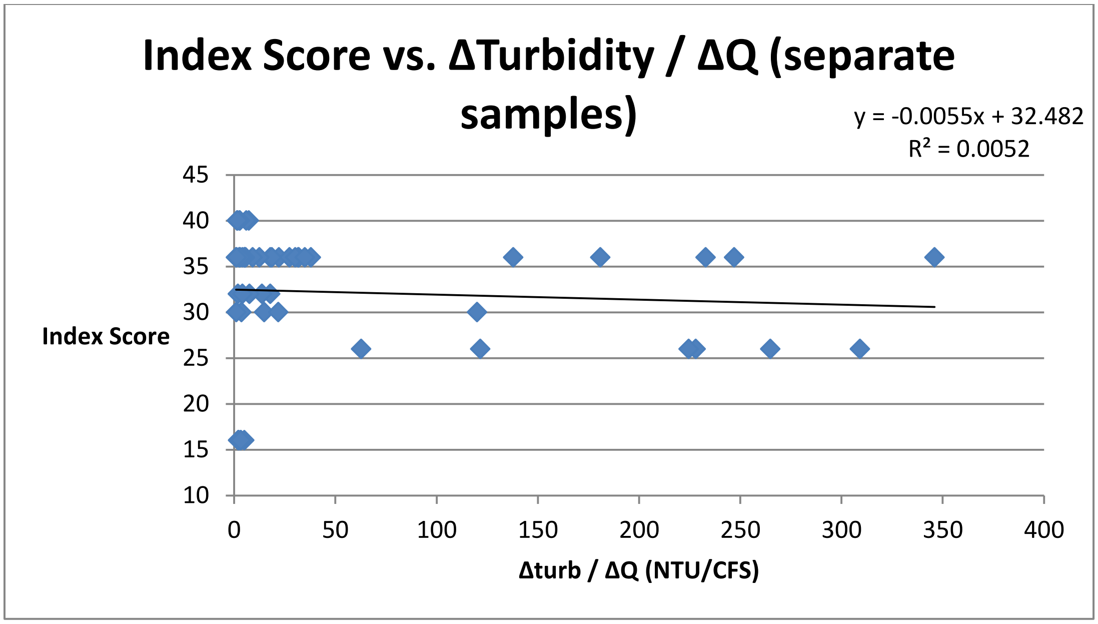


Figure 37: Index Score vs. change in turbidity per change in flow separated into individual storm events

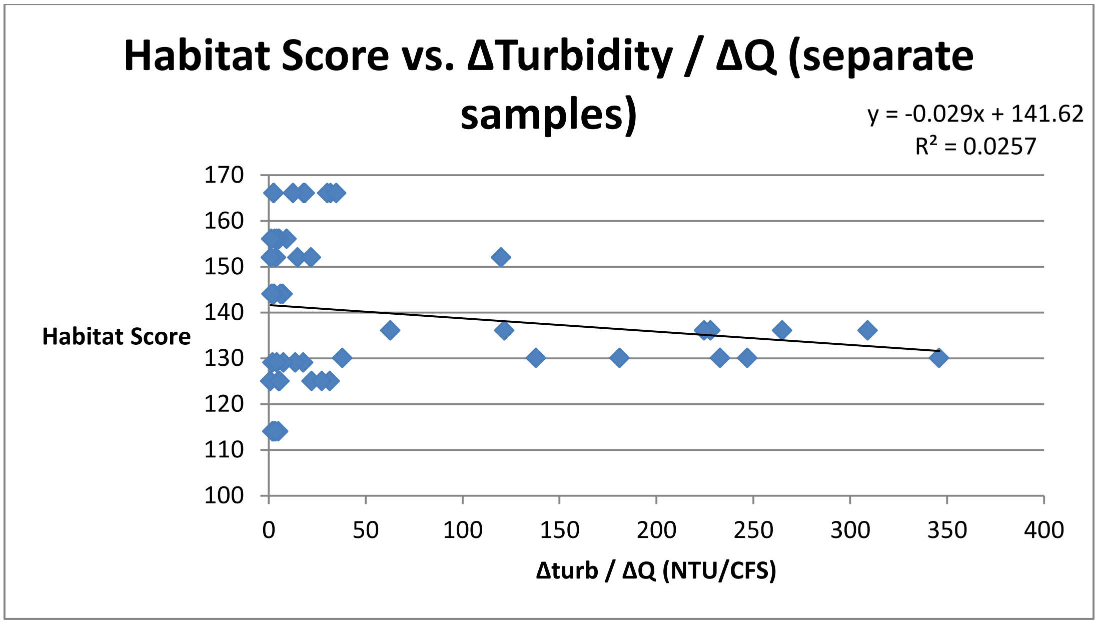


Figure 38: Habitat Score vs. change in turbidity per change in flow separated into individual storm events

### 4.5 Total Suspended Solids

This was an interesting correlation to observe, as there was no relationship found between the averages of the TSS samples from each site and their TMI scores ($R^2 = 0.0208$, $p = 0.691$), but there was a correlation with the Habitat Score ($R^2 = 0.456$, $R^2$ Adj = 0.383, $R^2$ Pred = 0.288, $p < 0.05$). Strangely, the correlation was a positive one, not a negative one as we have seen so far and would anticipate. Below the data is displayed graphically in Figures 39 and 40.

