AN ABSTRACT OF THE THESIS OF

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Abstract Approved:

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Arne E. Skaugset III

Suspended sediment and *in situ* turbidity data from two western Oregon streams, Oak Creek and South Fork Hinkle Creek, were used to estimate annual sediment loads for the 2006 water year (October 1, 2005 to September 30, 2006). Water samples and *in situ* turbidity observations were taken following the Turbidity Threshold Sampling (TTS) protocol.

The annual hydrographs for Oak Creek and South Fork Hinkle Creek were divided into storms. This stratification resulted in storm-specific relationships between *in situ* turbidity and Suspended Sediment Concentration (SSC). The annual hydrograph for Oak Creek was separated into 15 storms. The annual hydrograph for South Fork Hinkle Creek was separated into 8 storms.

In the relationship between SSC and *in situ* turbidity, especially for Oak Creek, there are counterintuitive values. Before statistical relationships between suspended sediment concentration and *in situ* turbidity could be developed, these counterintuitive and erroneous values had to be vetted. This was carried out with values of laboratory turbidity, hydrograph characteristics, and hysteresis loops.

Observations of *in situ* turbidity considered erroneous were adjusted manually with the TTS-adjuster program. The estimates of sediment load

determined with the TTS approach were defined as the true sediment load in the stream. The observations of *in situ* turbidity that were considered erroneous were also adjusted with a Turbidity-Threshold Macro (TTM), which automatically adjusted the turbidity record. The estimates of sediment load determined with the TTM approach are compared with the estimates of sediment load determined with the TTS approach to determine the efficacy of the TTM method. The objectives of this study were to determine the efficacy of an automated turbidity adjustment program compared with a manual turbidity adjuster, and to determine the efficacy of two *in situ* turbidity and SSC relationships to predict annual sediment loads.

Relationships between SSC and *in situ* turbidity were made to estimate annual sediment load for Oak and South Fork Hinkle Creeks. The SSC vs. *in situ* turbidity relationships were made for storm-specific time periods and for the whole water year. Estimates of annual sediment load for Oak Creek were approximately 10 tonnes (2 percent) higher when the TTM-adjustment was made for annual and storm-specific relationships. Estimates of total annual sediment load for Oak Creek were approximately 100 tonnes (17 percent) higher when separate-storm relationships between SSC and *in situ* turbidity were used compared to an annual relationship.

The estimates of annual sediment load at South Fork Hinkle Creek were much lower when the TTM-adjustment was compared to the TTS-adjusted record. When the annual relationship between *in situ* turbidity and SSC was used the estimate of annual sediment load for South Fork Hinkle Creek was 1,336 tonnes for TTM-adjusted turbidity data, compared to 1,526 tonnes for TTS-adjusted turbidity data. Estimates of total annual sediment load for South Fork Hinkle Creek were approximately 700-800 tonnes lower when the separate-storm relationships between SSC and *in situ* turbidity were used, compared to an annual relationship.

The TTM method for adjusting *in situ* turbidity records was useful to remove spikes of *in situ* turbidity. In the case of Oak Creek, the TTM-adjuster worked satisfactorily. However, in the case of South Fork Hinkle Creek, the TTM-adjuster did not work as well. For neither stream was the TTM-adjuster able to recreate the record that resulted from the TTS-adjuster. A TTM-adjuster appears to be able to work well but it would be best used in conjunction with a final adjustment using the TTS-adjuster. Thus, a hybrid approach that uses the strengths of both approaches might be the best approach. The TTM-adjuster as presented in this thesis is not a finished product. No method was developed to calibrate a data set to a TTM threshold value. Thus, while a bottom-up, TTM-adjuster program to edit and adjust records of *in situ* turbidity appears to be viable, the details of the method are not perfected and it remains a work in progress.

Both annual and storm specific relationships between *in situ* turbidity and SSC can be used to estimate sediment loads in streams. The record of success for these two methods depended on the stream. Oak Creek had a lot of samples (294) and the data was well-behaved. For that stream both approaches seemed to work well. However, South Fork Hinkle Creek had fewer samples (138) and the data was not as well behaved. It is probably best to use annual relationships when data is sparse or poorly behaved. Also, annual data alleviates the problem, to a degree, of extrapolating beyond the range of data that could be a problem for storm-specific relationships.

Using *in situ* Turbidity to Estimate Sediment Loads in Forested Headwater Streams: A Top-down versus Bottom-up Approach

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APPROVED:

Major Professor, representing Forest Engineering

Head of the Department of Forest Engineering, Resources and Management

---

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Matthew W. Meadows, Author

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TABLE OF CONTENTS

Page

1. Introduction 1
1.1 Objectives 2
2. Literature Review 4
2.1 Sediment and Turbidity Monitoring of Streams 4
2.2 Sediment and Turbidity Concerns 7
2.3 Calibration and Turbidity Measurement 8
2.4 Discharge, Suspended Sediment Concentration, and Turbidity 9
3. Methods 12
3.1 Site Description 12
3.1.1 Oak Creek 12
3.1.2 South Fork Hinkle Creek 15
3.2 Instrumentation 18
3.2.1 Turbidity Threshold Sampling 18
3.2.2 Equipment 19
3.3 Water Sample Analysis 19
3.4 Idetifying Time Periods and Storms 20
3.5 Partial Duration Series Frequency Analysis 20
4. Results 22
4.1 Oak Creek 22
4.1.1 Hydrology 22
4.1.2 *In situ* Turbidity 27
4.1.3 Turbidity and SSC 31
4.2 South Fork Hinkle Creek 34
4.2.1 Hydrology 34
4.2.2 *In situ* Turbidity 39
4.2.3 Turbidity and SSC 45
4.3 Estimation of Total Sediment Load 47

TABLE OF CONTENTS (Continued)

Page

4.3.1 *In situ* Turbidity and SSC Relationships 48

4.3.2 Identifying Erroneous Turbidity Observations 50

4.3.3 Developing SSC vs in situ Relationships...................................62

4.3.4 Oak Creek Annual Relationship...64

4.3.5 Oak Creek Storm-Specific Relationships...................................67

4.3.6 South Fork Hinkle Creek Annual Relationship...........................70

4.3.7 South Fork Hinkle Creek Storm-Specific Relationships 73

4.3.8 *In situ* Turbidity Adjustment 77

4.4 Sediment Load Estimates 81

4.4.1 Oak Creek Sediment Load Estimates..81

4.4.2 South Fork Hinkle Creek Sediment Load Estimates 93

5. Discussion 106

5.1 Erroneous Observations...106

5.2 Efficacy of TTM-adjustment 109

5.3 Efficacy of Annual and Storm-Specific Relationships 110

5.4 Relevance To Hydrologic Studies..112

6. Conclusion 114

7. Literature Cited 116

LIST OF FIGURES

Figure Page

1. Map of Oak Creek Watershed 14

2. Map of North and South Fork Hinkle Creek Watersheds 17

3. Partial Duration Frequency Curve for Oak Creek discharge 22

4. Annual precipitation and discharge at Oak Creek 25

5. Discharge and precipitation for Oak Creek during the Storm 1 time period 26

6. Discharge and precipitation for Oak Creek during the Storm 7 time period 27

7. Precipitation, discharge, and *in situ* turbidity at Oak Creek: water year 2006 29

8. Precipitation, discharge, and *in situ* turbidity at Oak Creek during the Storm 1 time period 30

9. Precipitation, discharge, and *in situ* turbidity for Oak Creek during the Storm 7 time period 31

10. Precipitation, discharge, *in situ* turbidity, and water samples at Oak Creek 33

11. Partial Duration Frequency Curve for South Fork Hinkle Creek 34

12. Annual precipitation and discharge for South Fork Hinkle Creek 37

13. Discharge and hourly precipitation for South Fork Hinkle Creek during the Storm 1 time period 38

14. Discharge and precipitation for South Fork Hinkle Creek during the Storm 4 time period 38

15. Precipitation, discharge, and *in situ* turbidity at South Fork Hinkle Creek 42

LIST OF FIGURES (Continued)

Figure Page

16. Precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the Storm 1 time period 43

17. Precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the Storm 4 time period 43

18. Precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the maximum annual peak flow 44

19. Precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the Storm 4 time period showing erratic *in situ* turbidity 44

