CHAPTER 4 – ESTABLISHING A RELATIONSHIP BETWEEN SEDIMENT CONCENTRATIONS AND TURBIDITY

Introduction

Estimation of sediment loading in a stream typically requires utilizing automated event samplers to collect a limited number of total suspended solids (TSS) samples for laboratory analysis. These discrete samples are used in combination with stream discharge to estimate sediment concentrations along the entire storm hydrograph to predict loads. Because of budget limitations and the labor intensive nature of water sampling, sediment loads are often based on only a small number of sample points. The use of optical sensors to continuously monitor turbidity throughout a storm event may provide a more accurate estimate of sediment fluctuations without the collection and analysis costs associated with intensive storm water sampling. Also, continuous turbidity measurement permits assessment of short term variability of sediment concentrations that stress aquatic life (Ehlinger 2002).

Turbidity is a measurement of the decrease in transparency of stream water as light is scattered by suspended particulate matter (Ziegler 2002). Results from other studies have shown that turbidity measurements may correlate closely with sediment concentrations in streams. Research conducted by the Pacific Southwest Research Station of the U.S. Forest Service showed that simple linear regression of turbidity and sediment samples provided a more accurate daily prediction of sediment loads than discharge-derived methods, but relationships had to be established separately for samples taken on the rise and fall of event hydrographs (Lewis 1996). Similar studies by USGS on the Kansas River produced sediment-turbidity relationships that explained 99% of the model variance (Christensen et al. 2002). Statistical analysis of relationships established for the Little Arkansas River showed that collection of 35 to 55 sediment samples was sufficient to formulate a model, and that outliers exceeding two standard deviations from the mean required further investigation for potential equipment malfunction (Christensen et al. 2000).

Benefits and Limitations of Using Turbidity to Predict Sediment Loads

Using turbidity to predict sediment loading in streams can provide many benefits for water research. First, turbidity accurately depicts sediment fluctuations during storm events, providing the ability to catch concentrations due to short-term events such as bank slumping (Christensen et al. 2000). Turbidity can also be used to estimate loads for contaminants typically bound to sediment particles, such as nutrients and bacteria (Ankcorn 2003). Battery-operated, internally-logging probes allow monitoring of remote locations which are neglected by intensive sampling methods (Lewis 1996). The real-time nature of continuous turbidity data also permits quicker calculation of sediment loads, and may even allow online posting of real-time sediment loads to accompany available discharge data (Ankcorn 2003).

However, relying entirely on turbidity predictions of sediment loads may have substantial limitations, including issues with equipment and physical stream characteristics. Optical turbidity probes can use a variety of different wavelengths, recording units, and sensor types. As stated by Ankcorn (2003), “turbidity is not an absolute value, but a relative value representing a qualitative measurement that can yield different readings based on the method used." Therefore, similar equipment must be deployed at sampling locations to reliably draw comparisons between sites. Probes must also be calibrated frequently to prevent equipment drift, and equipment fouling can result in the loss of data for particular storm events (Lewis 1996). Turbidity readings may vary between streams due to water color and suspended particle size and composition (Packman et al. 1999). Organic particles have been shown to absorb light, and therefore provide different turbidity values than streams carrying primarily mineral soils (Lewis 1996). In conclusion, although general sediment-turbidity relationships have been reported, load predictions are best estimated by establishing relationships on a site specific basis.

Research Objectives

Developing a relationship between sediment and turbidity in Baird Creek may provide rapid, cost effective information on the effects of land use change in the watershed on sediment delivery. The objectives of the study presented here were to:

1) Determine relationships between sediment and turbidity in Baird Creek.
2) Investigate the effects of streamflow on sediment-turbidity relationships.
3) Compare sediment-turbidity relationships between upstream and downstream sites.
4) Compare turbidity-derived loads to those based on discrete sediment samples.