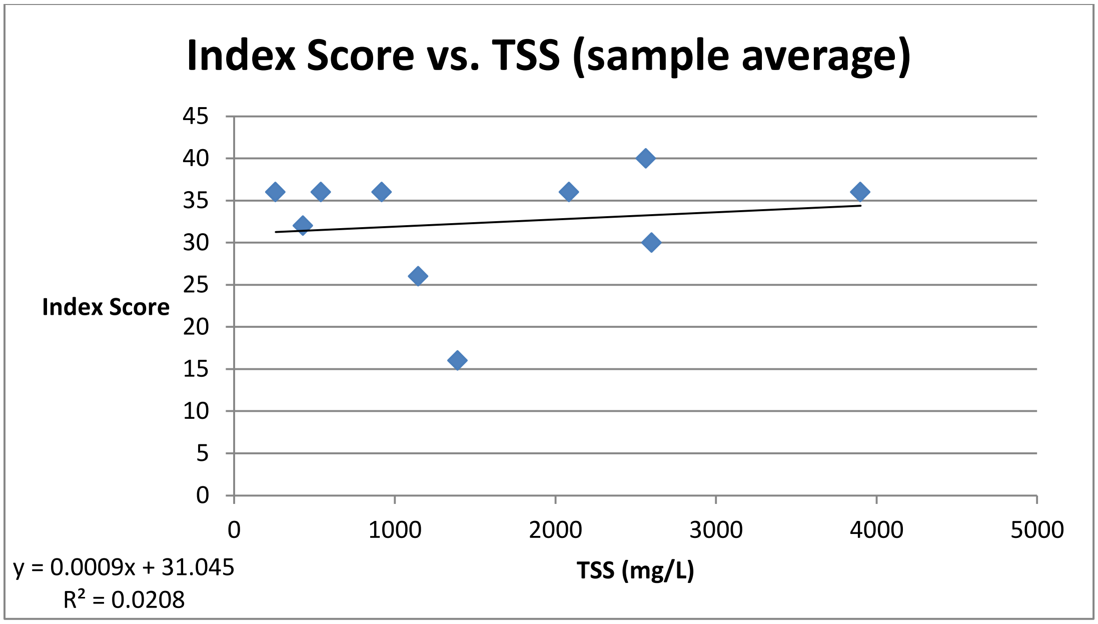


Figure 39: The Index Score vs. the average TSS sample value for each site

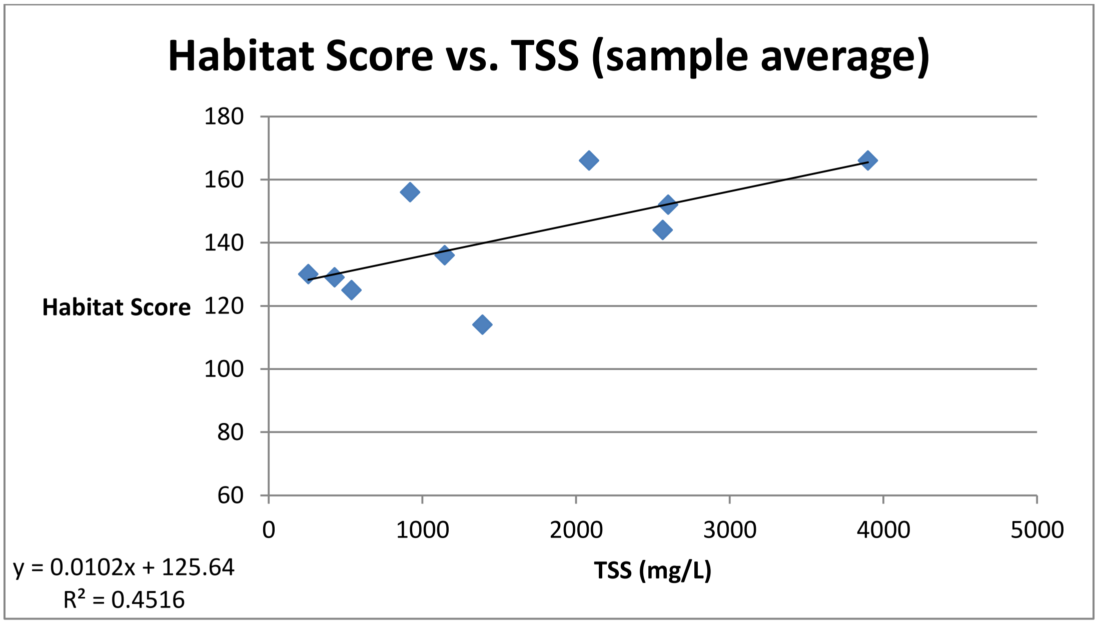


Figure 40: The Habitat score vs. the average TSS sample value for each site

## 5.0 DISCUSSION

### 5.1 Turbidity vs. TSS

For the correlation between turbidity and TSS for our stream sites, the data was found to have a strong linear relationship, which agrees with most of the previous experiments. Figure 4 in the appendix shows the plot of the data points, as well as the correlation coefficient, best fit line, and the equation for that line. An $R^2$ value of 0.975 shows a strong linear relationship between the two variables, and it is significant at the 99% confidence level. Figure 5 shows the same data points but indicates which streams they all came from. This graph shows the consistency of the relationship from various stream locations. While this information shows that turbidity can be a reliable surrogate for TSS under controlled conditions, using turbidity measurements in the field is still difficult, due to the problems discussed earlier with confounding variables. The rest of the stats analyses were run using turbidity data from the in situ probes, as opposed to this analysis, so we expect to see plenty of extra “noise” in the data and subsequent correlations.

### 5.2 Number of Events above a Turbidity Threshold

Due to the fact that a stream’s biological health is affected by many factors, it is not surprising that the $R^2$ values are not high and the p-values are low when comparing the turbidity thresholds with TMI scores. There is sure to be plenty of noise in the data that is difficult to account for. The main problem with the results lies in the $R^2$ predicted values. While the regular $R^2$ value shows the expected trend in the data, the value of these relationships is in their ability to predict biological impairment in lieu of sending people to do a detailed investigation of the stream. Without the ability to actually predict a TMI score within some reasonable margin of error the relationship is not helpful in predicting impairment.