20. Precipitation, discharge, *in situ* turbidity, and water samples at South Fork Hinkle Creek 46

21. Relationship between *in situ* turbidity and SSC of water samples for Oak Creek 48

22. Relationship between *in situ* turbidity and SSC of water samples for South Fork Hinkle Creek 49

23. Relationship between ln[*in situ* turbidity] and ln[SSC] of water samples for South Fork Hinkle Creek 50

24. Relationship between laboratory turbidity and SSC of water samples for Oak Creek 52

25. Discharge, precipitation, *in situ* turbidity, and water samples at Oak Creek during the Storm 1 time period 53

26. Hysteresis loops of discharge and SSC from water samples collected during three storms Oak Creek 54

27. Relationship between laboratory turbidity and SSC of water samples for South Fork Hinkle Creek 55

27. Discharge, unadjusted *in situ* turbidity, precipitation, and water samples at South Fork Hinkle Creek for three storms 57

LIST OF FIGURES (Continued)

Figure Page

28. *In situ* turbidity and SSC at South Fork Hinkle Creek during Storm 4 and hysteresis loop of sequential water samples 58

29. Lab turbidity and SSC at South Fork Hinkle Creek during Storm 4 59

30. *In situ* turbidity and SSC at South Fork Hinkle Creek during Storm 8 and hysteresis loop of sequential water samples 61

31. Lab turbidity and SSC at South Fork Hinkle Creek during Storm 8 61

32. The relationship annual between *in situ* turbidity and SSC for Oak Creek 65

33. Relationships between the *in situ* turbidity and SSC at Oak Creek for separate storms 68

34. Annual relationship between the ln[*in situ* turbidity] and ln[SSC] for South Fork Hinkle 71

35. Relationships between the SSC of water samples and *in situ* turbidity at South Fork Hinkle Creek for separate storms 75

36. Relationship between the SSC of water samples and *in situ* turbidity at South Fork Hinkle Creek for January 9-13 76

37. Relationship between discharge and *in situ* turbidity for Oak Creek................ 79

38. Relationship between discharge and *in situ* turbidity for South Fork Hinkle Creek 80

39. Adjusted *in situ* turbidity for Oak Creek 83

40. Estimated annual sediment load determination for TTM adjustment at Oak Creek 84

41. Annual sediment load by *in situ* turbidity vs. SSC relationship type for Oak Creek 88

42. Annual sediment load by *in situ* turbidity adjustment type for Oak Creek 88

LIST OF FIGURES (Continued)

Figure Page

43. Cumulative sediment load for Oak Creek using the annual relationship between *in situ* turbidity and SSC 89

44. Cumulative sediment load for Oak Creek using the separate storm relationships between *in situ* turbidity and SSC 90

45. Cumulative sediment load for TTS-adjusted *in situ* turbidity at Oak Creek using annual and separate storm relationships 91

46. Cumulative sediment load for TTM-adjusted *in situ* turbidity at Oak Creek using annual and separate storm relationships 92

47. Adjusted *in situ* turbidity values for South Fork Hinkle Creek........ 95

48. Estimated annual sediment load determination at South Fork Hinkle Creek 96

49. Annual sediment load by *in situ* turbidity vs. SSC relationship type for South Fork Hinkle Creek 99

50. Annual sediment load by *in situ* turbidity adjustment type for South Fork Hinkle Creek........ 99

51. Cumulative sediment load using the annual relationship between *in situ* turbidity and SSC at South Fork Hinkle Creek 102

52. Cumulative sediment load using separate storm relationships between *in situ* turbidity and SSC at South Fork Hinkle Creek 103

53. Cumulative sediment load for TTS-adjusted *in situ* turbidity at South Fork Hinkle Creek using annual and separate storm relationships between *in situ* turbidity and SSC 104

54. Cumulative sediment load for TTM-adjusted *in situ* turbidity at South Fork Hinkle Creek using annual and separate storm relationships between *in situ* turbidity and SSC 105

55. Discharge, precipitation, un-adjusted *in situ* turbidity, and water samples at Oak Creek: December 5-25, 2004........ 108

LIST OF TABLES

Table Page

1. Annual and separate-storm peak discharge and water samples collected at Oak Creek 23

2. Annual and separate-storm peak discharge and water samples collected at South Fork Hinkle Creek 35

3. Annual and separate-storm turbidity-SSC relationships and regression parameter estimates for each storm period for Oak Creek 66

4. Annual and separate-storm turbidity-SSC relationships for each storm period and regression parameter estimates for South Fork Hinkle Creek 72

5. Estimates of annual sediment loads for Oak Creek using the TTM-adjustment with specified thresholds 82

6. Annual sediment load estimates for Oak Creek 85

7. Annual and separate-storm sediment load estimates for Oak Creek 86

8. Estimates of annual sediment loads for South Fork Hinkle Creek using the TTM-adjustment with specified thresholds 94

9. Annual sediment load estimates for South Fork Hinkle Creek 97

10. Annual and separate-storm sediment load estimates for South Fork Hinkle Creek 98

Using *in situ* Turbidity to Estimate Sediment Loads in Forested Headwater Streams: A Top-down versus Bottom-up Approach

1. INTRODUCTION

There are many reasons why monitoring fine sediment in stream water is important to society. The concentration of fine sediment in stream water can directly affect aquatic organisms through mechanisms like gill abrasion, fouling of macroinvertebrate collectors, or reduced feeding due to impaired visibility (Berg and Northcote, 1985; Martens and Servizi, 1993; Phillips et al., 1975; Zirbser et al., 2001). It can indirectly affect organisms by burying or filling streambed gravels (Phillips et al., 1975). Fine sediment can also fill reservoirs, clog or damage irrigation equipment, and even reduce the ability of communities to disinfect drinking water. The load of sediment coming in runoff from a basin and the timing of fine sediment concentration increases can be used as an integrating measure of the erosion and transport processes that occur in the basin (Thomas, 1988). The quantity of fine sediment in water can affect aquatic, terrestrial, and human life, through transport of nutrients and contaminants, and by influencing dispersion of micro-organisms. For these and many other reasons, it is important to monitor fine sediment concentrations and sediment loads in streams. This has also led Federal and State governments to impose regulations that limit the load of sediment in streams and rivers. The Federal Clean Water Act requires that Total Maximum Daily Loads (TMDLs) be established for water-bodies to protect beneficial uses by meeting water quality criteria.

Discharge in streams can be used to estimate the concentration of fine sediment in streams (Walling, 1977; Williams, 1989). However, relationships between discharge and concentrations of fine sediment or suspended sediment concentrations (SSC) are uncertain and prone to high variability (Brasington and Richards, 2000; Walling, 1977). Discharge is a poor predictor of the amount of fine sediment in streams with limited sediment supplies that have patterns of SSC during storms that show hysteresis (Langlois et al., 2005). SSC in streams can be episodic and has trends that are seasonal and based on precipitation, runoff, and erosion processes (Clifford et al., 1995).

Turbidity can be used as a surrogate for SSC to estimate sediment loads in streams and is a better estimator of SSC than discharge (Lewis, 1996). However, measuring turbidity *in situ* is prone to uncertainty (Ankcorn, 2003; Gippel, 1995; Sadar, 2004). Errors in the measurement of either *in situ* turbidity or SSC can influence the accuracy of suspended sediment load estimates (Sivakumar, 2006). Sensors that measure *in situ* turbidity are prone to errors that reduce the accuracy of turbidity data. Errors of *in situ* turbidity data are identified as sensor fouling, the influence of sunlight, turbulent water, non-submergence of the sensor, interference from the water surface, and interference from the streambed (Anonymous, 2006; Sadar, 2004). Errors in the measurement of *in situ* turbidity are commonplace and can be adjusted to estimate sediment load accurately (Anonymous, 2006; Lewis, 1998; Lewis, 2002; Lewis, 2003).

The purpose of this research was to investigate two techniques used to correct *in situ* turbidity values and two methods used to develop SSC versus turbidity relationships that are used to estimate suspended sediment loads in streams. This research compared the results of an automated program to adjust turbidity values with a manual program. This comparison was important to see if an automated system could be used to reduce the amount of time and effort required to process large amounts of turbidity data. Also, this research compared total annual sediment loads estimated with total annual versus storm specific SSC/Turbidity relationships.

1.1 OBJECTIVES

Total annual or storm sediment loads for a stream can be estimated with real time measurements of *in situ* turbidity. Real time estimates of SSC for streams can be estimated with relationships that correlate SSC with *in situ* turbidity. The estimates of SSC are multiplied by corresponding values of discharge and result in an estimate of suspended sediment discharge. Total annual or storm sediment loads are estimated by summing suspended sediment discharge over the time interval of interest.

In situ turbidity can be highly variable and the record can contain erroneous values. Correlations of *in situ* turbidity with SSC can be carried for many intervals of times. The purpose of this research was to determine the most appropriate ways to edit the *in situ* turbidity record and develop *in situ* turbidity and SSC relationships. Specifically, the objectives of this study were:

1. To determine the efficacy of an automated program to edit values of *in situ* turbidity with a manual method, and
2. To determine the efficacy of total annual relationships between *in situ* turbidity and SSC with storm specific relationships to estimate sediment load.