Methodology

As described in Chapter 3, established USGS methods were used for gaging streamflow and for collecting, processing, and analyzing water samples at the USGS station, North Branch, and South Branch sites from April to December 2004. Samples were collected under both event and low-flow conditions. Turbidity data were collected on 10-minute intervals at each site using YSI-6200 multi-parameter sondes, and were reported in nephelometric turbidity units (NTU). Sondes were positioned within the stream channel at locations that were representative of the entire stream cross section during both low and high flow conditions. Automated wipers on the optical turbidity sensors reduced equipment fouling.

Sonde data were processed to exclude anomalous observations due to sediment deposition and equipment-associated false spikes in turbidity. Where spikes occurred, observations greater than three standard deviations from the running median were replaced with the 50-minute median value. Individual sediment sample times were then matched to the closest corrected turbidity measurement taken by the sonde. Samples were coded as being collected during event or low-flow conditions. Samples taken during a flow event were also coded for position on the rising or falling limb of the stream hydrograph based on an analysis of depth measurements. Linear regression analysis was then performed using Microsoft Excel 2003 and SAS 9.1 to generate the predictive relationships between sediment and turbidity (SAS Institute Inc. 2003). Outliers were removed from the data set if the standardized residual exceeded three standard deviations from the regression. Once final models were generated for the sites, comparisons were made between sites, between event and low-flow samples, and between samples taken on the rising versus the falling hydrograph positions by assigning different numerical multipliers to categorical variables using the dummy variable option for the PROC REG procedure in SAS (Cody and Smith 1997). There were not sufficient data to test for the significance of seasonality due to the lack of late summer and fall event samples.

Results and Discussion

Establishing Sediment-Turbidity Relationships for the Sampling Locations

The sonde data set for the USGS Station was inclusive from April to October 2004. Figure 4.1 shows continuous discharge, post-corrected turbidity, and TSS concentrations for samples taken at the USGS Station site from May 14 to June 25, 2004. This figure

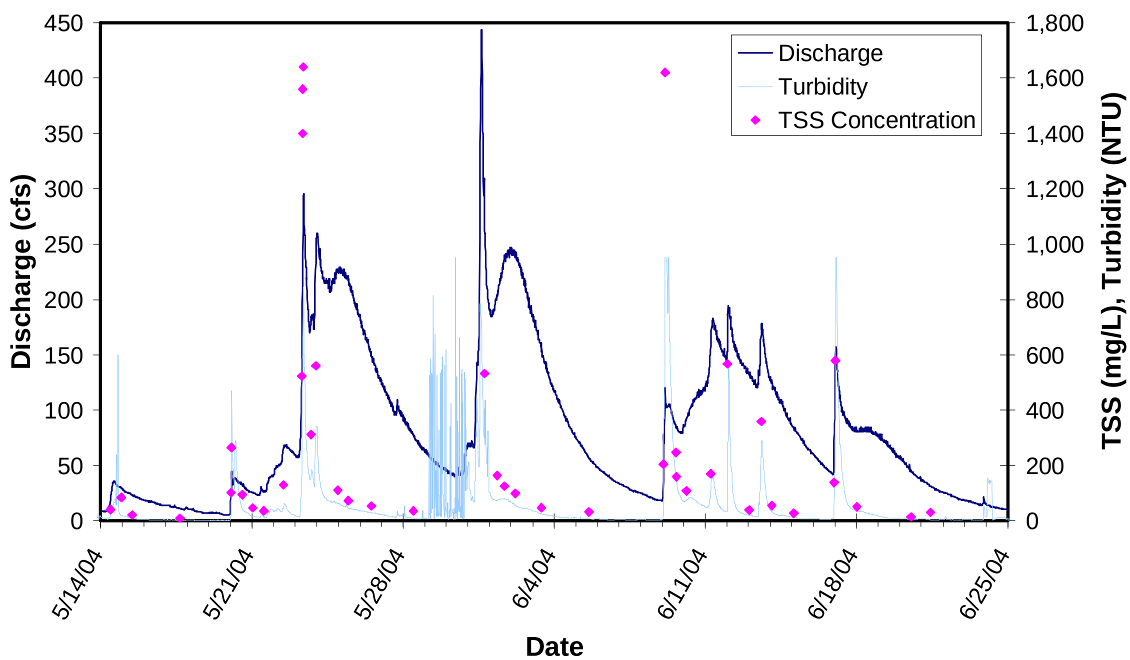

Figure 4.1. Discharge, sediment sample concentrations, and turbidity data for the USGS Station site, 14 May – 25 June, 2004.

illustrates the variability of continuous turbidity observations during storm events, and demonstrates the close correlation between turbidity and sediment concentrations. However, the graph also shows the potential for loss of data due to equipment fouling or burial, as seen in the extreme fluctuations in turbidity readings on May 29 and 30.