The correlation of turbidity with habitat scores turned out to be not as consistently valuable across different threshold levels, but the results are not surprising either. Low turbidity thresholds did not correlate with the habitat scores, but at every level the $R^2$ level went up and the p-value dropped, indicating higher levels of turbidity affect the habitats of aquatic life more than low levels. This is not an unexpected result, but it is good to see what might already be assumed as true validated by the information. Unfortunately, the $R^2$ predicted values were again zero in every case except one, the 1000 NTU threshold. So while this data may not be helpful in prediction, it may be that a turbidimeter with a higher NTU cap could give valuable results based on the continuing increase in statistical significance with threshold value seen here. A separate analysis withholding Fourth Creek from the dataset was not necessary, as the Habitat Scores are far more evenly distributed.

The %EPT correlations mirrored that of the TMI correlations, which is unsurprising given that %EPT makes up a portion of the TMI score. The EPT taxa are specifically vulnerable to fine sediments (Kaller and Hartman, 2004), which may explain why the lower NTU values are more significant both for EPT testing and the total TMI score. If the biggest pollutant in a benthic macroinvertebrate community is sediment, then the EPT taxa should be affected the worst, and this %EPT score would be the biggest influence on the TMI score.

## 5.3 Total Suspended Solids

The correlation between Habitat Score and TSS is puzzling. One would expect that siltation in a stream would leave deposits that would negatively affect, or ever bury, habitat structures. While it is not clear from this study why this correlation appeared, it seems to warrant further investigation to see if this relationship was just a coincidence in this study or if there is a real reason for this correlation and we should expect to see it repeated.

One potential problem with this analysis was that the number of samples from each site was small, 2-4 for most sites. To look at TMI vs. TSS more thoroughly, TSS samples could be taken more diligently during storm events, and the sites chosen should have a more varied level of TMI scores than our current stream sites do. There would also have to be strong standards for how the samples are gathered. For instance, there may be a sediment gradient that changes with stream depth, so the passive samplers would need to be installed at a consistent bankfull level.

The purpose of this research was to look at ways of determining biological health that were cost effective and simpler than intensive TSS sampling, so this was not a testing avenue we pursued rigorously. This particular attempt at correlating these two variables may not have been particularly robust, but still does not give an indication that this is a line of investigation that merits pursuing.

## 6.0 RECCOMENDATIONS

### 6.1 Instruments

The biggest obstacle to obtaining more results, and more reliable results, from this study was the instrumentation. The first problem was the quick and easy fouling of the turbidity lenses. The second problem was the sediment catching in the device housings. The first problem can be addressed through a few different means. To address the first problem, further studies of this kind should use turbidimeters that have cleaning wipers installed on them. This leads to batteries draining faster, but the instrument will take better and more consistent data. Also, we recommend that the study sites be located geographically in a way that accommodates more frequent maintenance checks. Between battery changes and the potential need for regular cleaning, the sites should be located in areas that allow for the instruments to be checked on regularly without too much hassle.

The second problem should be addressed by a new housing design that is not prone to catching sediment, such as a cage housing instead of a pipe housing. While the reasons behind our sites catching and holding sediment to such a great degree are not fully understood, a design could be implemented that simply doesn't allow sediment anywhere to rest.

One of the most important benefits of turbidity probes that lack confounding variables will be the ability to look at the duration of events above NTU thresholds, and not just the frequency. Newcombe and MacDonald (1991) found that the duration and frequency of high SSC events together were far better indicators of sediment effects than looking only at the frequency of turbidity exceedance, and other studies and standards have begun to move in the direction of including duration factors (Diehl and Wolfe, 2010). The noise in our data prevents us from accurately assessing the duration of different turbidity events, but it should be examined in future studies if the right equipment is used.

## 6.2 Testing Sites

Along with being easy to access, stream sites should be more varied in biological condition. The sites tested in this study were unfortunately not varied in their TMI scores, which made conclusions difficult to draw statistically. Sites more varied in geography and biological state will give a more robust understanding of the relationships that exist between turbidity and the biological state of a stream. While streams with a lower TMI score likely have more variables affecting their poor state, we can see in this study how turbidity and biological metrics do not correlate well over small ranges, and we need to see the relationship between siltation and all ranges of biological impairment, not just a select range.