2. LITERATURE REVIEW

2.1 SEDIMENT AND TURBIDITY MONITORING OF STREAMS

The dominant method used to estimate sediment loads in streams is based on discharge (Thomas, 1988). Sediment rating curves relate discharge and sediment concentrations and they often underestimate suspended sediment yields (Thomas, 1985). Methods of sediment load estimation that use sediment-rating curves often lack a continuous record of sediment concentration and are unsuitable for streams that have high temporal variability in sediment load (Brasington and Richards, 2000; Walling, 1977). Turbidity of stream water is a better predictor of suspended sediment concentrations (SSC) than discharge since turbidity is a measure of water clarity, which is directly affected by SSC (Gippel, 1995; Kunkle and Comer, 1971; Lewis and Eads, 1996). The measurement of *in situ* turbidity can be used to create a continuous record of suspended sediment concentration. Turbidity measurement techniques contain limitations. The measurement and interpretation of *in situ* turbidity data is prone to uncertainty (Foster et al., 1992; Gippel, 1995; Wass and Leeks, 1999; Wass et al., 1997). The uncertainty associated with *in situ* turbidity data include: differences in the methods and technologies used for measurements, the effects of physical properties of the stream water on turbidity, and *in situ* stream monitoring strategies (Ankcorn, 2003).

The concentration of suspended sediments can include both organic and non-organic constituents. Sediment concentrations reported as SSC contain suspended material that is made up of non-organic particle, such as sand, silt, and clay. Sediment concentrations reported as Total Suspended Solids (TSS) contain both organic and non-organic particles.

Use of varying technologies and methods associated with turbidity monitoring can lead to confusing interpretations. The objective of turbidity observation is to quantify water clarity, using light and scattering angle or sound to measure water clarity (Sadar, 2004). The use of different technologies makes it difficult to compare turbidity measurements. In addition, stream turbulence can also affect turbidity readings (Clifford *et al.*, 1995). Variations in turbulence can occur on the timescale of 10 to 20 seconds, which can cause turbidity readings to fluctuate up to 10 percent of daily fluctuations. However, integration times can be used to avoid this scatter in turbidity values. The interpretation of turbidity data from different studies is confounded by the method that turbidity is observed. The U.S. Geological Survey has set standards for reporting turbidity data based on instrument design (Anderson, 2004).

Uncertainty in the estimates of sediment load that are based on turbidity measurements are difficult to quantify. The sources of the uncertainty stem from instrument error, variations in the specific turbidity of the water, and sensor location (Wass and Leeks, 1999). Measurements of turbidity from methods that use optical backscatter turbidity measurements are sensitive to particle types with large surface areas relative to size. The turbidity value associated with the mass of the suspended material is known as specific turbidity. Specific turbidity is the turbidity caused by a unit mass of suspended sediment in a unit volume of water, T_s= (turbidity)/SSC (Wass and Leeks, 1999). Organic particles are associated with higher turbidity values and lower suspended sediment concentrations than suspended inorganic materials and result in high values of specific turbidity (Gippel, 1995). Turbidity values that exceed the maximum of the turbidity sensor occur often and can be either removed or adjusted (Brasington and Richards, 2000).

The use of *in situ* turbidity as a surrogate for SSC is typically a point measurement in the stream. The location of *in situ* turbidity readings and single point automated water samples is a source of systematic variation, that ranges from 2 to 12 percent, compared to depth-integrated cross-sectional sampling methods (Wass and Leeks, 1999). Short-term variations in SSC (20 to 30 minutes) have been reported using time-series depth-integrated sampling, where concentration is dependant on sampling technique (Horowitz *et al.*, 1990). Conroy and Barrett

(2003) found, however, that a single point sampling position is adequate to determine turbidity level of water samples at 30 minute intervals. When using turbidity monitoring coupled with point water sampling, the location of the sampling equipment should represent an average of the stream cross-section.

Complications arise for both *in situ* and laboratory turbidity values due to physical effects. Various constituents affect turbidity in stream water which include: clay, silt, sand, finely divided organic and inorganic material, soluble colored organic compounds, plankton, and microscopic organisms can all be part of the suspended load in streams, and all affect turbidity (Ankcorn, 2003). Measurements of turbidity include positive and negative bias due to interferences such as absorbing (colored) particles, color in the water matrix, particle size, bubbles, sample cell variations, stray light, particle density, particle settling, instrument error, and contamination (Sadar, 2004). Turbidity values taken in the laboratory are subject to changes in water sample conditions such as growth of algae during storage and the settling of particles during measurement. Furthermore, suspended particles may agglomerate and increase particle size and thus decrease the turbidity (Gippel, 1995). These particles can be dispersed by vigorous, hand shaking; in a sonic bath; or with a sonic probe; resulting in increasingly better correlations between turbidity and SSC (Gippel, 1989). Values of laboratory turbidity can be improved by increasing the viscosity of the water with sucrose to keep large, particles in suspension during measurement (Ginting and Mamo, 2006). Suspended sediment particles have a slower settling time in the sucrose solution, which gives time for the turbidity reading to occur. This process is reported to increase accuracy of total suspended solids concentration by 20 percent. However, this process has no use for *in situ* turbidity measurements. Although turbidity values are subject to interferences, not all turbidimeters respond equally or similarly. Gippel (1995) found that an increase in the color of the water due to increased dissolved organic carbon resulted in a low turbidity readings from a Hach Model 2100A bench top turbidimeter, while high turbidity readings were observed from an *in situ* Partech

Type 7000 suspended solids monitor. This bias may be insignificant because highly colored water altered turbidity readings less than 10 percent and adjustments of turbidity did not increase the correlation between turbidity and SSC.

2.2 SEDIMENT AND TURBIDITY CONCERNS

The quantity of fine sediment in water can affect aquatic, terrestrial, and human life, through transport of nutrients and contaminants, and by influencing dispersion of micro-organisms (Zirbser *et al.*, 2001). Federal and State governments have promulgated regulations that limit the load of sediment in streams and rivers. The Federal Clean Water Act requires that total maximum daily loads (TMDLs) be established for water-bodies to meet water quality criteria and to protect beneficial uses. Anthropogenic impacts, such as increased erosion processes in streams, can affect salmon health and habitat. Timber harvest activities and forest road construction can lead to alterations in the hydrologic cycle and additions of sediment to the stream channel (Beschta, 1978; Lewis, 1998; Troendle and King, 1985). Increased sedimentation can have negative effects on aquatic resources by limiting primary productivity, smothering invertebrate communities, and by transporting contaminates (Beschta, 1978; Davies-Colley and Smith, 2001).

Pacific Salmon are anadromous fish that live part of their lives in freshwater before migrating to the ocean, and then returning to spawn. Salmon are important to the Pacific Northwest commercially and ecologically. Increased sedimentation can cause pools to fill and can reduce oxygen flow through streambed gravels, which can lead to suffocation of fish eggs or prevent fingerling emergence (Bilby et al., 1989). Several studies of juvenile coho salmon (*Oncorhynchus kisutsh*) and steelhead trout (*Oncorhynchus mykiss*) have found that increased concentrations of suspended sediment can lead to changes in behavior, growth and production, physiology, and survival (Berg and Northcote, 1985; Bisson and Bilby, 1982; Redding et al., 1987; Servizi and Martens, 1992; Sigler et al., 1984; Tschaplinski and Hartman, 1983). Early emigration of fish from sediment laden water suggests stressful conditions (Sigler *et al.*, 1984). Salmon that have a strong avoidance behavior may be more likely to emigrate out of sediment impaired stream reaches (Tschaplinski and Hartman, 1983). Furthermore, changes in dominance and feeding behavior caused by increased SSC can hinder growth and reduce ingestion of prey (Berg and Northcote, 1985). Although juvenile coho tend to avoid suspended sediments, the avoidance tendency can be reduced for coho that are acclimated to chronic high SSC conditions (Berg and Northcote, 1985; Bisson and Bilby, 1982). The behavior that juvenile coho display is a reaction to stressful conditions that elevate blood sugar, increase red blood cells, decrease white blood cells, increase plasma cortisol levels, and increase cough frequency (Lake and Hinch, 1999; Redding et al., 1987; Servizi and Martens, 1992). Physical damage to the fins and abrasions to the body of juvenile salmon exposed to high SSC increase the likelihood of infection by microbes and other adverse conditions (Herbert and Merkens, 1961; Redding *et al.*, 1987). Damage to the gills occurs when sediment irritates or damage lamellae, which leads to fusion of the gills and sediment intrusion into gill cells (Herbert and Merkens, 1961; Lake and Hinch, 1999; Martens and Servizi, 1993; Newcomb and Flagg, 1983; Stober et al., 1981).