Linear regression was used to establish the sediment-turbidity relationship at the USGS station. Two outlying data points with residuals that exceeded three standard deviations from the predicted line were removed from the regression. The intercept of the final model did not significantly differ from zero ($p = 0.56$); thus, the line was forced through the origin. The final relationship between sediment and turbidity at the USGS Station was highly significant at the 95% confidence level ($n = 53$; $R^2 = 0.97$; $p < 0.0001$), and accounted for 97% of the variance (Figure 4.2):

TSS mg/L = 2.0628(Turbidity NTU) *Equation 4.1*

Due to a computer software error in the sonde equipment, no turbidity data were collected by the North and South Branch sondes until June 8, 2004. Events occurring

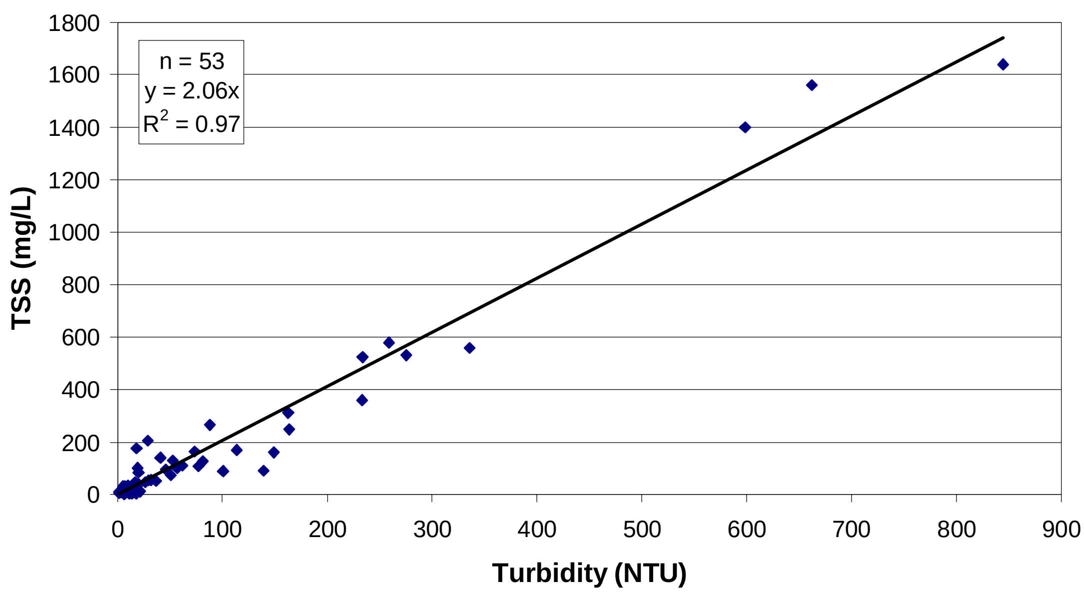

Figure 4.2. Relationship between sediment concentrations and turbidity at the USGS Station site, April – October 2004 (n = 53).

after this date were intensively sampled to generate a sufficient quantity of samples for statistical analysis. Figure 4.3 displays continuous discharge, turbidity, TSS, and SSC concentrations for event samples taken at the North Branch site from June 8 to June 20, 2004. Data from the South Branch for this time period were compromised by sonde burial and turbidity probe malfunction. Therefore, we were unable to establish a relationship between sediment and turbidity for the South Branch site.