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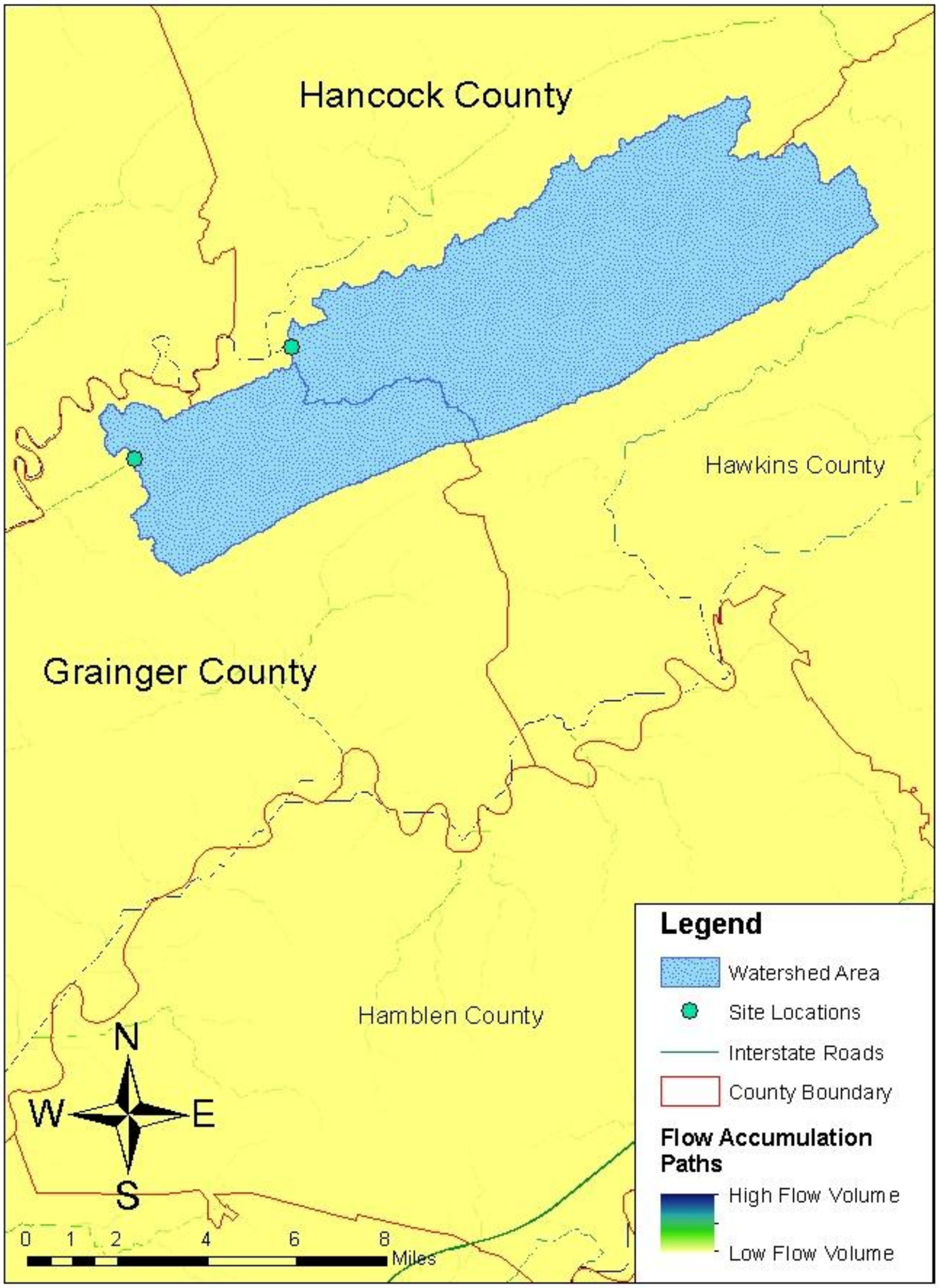
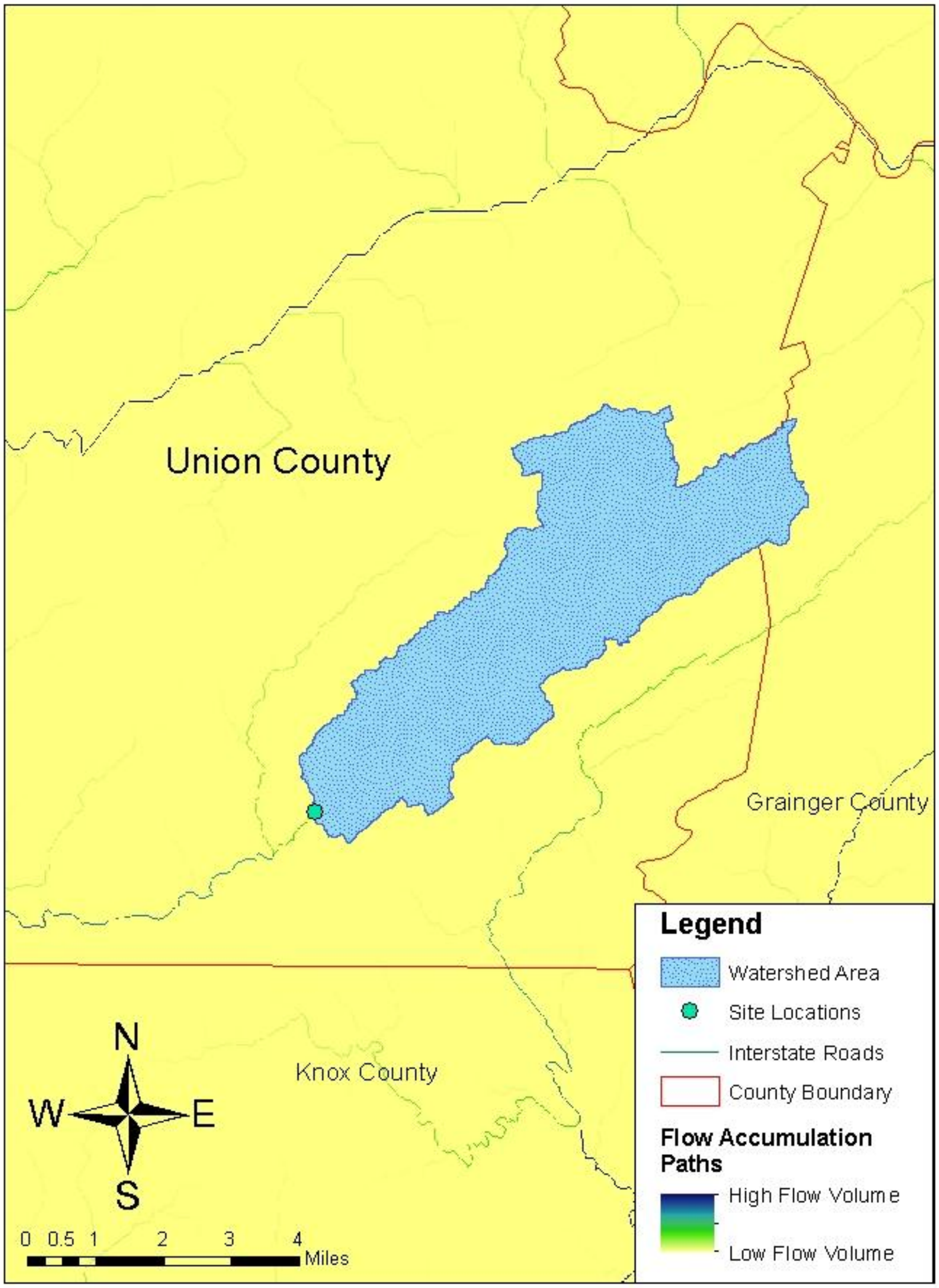
# Appendix