2.3 CALIBRATION AND TURBIDITY MEASUREMENT

The most common cause of error in turbidity data stems from improper calibration (Anonymous, 1991). Instrument calibration techniques for laboratory and *in situ* turbidity probes have varying results. Laboratory and *in situ* turbidity probes are generally calibrated with a formazin turbidity constant in controlled settings. Laboratory calibration of *in situ* turbidity probes can also be done using site specific sediment in solution (Brasington and Richards, 2000; Hofmann and Dominik, 1995). Calibration of *in situ* turbidity probes with sediment allows direct recording of SSC with no required water sampling. This procedure does not take into account the high temporal and spatial variability of sediment that can occur in the stream. Conroy and Barrett (2003) observed this variability and found that two identically calibrated turbidimeters gave significantly different turbidity values. The relationship between turbidity and SSC can vary spatially (Markman, 1990; Wass and Leeks, 1999) or be similar between like basins (Kunkle and Comer, 1971), and can also depend on discharge or time (Clifford *et al.*, 1995; Pfannkuche and Schmidt, 2003).

Calibration of *in situ* turbidity probes can also be done by correlating SSC and turbidity readings that are taken simultaneously, which can occur throughout the monitoring period. This frequent *in situ* calibration can be used to more effectively estimate sediment loads, where the continuous turbidity record is used to interpolate between calibration points (Lewis and Eads, 1996; Sun *et al.*, 2001). Frequent field calibration of *in situ* turbidity probes requires the use of a synchronized automatic-pump sampler. Use of automated samplers may introduce error due to contamination of successive samples (Thomas and Eads, 1983). Sample contamination can be a problem for streams that have rapid changes in sediment concentrations. *In situ* calibration is done best by using a probability proportional to sampling technique, where water samples are collected more frequently during increases in discharge or turbidity (Lewis and Eads, 1996; Thomas, 1985). The use of turbidity controlled sampling techniques, such as the turbidity-threshold sampling procedure, use the continuous monitoring of discharge and turbidity coupled with automated water samples triggered by changes in turbidity (Lewis and Eads, 1996). This sediment sampling method allows for samples to be taken at short intervals during sediment producing hydrologic events.

2.4 DISCHARGE, SUSPENDED SEDIMENT CONCENTRATION, AND TURBIDITY

The increase of SSC with discharge in streams is well documented (Benkhaled and Remini, 2003; Chappell et al., 2004; Kunkle and Comer, 1971; Smith et al., 2003). The relationship between the SSC of water samples and discharge is often hysteretic, where for a given hydrologic event the sediment concentration will be different on the rising and falling limbs of the hydrograph at any given discharge (Beschta, 1987). This single-event hysteresis is often presented in a time sequential loop. Williams (1989) identified five types of concentration versus discharge relationships: single value (non-hysteretic), clockwise, counter clockwise, single value with a loop, and figure-eight. SSC data for a monitoring location can experience many types of hysteresis during different storms, which may be explained by turbidity and precipitation (Brasington and Richards, 2000). The different hysteresis relationships can be related to sediment sources, sediment travel time, sediment storage, and sediment availability (LeFrancios et al., 2005; Williams, 1989). The source of sediment can be identified by using characterizing mineral assemblages of sediment samples (Bates et al., 1998).

The single event hysteretic nature of sediment loads can affect the relationship between *in situ* turbidity and the SSC of water samples. The correlation of *in situ* turbidity and SSC is often linear (Brasington and Richards, 2000; Pfannkuche and Schmidt, 2003). However, this correlation may contain high variance and is linear only when particle properties are constant (Foster et al., 1992; Gippel, 1989). The hysteresis effect can cause SSC to be several times greater on the rising limb than the falling limb (Pfannkuche and Schmidt, 2003). Along with the hysteretic response of sediment loads, the variance in the relationship between turbidity and SSC can be explained by particle size distributions (Manka, 2005). Small particles can make a significant contribution to light scattering and thus turbidity. The selection of filter pore size for sieving water samples may play an important role so that small particle sizes are measured (Gippel, 1989).

A single correlation between *in situ* turbidity and SSC may not be appropriate since the relationship can change from one event to the next (Lewis, 1996). Different time scales are used to estimate sediment load from the relationship between *in situ* turbidity and SSC: multi-year (Wass and Leeks, 1999), annual (Kunkle and Comer, 1971), multi-storm (Sun *et al.*, 2001), and single storm (Brasington and Richards, 2000; Lewis, 1996). Relationships have also been developed for different volumes of discharge (Pfannkuche and Schmidt, 2003).

In situ turbidity versus SSC relationships are often site specific (Gippel, 1995). This can be partially explained by the highly variable size distribution of sediment particles within a catchment (Walling and Moorehead, 1989). Variation of suspended sediment size can occur seasonally and during individual storms (Bogen, 1992; Peart and Walling, 1982). This spatial and temporal variation in suspended sediment size affects the relationship between *in situ* turbidity and SSC, especially during large storms. Wass and Leeks (1999) found that during extreme discharges, suspended sediment loads coarsen. Since *in situ* turbidity sensors are more sensitive to small particle sizes, they respond differently for higher SSC with large particle sizes. Non-linearity in the relationship between *in situ* turbidity and SSC is dependent on discharge during large storms. SSC on the falling and rising limbs of the hydrograph can have different values of turbidity (Manka, 2005). Thus, different relationships between turbidity and SSC can be developed for the rising and falling limbs of the hydrograph to account for the variability caused by hysteresis patterns. Use of short time-scale relationships between *in situ* turbidity and SSC can provide more precise estimates of sediment load (Manka, 2005). These short time-scales can be storm-based or include storm partitioning of the relationship between *in situ* turbidity and SSC.

3. METHODS

3.1 SITE DESCRIPTION

Suspended sediment and turbidity data from two western Oregon streams, Oak Creek and South Fork Hinkle Creek, were used in this analysis. The data used are for the 2006 water year (October 1, 2005 to September 30, 2006). The watersheds for both of these streams are actively managed. Oak Creek is located within the McDonald/Dunn Research Forest, the research forest for the College of Forestry, and is managed in accordance with the wishes of the donors of the land. The South Fork Hinkle Creek watershed is owned and managed by Roseburg Forest Products, Inc. for the production of solid wood products.

3.1.1 OAK CREEK

Oak Creek is a fourth-order stream that drains an 824-hectare watershed in the McDonald-Dunn Research Forest, which is the Research Forest for the College of Forestry at Oregon State University (Figure 1). Oak Creek is located approximately 3 miles west of Corvallis in Oregon Coast Range. Elevations in the watershed range from 140 m to over 655 m and hillslope gradients can exceed 60 percent (Toman, 2004). The stream and road densities are 5.92 m/ha and 5.55 m/ha, respectively. Oak Creek is a tributary to Mary's River, which drains into the Willamette River in Corvallis, Oregon.

The geology of Oak Creek watershed is basalt from the Siletz Volcanics formation. Soils for the Oak Creek watershed are silty clay loams that are deep, well weathered and well drained (Knezevich, 1975). Precipitation is predominantly rainfall that occurs during winter storms between October and April. Mean annual precipitation for Oak Creek ranges from 178 to 191cm. Snow occurs in the watershed but melts in days to a few weeks.

Overstory vegetation in the Oak Creek basin is dominated by Douglas-fir (*Pseudotsuga menziesii*) with minor components of grand fir (*Abies grandis*), western hemlock (*Tsuga heterophylla*), big leaf maple (*Acer macrophyllum*), and Oregon white oak (*Quercus garyyana*). Red alder (*Alnus* rubra) and Oregon ash (*Fraxinus latifolia*) are located along stream channels. The understory vegetation consists of California hazelnut (*Corylus cornuta* var. *californica*), vine maple (*Acer circinatum*), blackberry (*Rubus* sp.), poison-oak (*Toxicodendron diversilobum*), swordfern (*Polystichum munitum*), bracken fern (*Pteridium aquilinum*), and an invasive grass (*Brachypodium sylvaticum*).

The Research Forest is actively managed for timber. Logging operations are carried out by logging contractors or the College of Forestry student logging crew. Vehicle traffic consists of passenger vehicles and small truck traffic for research and educational purposes. Roads in the Oak Creek watershed are also used for recreation by hikers, bicyclist, horse-back riders, and off-leash dog walkers. The Oak Creek gauging station is close to the main access road and is visited frequently by recreationists and domesticated animals.