As shown in Figure 4.3, both TSS (n = 22) and SSC (n = 19) concentrations closely parallel turbidity measurements at the North Branch site. Because including a greater number of sample points improves a statistical model, a comparison was made between the slopes of regression models generated separately from the two sample analysis techniques to determine if all points could be included in a single regression relating sediment and turbidity on the North Branch. Using the dummy variable option in SAS, it was found that the neither the regression slope (p = 0.61) nor intercept (p = 0.17) for TSS

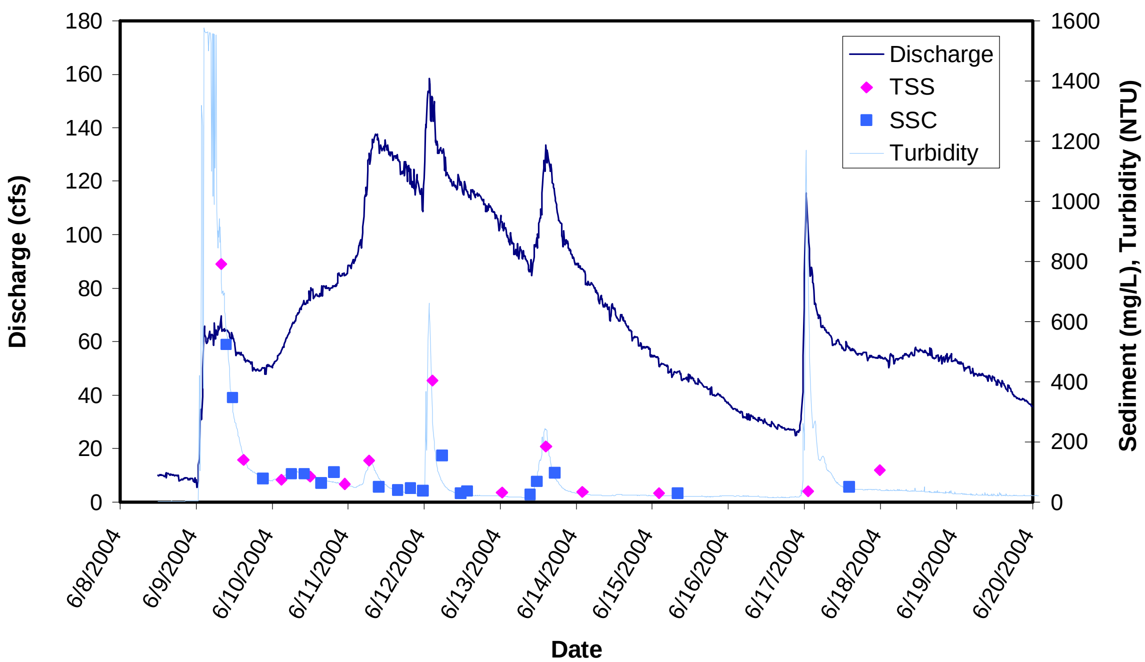

Figure 4.3. Discharge, sediment sample concentrations, and turbidity data for the North Branch site, 8 – 20 June, 2004.

versus turbidity differed significantly at the 95% confidence level from the equation generated for SSC versus turbidity. Therefore, concentrations from both sample analysis methods were combined to generate a single relationship between sediment and turbidity for the North Branch site.

Linear regression was used to establish the final sediment-turbidity relationship at the North Branch site using all TSS and SSC sample concentrations. Two outlying data points with residuals that exceeded three standard deviations from the predicted line were removed from the regression. The intercept of the final model did not significantly differ from zero ($p = 0.40$); thus, the line was forced through the origin. The final relationship between sediment and turbidity at the North Branch site was highly significant at the 95% confidence level ($n = 39$; $R^2 = 0.98$; $p < 0.0001$), and accounted for 98% of the variance (Figure 4.4):