## **Site Location and Watershed Maps**

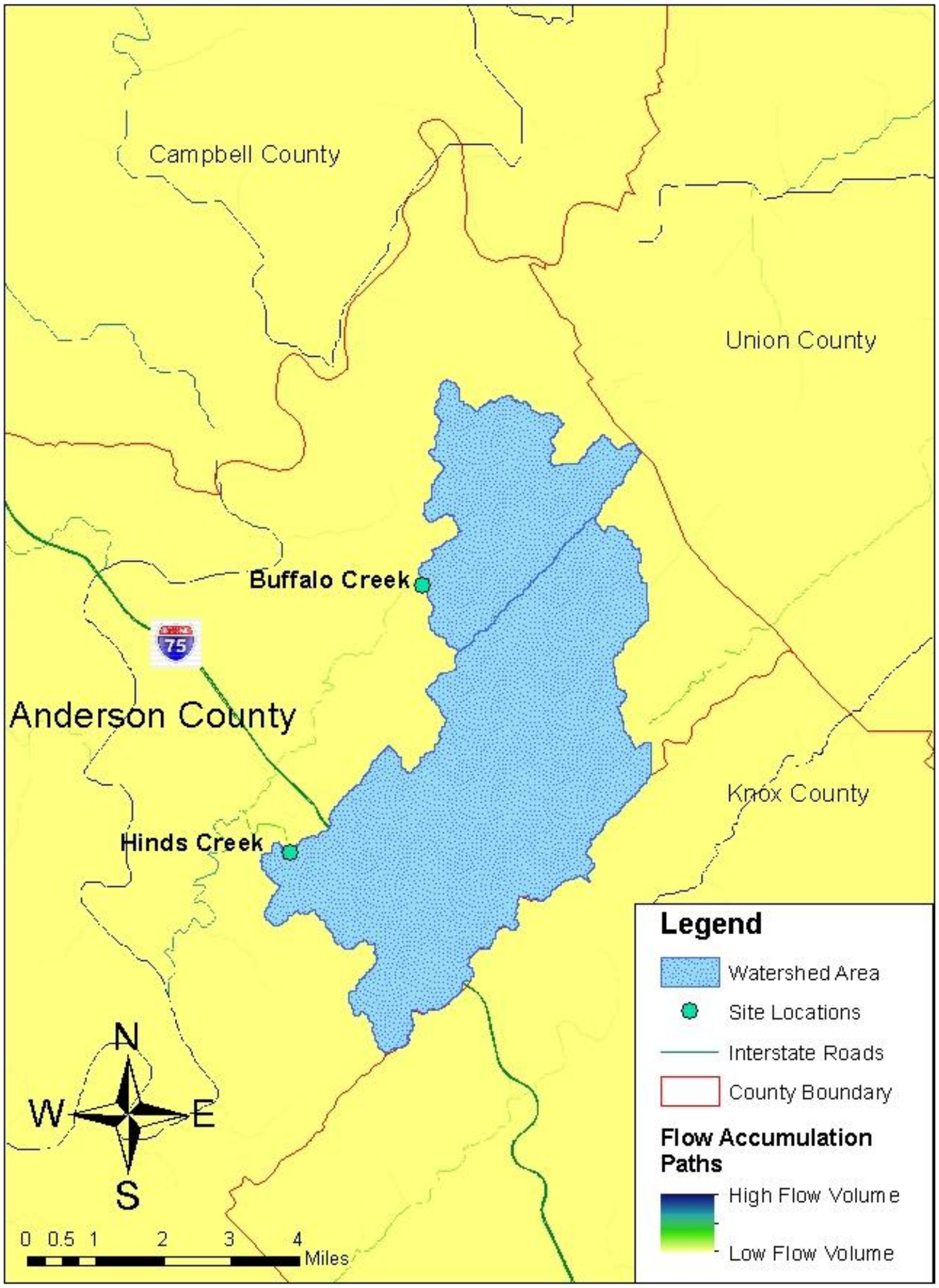
Big War and Joe Mill Creek



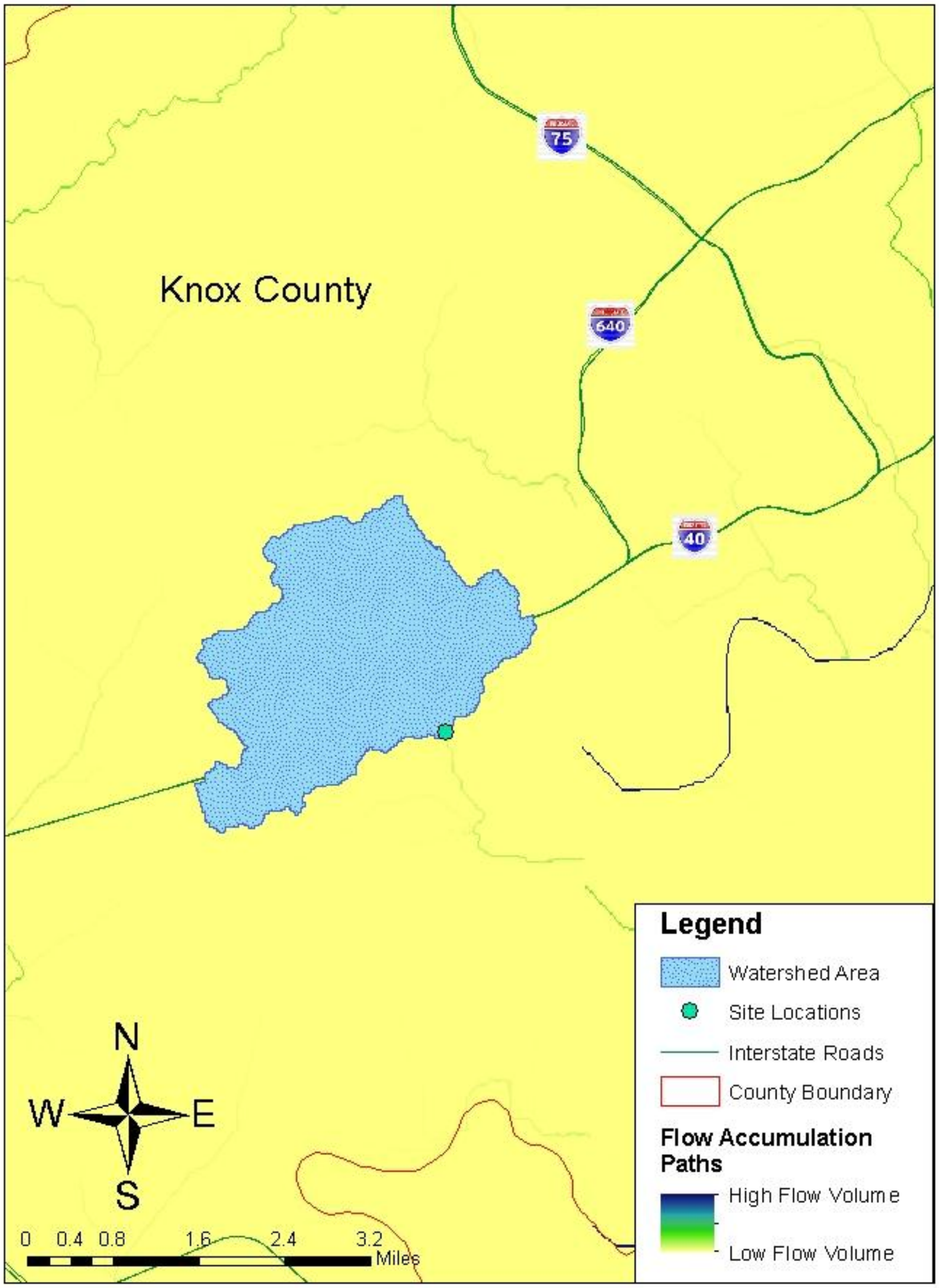
## Bull Run Creek



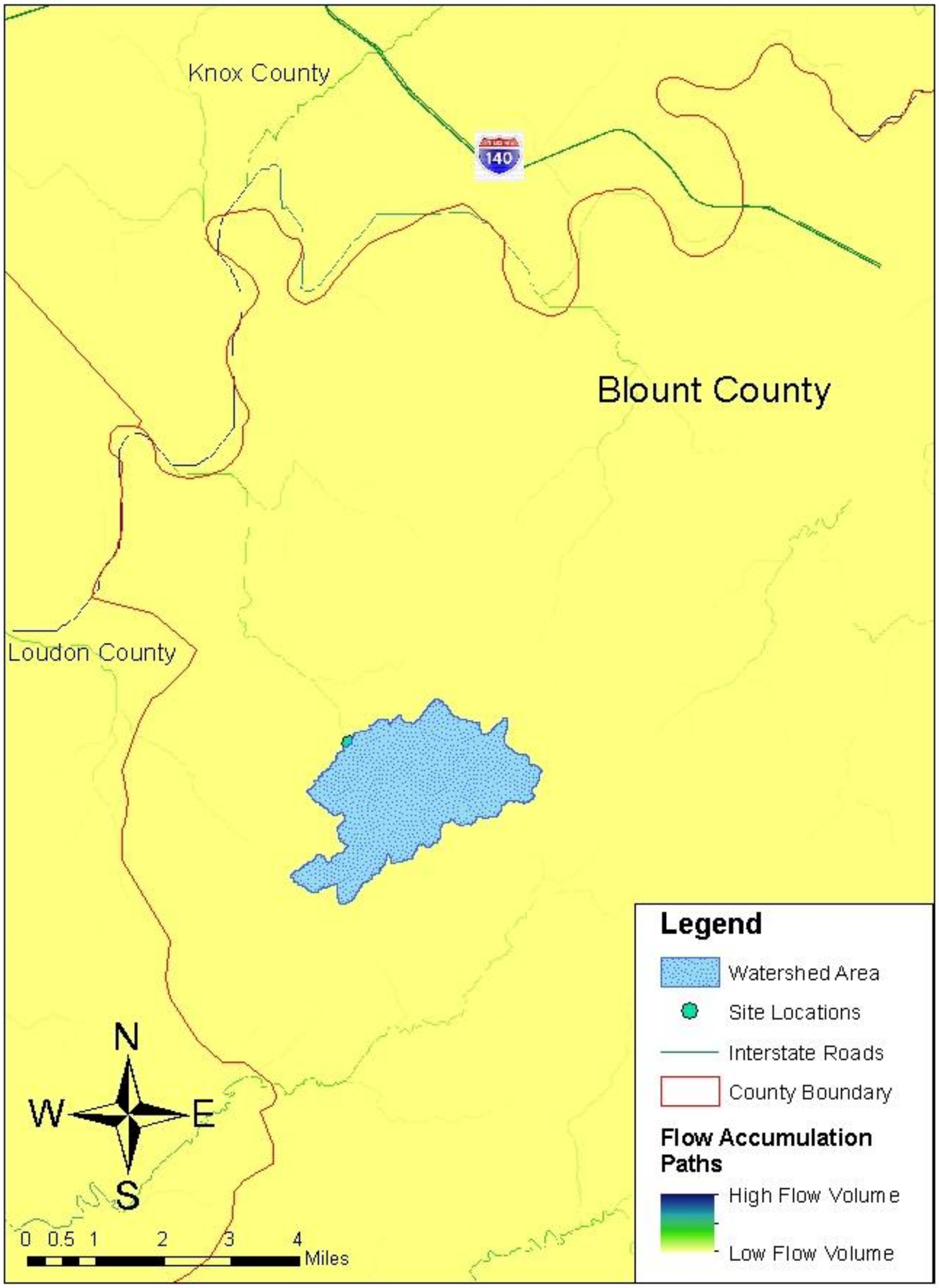
Buffalo and Hinds Creek



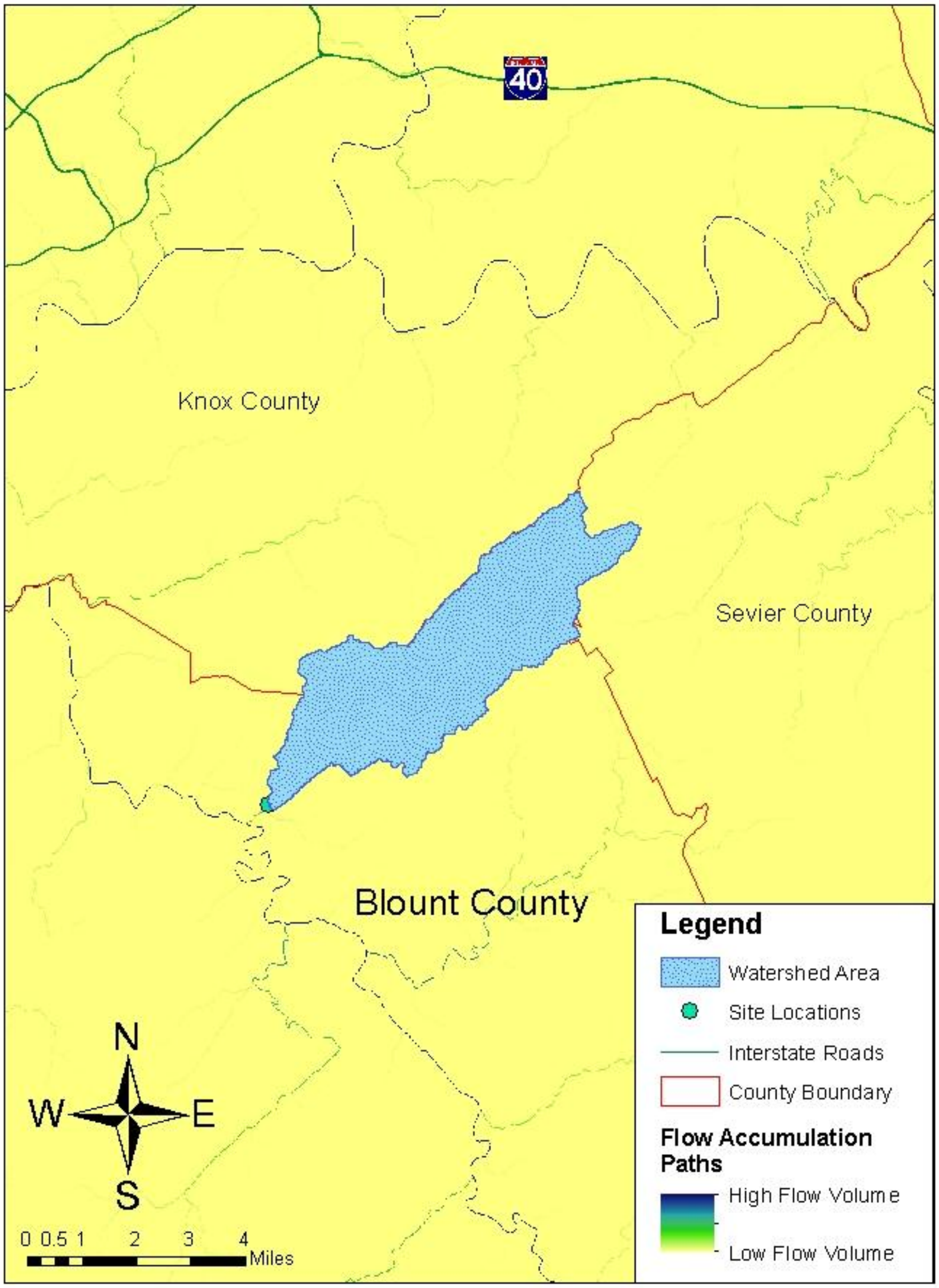
## Fourth Creek



Gallagher Creek



Nails Creek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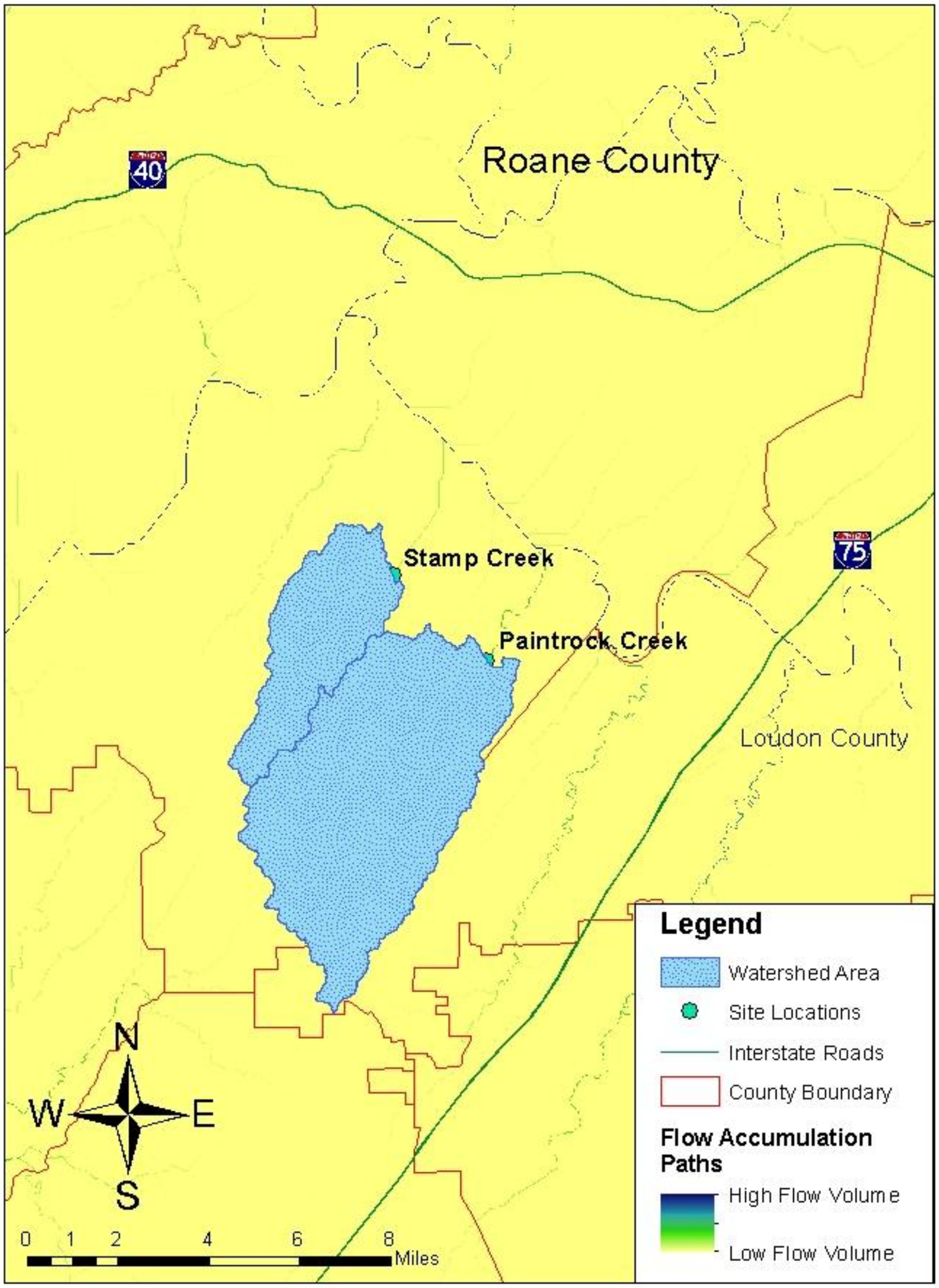
Knox County
Sevier County
Blount County
Legend
Watershed Area
Site Locations
Interstate Roads
County Boundary
Flow Accumulation Paths
High Flow Volume