The Oak Creek watershed was the site of intensive sediment transport studies (Beschta *et al.*, 1981; Parker *et al.*, 1982). The outlet of the basin is gauged at a concrete hardened cross section where a stage-discharge relationship has been developed. Stage (water height), turbidity, temperature, and specific conductivity measurements are taken and recorded at 10-minute intervals. Water samples are taken with an ISCO 3700 automated water sampler following the TTS method (Lewis, 1996). The ISCO intake tube, turbidity probe, and specific conductivity probe are mounted on an articulated boom, which allows for displacement by debris transported during storms. The boom also allows the probes to move vertically in the water column with changes in discharge due to drag created by the submerged portion of the boom arm. Precipitation is measured with four tipping-bucket rain gauges located in the watershed. Wind speed and direction, relative humidity, air temperature, and solar radiation are measured at a micrometeorological tower located low in the watershed (Figure 1).

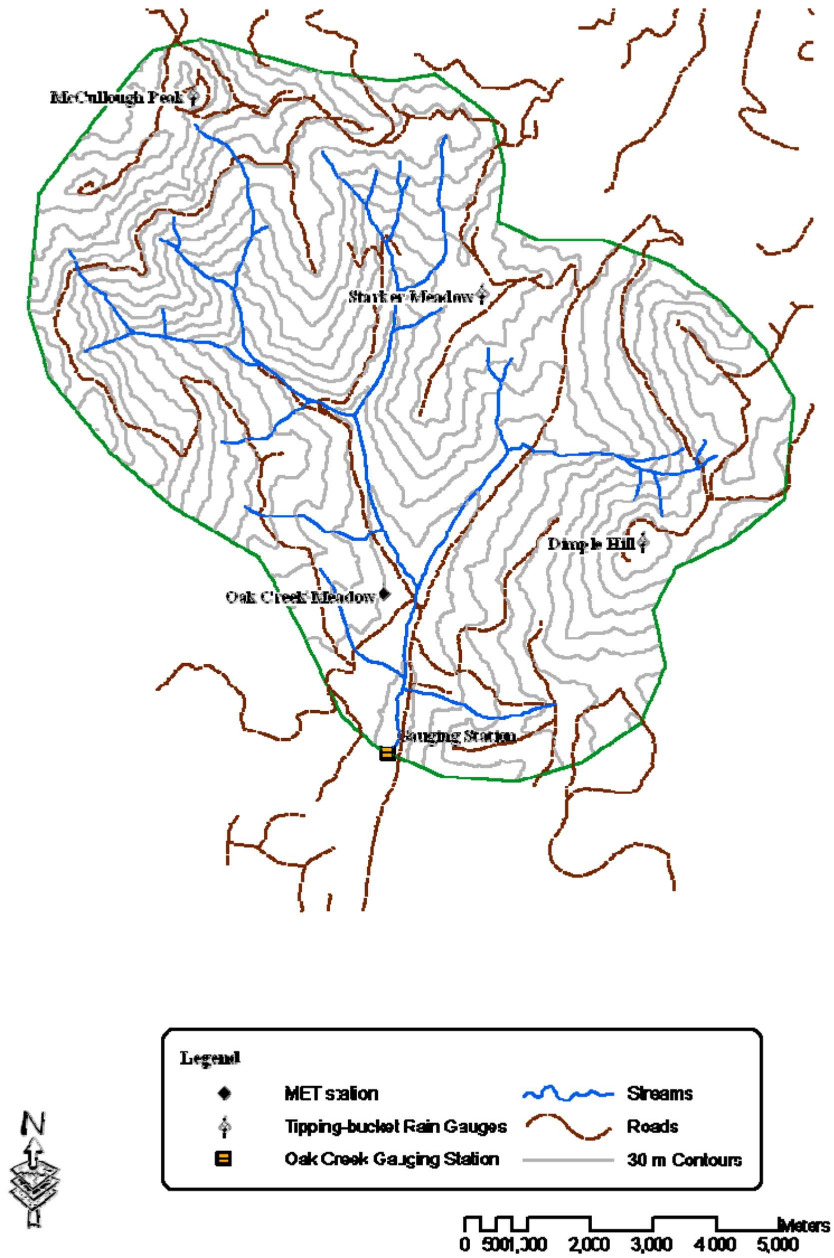


Figure 1. A map of Oak Creek Watershed

3.1.2 SOUTH FORK HINKLE CREEK

The Hinkle Creek watershed is located 25 miles northeast of Roseburg, Oregon owned and managed by Roseburg Forest Products, Inc. Hinkle Creek is a tributary of Calapooya Creek, which drains into the Umpqua River near Oakland, Oregon. The Hinkle Creek Paired Watershed Study includes stream gauging stations at the mouths of the North and South Forks of Hinkle Creek and six nested and paired subwatersheds (Figure 2). The South Fork Hinkle Creek watershed is the treatment watershed for the paired watershed study and has an area of 1,083 hectares. Four of the six nested, subwatersheds are located in the South Fork Hinkle Creek watershed.

Mean annual precipitation ranges from 140 to 190 cm. The geology of the basin is basalt from the Siletz Volcanics formation. The soils are Typic Palehumults or Typic Haplohumults. These soils are deep and well drained with loamy textures ranging from extremely gravelly to silty clay. Overstory vegetation is predominantly 60-year old Douglas-fir (*Pseudotsuga menziesii*) with minor components of western hemlock (*Tsuga heterophylla*) and western red-cedar (*Thuja plicata*). The understory vegetation consists of sword fern (*Polystichum munitum*), vine maple (*Acer circinatum*), red huckleberry (*Vaccinium ovatum*), Oregon-grape (*Berberis nervosa*), rhododendron (*Rhododendron* sp.) and salal (*Gaultheria shallon*).

The South Fork Hinkle Creek watershed is commercial forestland that is intensively managed for solid wood products. The forest consists of a harvest-regenerated stand of small, uniform sized, 60-year old trees. Prior to the inception of the paired watershed study, 11 percent of the watershed was logged. The first harvesting entry in the South Fork Hinkle Creek watershed in conjunction with the paired watershed study occured between August 2005 and April 2006. The trees were harvested with contemporary forest practices prescribed by the Oregon Forest Practices Rules. The trees were removed from four harvest units in accordance with the Oregon Forestry Practice Act, Best Management Practices. All four harvest units were located adjacent to perennial, non-fish-bearing streams in the South Fork Hinkle Creek watershed. No formal buffer strips of overstory, merchantable trees were left adjacent to the streams. An existing road system, with little new road construction, was used to haul the timber from the watershed. Approximately 1.5 miles of new spur roads were constructed, along with approximately 3.5 miles of road reconstruction. Vehicle traffic during timber harvest consisted of passenger vehicles, logging equipment, and log trucks. Over 12 million board feet of timber was harvested from 154 hectares (14 percent) of the South Fork Hinkle Creek watershed in 3,281 loads of logs.

The U.S. Geologic Survey maintains a gauging station at the mouth of South Fork Hinkle Creek. Stage (water height) is measured and recorded at 30-minute intervals. Turbidity, temperature, and specific conductivity are measured and recorded at 10-minute intervals. Turbidity data were reduced to 30-minute intervals to correspond with the discharge measurements. Water samples were taken with an ISCO 3700 automated water sampler following the TTS method (Lewis, 1996). The South Fork Hinkle Creek gauging station had turbidity and specific conductivity sensors mounted on an articulated boom at the stream gauging installation. The intake for the automated pump sampler was mounted approximately 15 cm above the stream bed. Precipitation was measured with a single tipping-bucket rain gauge. Wind speed, wind direction, relative humidity, air temperature, and solar radiation were measured at a micrometeorological tower located roughly at the centroid of the North Fork and South Fork Hinkle Creek watersheds (Figure 2). The gauging station at South Fork Hinkle Creek was operated throughout the 2006 water year.