$$\text{TSS mg/L} = 1.0119(\text{Turbidity NTU}) \qquad \textit{Equation 4.2}$$

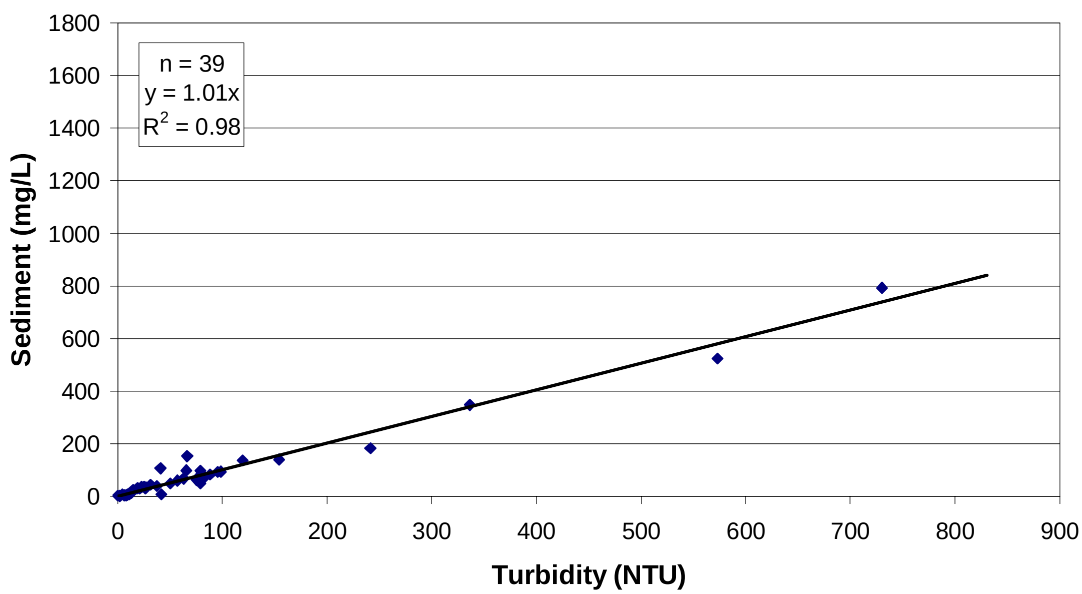

Figure 4.4. Relationship between sediment concentrations and turbidity at the North Branch site, June – October 2004 (n = 39).

Determining the Effect of Streamflow on Sediment-Turbidity Relationships

Once final relationships were determined between sediment concentrations and turbidity for the USGS Station and North Branch sites, comparisons were made between event and low-flow samples and between samples taken on the rising versus falling limb of event hydrographs. Statistical analysis of event versus low-flow samples found no significant difference at either the USGS Station ($p = 0.45$) or North Branch ($p = 0.21$) sites at the 95% confidence level. Similarly, the analysis of rising versus falling hydrograph showed no significant difference at the USGS Station ($p = 0.14$) or North Branch ($p = 0.74$) sites. Therefore, streamflow had no significant impact on the relationship between sediment concentrations and turbidity at either sampling location.

Comparing TSS-Turbidity Relationships between Sites

The USGS Station site showed an approximately 2:1 relationship between sediment concentrations (mg/L) and observed turbidity (NTU), while the relationship established at the North Branch site was approximately 1:1. Statistical analysis showed that the relationships significantly differed from each other at the 95% confidence level ($p < 0.0001$). When compared to sediment-turbidity relationships established for two other streams within the Lower Fox River watershed, it was interesting to note that the relationships at the two Baird Creek sites showed the greatest difference despite being located within one mile of each other on the same channel (Randerson et al. 2005).

Comparing Sediment Loads for Turbidity-Derived Predictions to Traditional Methods

USGS predicts stream constituent loads by relating stream discharge to individual sample concentrations using Graphical Constituent Loading Analysis System (GCLAS) software (Blanchard and Miller 2004). To evaluate the reliability of turbidity-derived loads compared to those calculated with the USGS method, loads were calculated using the sediment-turbidity relationship at the USGS Station site for the period of June 9-20, 2004, which included five storm events. Figure 4.5 shows precipitation, discharge, turbidity, TSS sample concentrations, GCLAS predicted sediment concentrations, and turbidity-predicted sediment concentrations at the site during the study period. Table 4.1 displays daily loads as calculated by the turbidity method and USGS.