Low Flow Volume
N
W
E
S
0 0.5 1 2 3 4
Miles

Paintrock and Stamp Creek



# **Vita**

Jeremy Robert Mefford was born on April 27, 1987 to parents James D. Mefford and Roberta L. Mefford in Fort Worth, Texas. He is the oldest of three children, having two younger sisters named Ashley and Audrey. He was homeschooled to start elementary school, and attended North Bay Christian Academy in Novato, CA to start the second grade. He then moved to Florence, KY and attended Yealey Elementary School until the fifth grade. To start middle school he attended North Bay Christian Academy again for sixth and seventh grade, and Sinaloa Middle School in Novato for the eighth grade. High school started at San Marin High School for the ninth grade, and was finished at Hendersonville High School in Hendersonville, TN. He graduated high school in May 2005. He attended Purdue University in Indiana for his freshman year of college beginning in August 2005, where he studied engineering and psychology. He then transferred to the University of Tennessee in August 2006. There he completed his Bachelors of Science in Civil Engineering in May 2010, while also completing three co-op terms with a local company. His focus was in water resources. He started graduate school immediately thereafter in June 2010 in environmental engineering at the University of Tennessee, again with a focus in water resources. He accepted a Graduate Research Assistant position that started simultaneously. His main responsibility during graduate school was running a project for the Tennessee Department of Environmental Conservation. This project was carried on after his graduation and is what this thesis is based upon. He graduated in December 2011 with his Masters of Science degree.