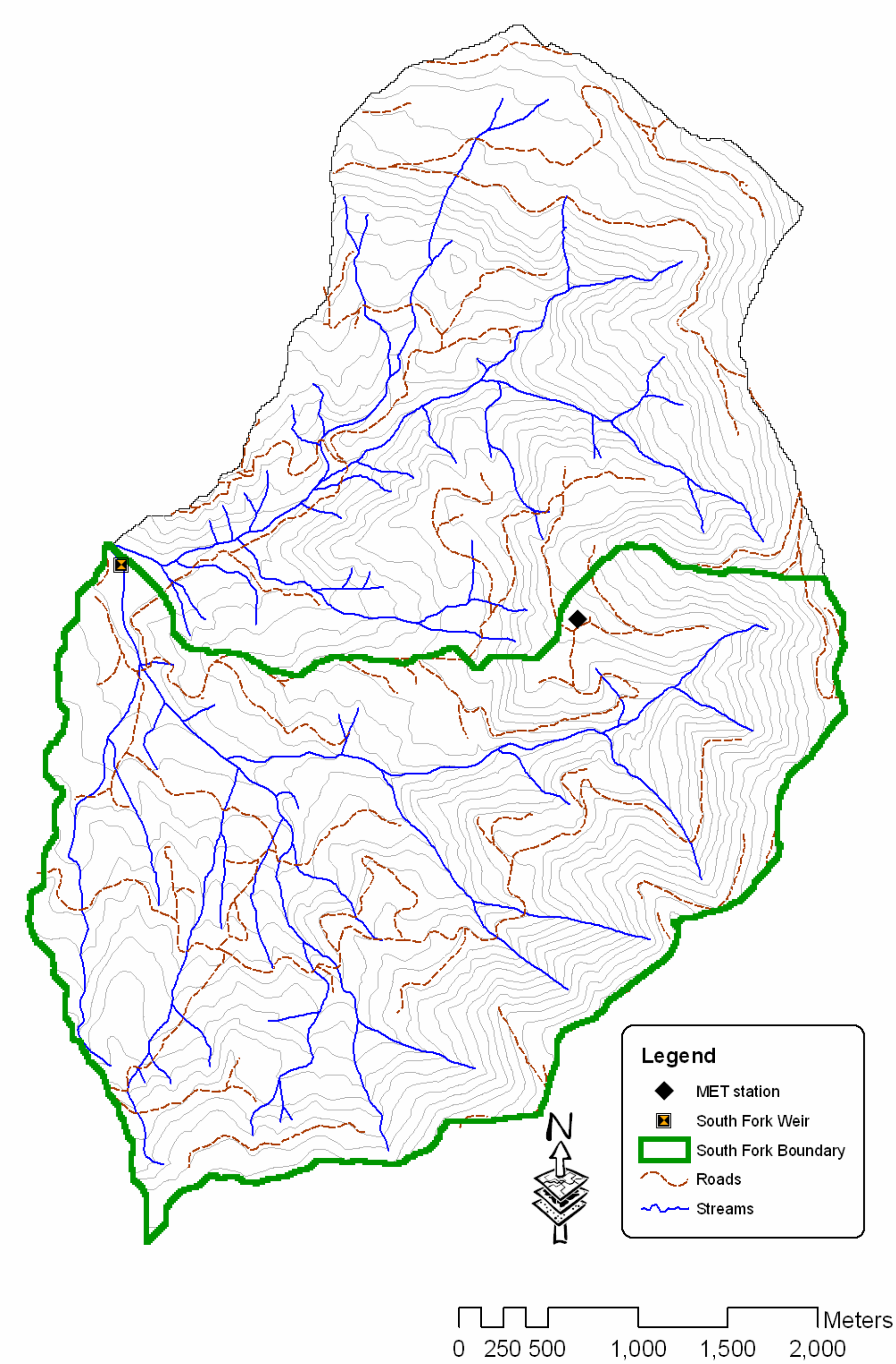


Figure 2. A map of North and South Fork Hinkle Creek watersheds

3.2 INSTRUMENTATION

Hydrologic data is collected at Oak Creek and South Fork Hinkle Creek with the turbidity threshold sampling (TTS) system developed by the Redwoods Sciences Lab (U.S. Forest Service Southwest Research Station, 2007). The TTS station at Oak Creek and the eight TTS stations in the Hinkle Creek Paired Watershed Study were installed during summer 2003.

3.2.1 TURBIDITY THRESHOLD SAMPLING

TTS is an automated data collection system that measures and records *in situ* turbidity and triggers collection of water samples to be analyzed for suspended sediment from the stream that it is gauging. The TTS system at Oak Creek and South Fork Hinkle Creek is controlled by a Campbell Scientific CR-10X programmable data logger, where data is recorded from measurements taken with an in-stream turbidimeter, a pressure transducer to measure water level, and an ISCO 3700 water sampler to collect water samples for SSC analysis (Lewis, 1996; Lewis and Eads, 2001). Measurements of turbidity and stage are taken at 10-minute intervals. The CR-10x uses data from the stage and turbidity measurements to trigger the automated sampler to take water samples over a range of turbidity values.

Correlations between *in situ* turbidity and the corresponding value of SSC from the water samples are used to estimate the sediment load in the stream. The use of discharge and turbidity to trigger the collection of water samples allows the water samples to be collected during all storms and discharges when a majority of the sediment load is carried by the stream. The TTS system uses a sampling proportional to probability technique that insures that water samples are taken when the probability that there is sediment in the water is high (Thomas, 1985). When fluctuations in turbidity occur in response to changes in discharge, water samples are taken when defined turbidity thresholds are surpassed, which allows water samples to be distributed throughout the rising and falling limbs of storms (Lewis and Eads, 1996; Lewis and Eads, 2001).

An algorithm in the CR-10X used by the TTS system uses turbidity thresholds and minimum discharge values to decide when discrete water samples are taken. Thresholds of turbidity are determined for individual streams based on the expected range of turbidity values. The value of the threshold turbidity is selected based of consideration of the maximum expected turbidity value, the range of values for the turbidimeter, and the desired number of samples. The range of values for the turbidity threshold considers values that produce the desired number of water samples. Turbidity thresholds are established for the rising and falling limbs of hydrographs and a minimum discharge is set, so that water samples are not triggered when there is insufficient water in the stream, or when the water level is too low to submerge the turbidimeter.

3.2.2 EQUIPMENT

Campbell Scientific CR-10X data loggers are used to control the water sampler and record turbidity and stage data. Stage, turbidity, and specific conductivity are measured and recorded every 10-minutes. *In situ* turbidity is measured with an OBS-3 turbidimeter (D&A, Inc.) in formazin backscatter units (FBU). The median turbidity value is determined and recorded from 60 consecutive measurements over a 30 second time-interval. The average stage is measured and recorded from 150 stage values over three-seconds. Temperature and specific conductivity are measured with a Campbell Scientific specific conductivity probe. Water samples are taken with an ISCO 3700 automatic pumping sampler. Precipitation is measured with a NovaLynx tipping bucket rain gauges and rainfall is recorded on Onset HOBO event recorders.

3.3 WATER SAMPLE ANALYSIS

The ISCO automatic water samplers collect 500 mL samples of stream water. The intake for the water sampler was near the turbidity probe either at the end of the boom or mounted above the streambed. Water samples were collected from each gauging station and were drawn through a 0.635 cm diameter tube. The water samples were labeled, transported to the laboratory, and stored in a refrigerator until analyzed. Turbidity of the water samples, in nephelometric turbidity units (NTU), was measured in a laboratory with a Hach 2100 turbidimeter. Suspended sediment concentration of the water sample was determined using standard methods using 0.45 µm filters (Amann, 2004; Clesceri et al., 1998).

3.4 IDETIFYING TIME PERIODS AND STORMS

The annual hydrographs for Oak Creek and South Fork Hinkle Creek were divided into shorter time period (Storms). The objective of separating the annual hydrograph into storms was to create storm-specific relationships between *in situ* turbidity and SSC. Storms were identified as time periods that contained increases and decreases in discharge that included water samples taken using the TTS sampling method. The storm time periods contained at least one hydrograph that had associated water samples taken, which allowed for the creation of a relationship between turbidity and SSC. The storm time periods may contain several hydrographs that have either no associated water samples or have only a small number of water samples that are inadequate for estimating sediment load on there own. Storms were numbered sequentially.

Storm-specific relationships were created for all storms that had a peak discharge greater than 470 L/s for Oak Creek and 1,000 L/s for South Fork Hinkle Creek during water year 2006. An exception was the hydrograph that immediately followed Storm 1 at Oak Creek. The SSC of water samples which occurred during the hydrograph just after Storm 1 were excluded from storm-specific analysis due to potential contamination of samples from mechanical problems with the automated sampler.

3.5 PARTIAL DURATION SERIES FREQUENCY ANALYSIS

The hydrologic context for the water years and peak flows that were investigated was determined with a partial series frequency analysis. The largest peak flows were analyzed for different periods of time for Oak Creek and the South

Fork Hinkle Creek. Twenty peak flows were selected for analysis for Oak Creek from the 2001 to 2007 water years. Twenty-two peak flows were selected for analysis for the South Fork Hinkle Creek from the 2004 to 2007 water years. All peak flows selected for analysis had discharges greater than 1,500 L/s. Frequency analysis of the peak flow data from the two watersheds was carried out with a partial series analysis (Chow, 1964; Kite, 1977). The Gringorten extreme value plotting equation was used to assign the recurrence interval (T_r) to the peak flows for the individual storms using Equation 1 (Gringorten, 1963).

$$T_r = \left(\frac{n + 1 - 2a}{m - a} \right)$$ **Equation 1**

Where n is the total number of storms in the partial duration series, m is the rank of a given storm, and a=0.375.