Table 4.1. Mean daily discharge and sediment loads predicted by turbidity and USGS GCLAS software for the USGS Station Site, 9 – 20 June, 2004.

Date	Mean Daily Discharge (cfs)	Turbidity-Predicted Suspended Solids Load, metric tons	USGS GCLAS Suspended Solids Load, metric tons	Percent Difference
06/09/04	84.1	173.7	102.5	+ 69%
06/10/04	105.0	37.8	29.9	+ 26%
06/11/04	154.2	59.9	147.0	- 59%
06/12/04	155.7	89.4	111.6	- 20%
06/13/04	138.8	61.9	51.0	+ 21%
06/14/04	108.2	12.2	11.4	+ 7%
06/15/04	73.8	3.8	4.3	- 11%
06/16/04	50.7	3.0	2.4	+ 28%
06/17/04	99.7	123.9	57.5	+ 115%
06/18/04	81.0	11.6	7.7	+ 50%
06/19/04	67.9	4.1	3.9	+ 5%
06/20/04	47.1	1.7	1.9	- 11%
Totals:		**583.0**	**531.0**	**+10%**

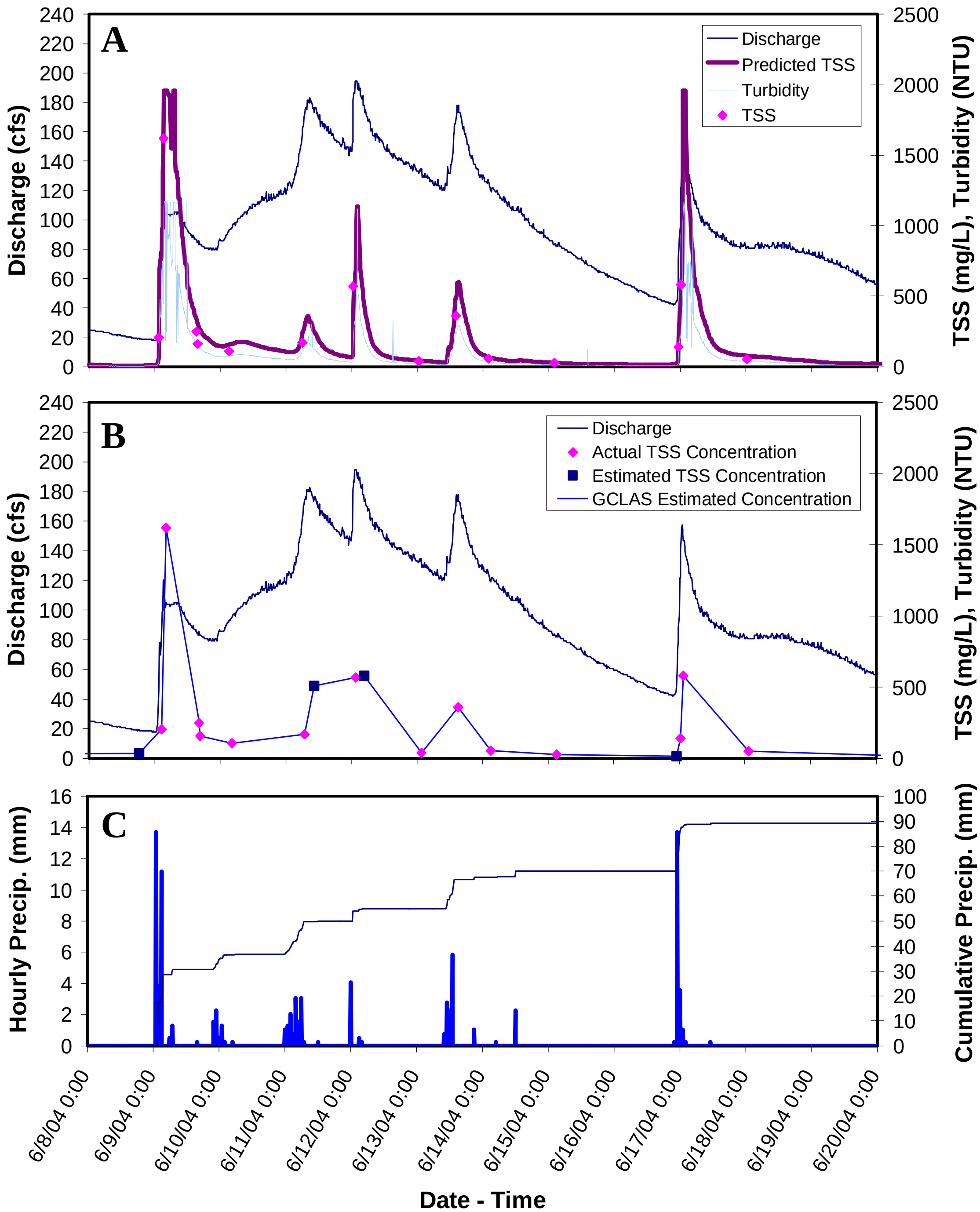

Figure 4.5. Comparison of turbidity-predicted and GCLAS estimated sediment concentrations for the USGS Station Site, 8 – 20 June, 2004: (a) discharge, sediment samples, turbidity-predicted continuous sediment concentrations, and turbidity data, (b) discharge, sediment samples, and GCLAS estimated continuous sediment concentrations, and (c) hourly and cumulative precipitation data.

Daily loads differed substantially between the two methods during the period of events. In comparing Figures 4.5A and 4.5B, it was evident that the limited number of water samples collected on June 11 and 12 led to difficulties in estimating fluctuations in stream sediment concentrations. The USGS load prediction for these two days was based on interpolating sediment concentrations from the single sample point from June 12 and relatively similar daily discharges, leading to substantial overestimation of loads on June 11. Estimates based on turbidity for the June 11 event were significantly lower and may be explained by examining discharge. The slow rise of the hydrograph over the previous day and the June 11 event may have resulted from exceeding the storage capacity of the headwaters wetlands complex, thus resulting in relatively low sediment concentrations in the stream. Comparisons between Figures 4A and 4B for the events of June 9 and June 17 also indicated that the first-flush of these intense storm events may have carried more sediment than estimated by USGS based on the limited number of sample points.

Despite daily differences in load prediction between the two methods, turbidity-based load estimates for the entire time period were within 10% of the loads calculated by USGS. Therefore, monitoring turbidity in conjunction with limited water sampling appears to be a reasonable surrogate for sediment-discharge predictions in load estimation on a weekly or monthly basis.

Conclusions

The turbidity of Baird Creek is highly dynamic. Sharp increases in turbidity were closely associated with runoff events and changes in stream discharge. Linear regression analysis showed a strong relationship between sediment concentrations and turbidity readings in Baird Creek at both stations, accounting for 97-98% of the model variance. However, no significant difference was found due to event versus low-flow samples or due to hydrograph position. The effect of seasonality was not analyzed due to lack of data from late summer and fall storm events and equipment malfunction.

The relationship between sediment concentrations and turbidity significantly differed between the upstream and downstream sampling sites. We hypothesize that the difference between these two models is directly related to watershed land use and the associated hydrologic response between the primarily agricultural North Branch site and the urban storm water additions above the USGS station. As discussed in Chapter 3, significant sediment load from urban tributaries and bank erosion enters Baird Creek below the North Branch monitoring station. The higher proportion of large-sized particles (e.g. sand) from these sources may be influencing the refraction of light through the water column and thus the turbidity sensor response, as compared to that of the silt and clay-sized suspended sediment carried from the agricultural watershed.

Continuous turbidity monitoring appears to be a reasonable surrogate for sediment concentration prediction for Baird Creek, and may provide cost effective, rapidly available information on watershed sediment delivery due to changes in land use. Future research on suspended particle properties and size distributions would assist in understanding site-to-site differences in the sediment-turbidity relationships. Relationships could also be strengthened by selecting samples for sediment analysis based solely on the real-time turbidity data, thus completing the curve with well-spaced samples throughout the full range of observed turbidity (Lewis 1996). Additional opportunities for further study include assessing seasonal variability and refining sonde deployments to lessen false spikes and/or equipment fouling.