4. RESULTS

4.1 OAK CREEK

4.1.1 HYDROLOGY

The magnitude of discharge and turbidity at Oak Creek is seasonal and varies with precipitation. Discharge and turbidity are low and constant during summer and fall low flows but vary greatly with winter storms (Figure 4). Total annual precipitation at Oak Creek for water year 2006 was 1,278 mm. Base flows at Oak Creek occurred in October, June, and July and rarely exceeded 20 L/s. The discharge of the maximum annual peak flow was 7,561 L/s, which occurred on December 28, 2005.

A partial duration frequency analysis of peak flows for Oak Creek was completed that used data from water year's 2001 to 2007. The Gringorten extreme value plotting equation was used to assign a T_R to the peak flows on record (Figure 3). The discharge for the December 28, 2005 peak flow was the largest peak flow in the six year record and it was assigned a T_R of 9.7 years.

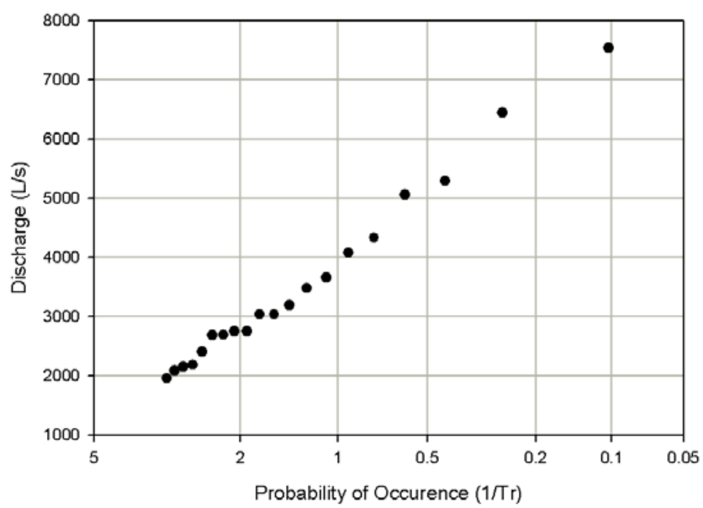


Figure 3. A graph of peak flow discharges and the probability of occurrence (1/ T_R) for Oak Creek water years 2001-2007.

The annual hydrograph was separated into individual storms. The annual hydrograph was separated into 15 time periods (Storms), so that storm-specific relationships between *in situ* turbidity and SSC could be developed (Table 1). Most of these storms contained only one maximum instantaneous peak flow. However, some storms contained multiple peak flows and periods of base flow. Hourly precipitation and the annual hydrograph for Oak Creek for the 2006 water year are shown in Figure 4. The figure shows the range in magnitude and duration of the storms. Fifteen storms resulted in the collection of 305 water samples and were designated for further analysis. The attributes of these storms are listed in Table 1.

Table 1. A table of annual and separate-storm time periods for Oak Creek: water year 2006.

Storm ID	Start Date	End Date	Peak Discharge (L/s)	Water Samples
Annual	10/1/2005 0:00	9/30/06 23:50	7,561	305
1	10/1/05 0:00	11/5/05 11:00	471	43
2	11/5/05 11:10	11/20/05 0:00	719	29
3	11/20/05 0:10	12/1/05 8:10	566	16
4	12/1/05 8:10	12/19/05 0:00	1,031	10
5	12/19/05 0:10	12/21/05 3:10	883	8
6	12/21/05 3:20	12/26/05 22:50	3,656	38
7	12/26/05 23:00	12/29/05 16:10	7,561	22
8	12/29/05 16:20	1/3/06 9:40	5,758	22
9	1/3/06 9:50	1/6/06 5:00	1,128	5
10	1/6/06 5:10	1/9/06 12:00	1,727	9
11	1/9/06 12:10	1/10/06 14:10	3,476	10
12	1/10/06 14:20	1/16/06 3:00	3,068	7
13	1/16/06 3:10	1/20/06 4:00	5,055	28
14	1/20/06 4:00	1/31/06 12:20	6,445	35
15	1/31/06 12:20	9/30/06 23:50	2,321	23

The time period that includes the first storm was the first time period to produce an adequate number of water samples for comparing SSC and *in situ* turbidity. This time period had the smallest peak discharge (471 L/s) of all of the time periods. Total precipitation during this time period was 142 mm. The first time period included nine instantaneous peak hydrographs that occurred between October and November, 2005 (Figure 5). Hydrograph peaks ranged from 57 to 471 L/s. The largest peak flow in the time period was preceded by six smaller peak flows with peak discharges less than 110 L/s. The slope of the rising limbs of the hydrographs are gradual for these small peaks when they are compared to the slope of the rising limb of the hydrograph that had the highest peak discharge of 471 L/s. From the initial rise of the hydrograph to the peak, discharge increased 1.9 L/s per minute for the peak hydrograph during the Storm 1 time period. For the smaller hydrographs, the slope of the rising limb was less than 0.2 L/s per minute. Two hydrographs followed the Storm 1 peak discharge. These hydrographs had peak flows of 235 L/s and 178 L/s. The slope of the rising limb of the hydrographs was less than 0.3 L/s per minute for these two hydrographs. There were 43 water samples that were taken during this time period.

The maximum annual peak flow was 7,561 L/s and it occurred during the Storm 7 time period. Total precipitation for this time period was 72 mm. This time period contained one hydrograph that occurred between December 26 23:00 and December 29 16:20, 2005 (Figure 6). The slope of the rising limb of the hydrograph was 8.3 L/s per minute. There were 22 water samples that were taken during this time period.

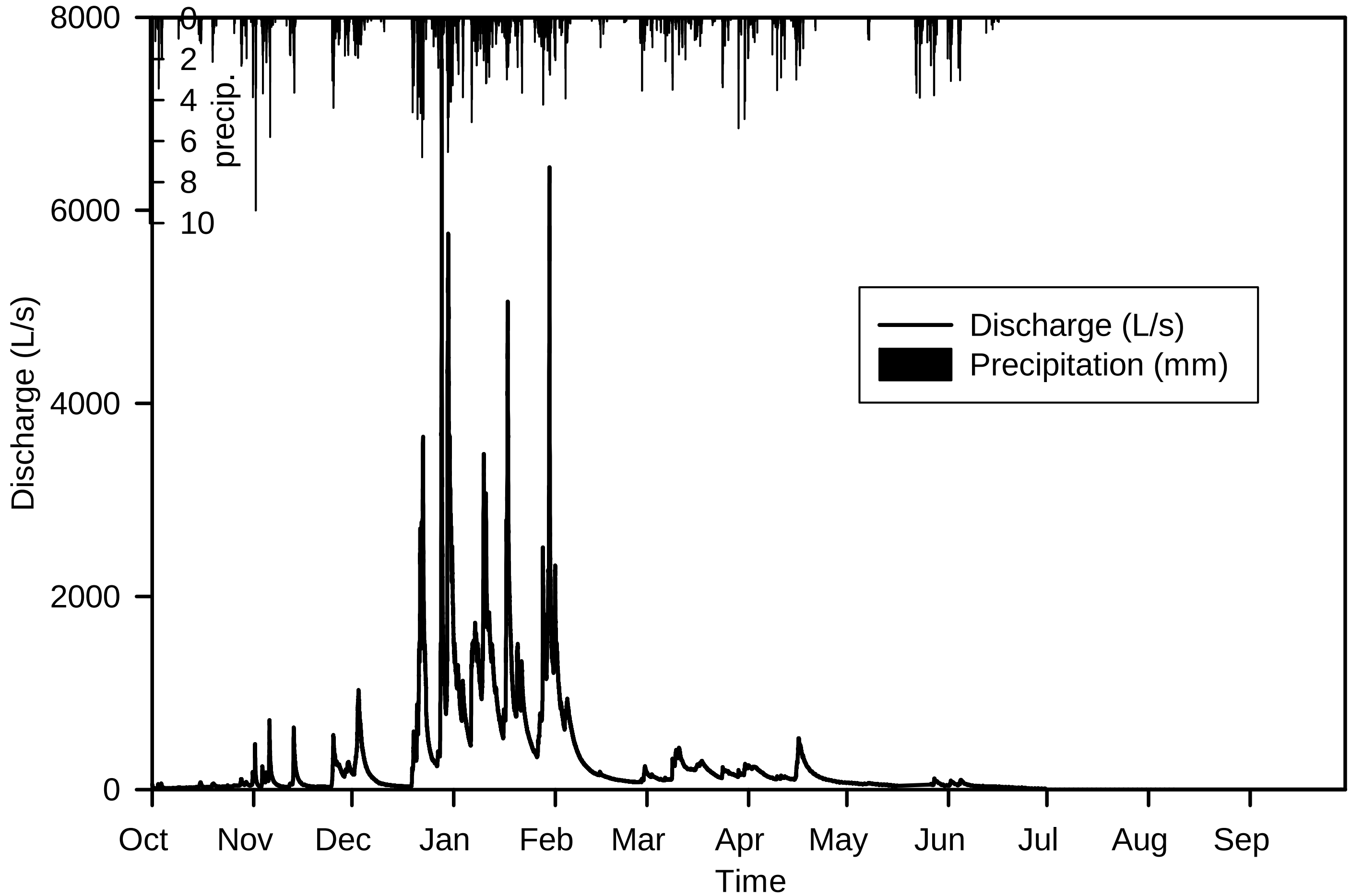


Figure 4. A graph of precipitation and discharge for Oak Creek: water year 2006.

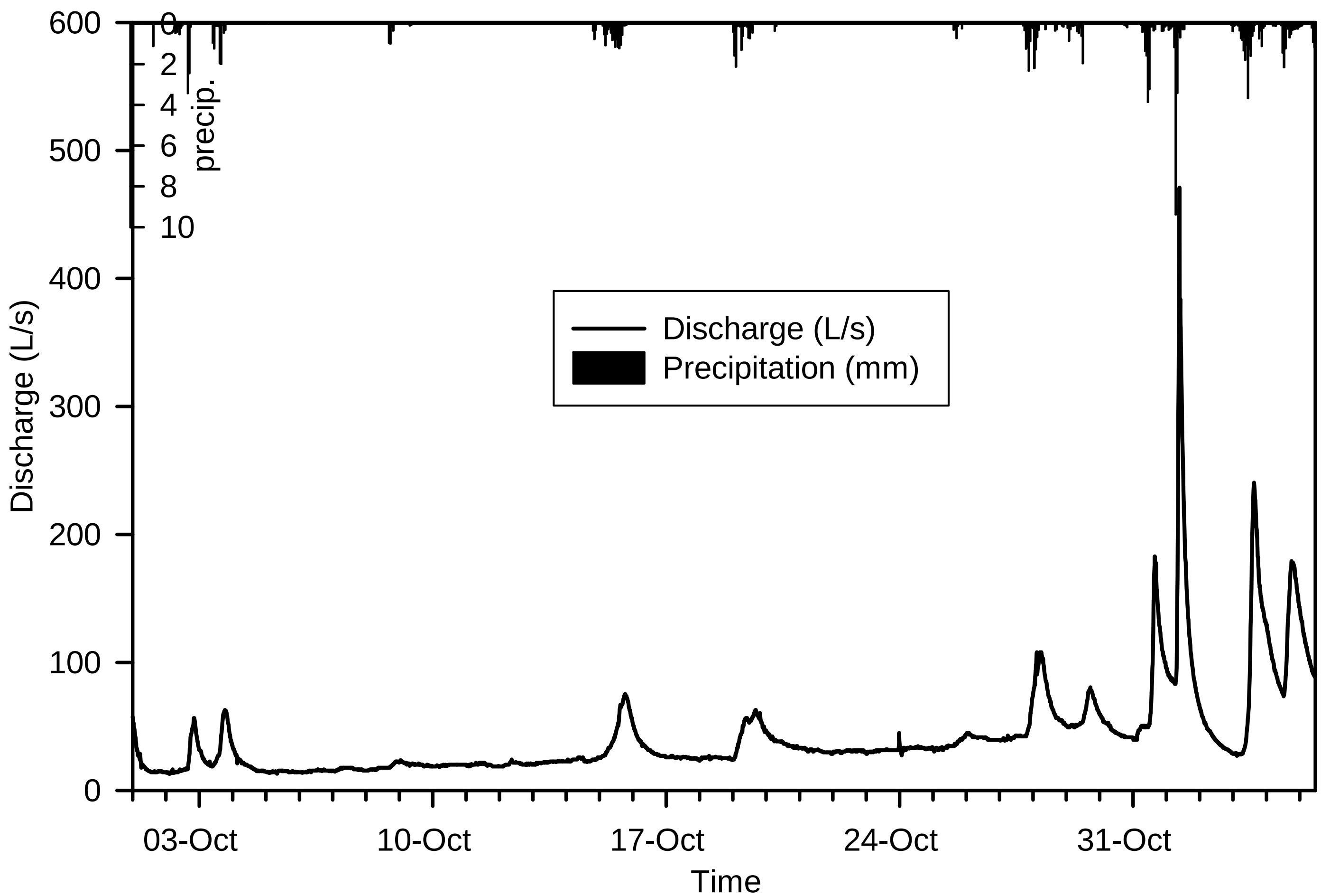


Figure 5. A graph of discharge and hourly precipitation for Oak Creek during the Storm 1 time period: October 1-November 5 11:10, 2005.

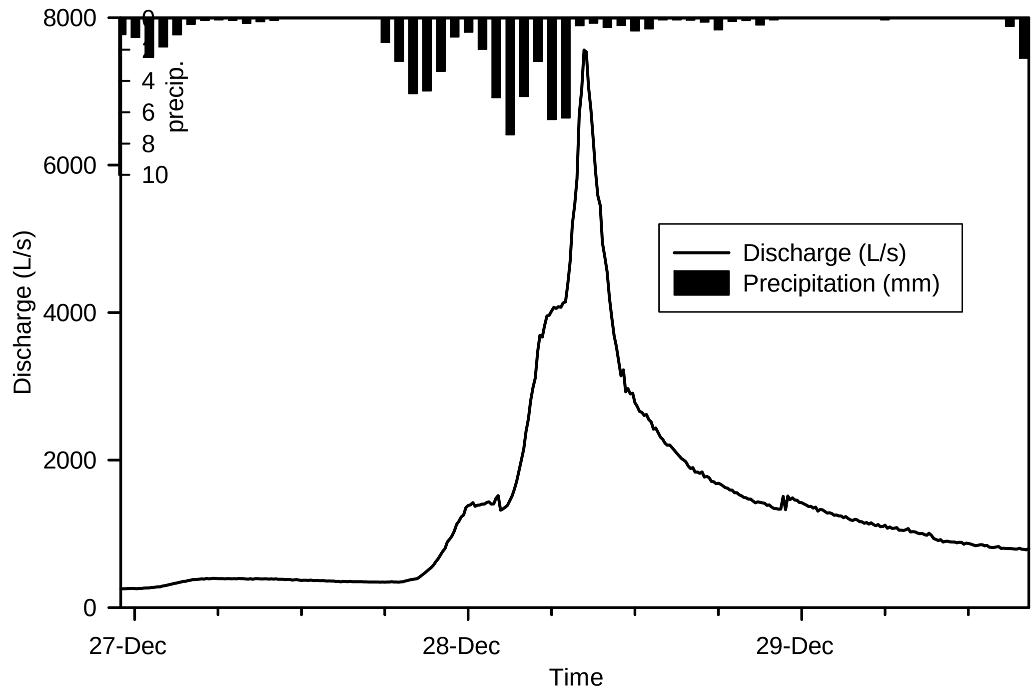


Figure 6. A graph of discharge and hourly precipitation for Oak Creek during the December 26 to 29 storm that contained the maximum annual peak flow.

4.1.2 IN SITU TURBIDITY

In situ turbidity at Oak Creek ranged from 0 to 1,631 FBU during water year 2006 (Figure 7). *In situ* turbidity increased during storms and high values of *in situ* turbidity occurred at times not associated with precipitation or a storm hydrograph. Highly variable turbidity data occurs during times of low discharge. The largest values of *in situ* turbidity, over 1,000 FBU, occurred between October and December and the discharge between October and December rarely exceeded 200 L/s. Spikes of *in situ* turbidity also occurred in May and reached maximum values between 150 and 500 FBU. Discharge in May was between 40 and 70 L/s. The largest peak flows occurred between December and February during winter storms and maximum *in situ* turbidity values were between 100 and 700 FBU during those storms.

A graph that shows the high variability *in situ* turbidity data for Storm 1 is shown in Figure 8. High values of *in situ* turbidity were short-term and persisted for only several observations, or they persisted for longer periods of time. Many of the high values of *in situ* turbidity occurred when the discharge was approximately 15-20 L/s. Low values of *in situ* turbidity, approximately 13-25 FBU, also occurred during these flows. There are three hydrographs that occurred during the time period that included Storm 1 that contained values of *in situ* turbidity that were highly variable. The hydrograph that contains the largest peak flow in the Storm 1 time period, a peak flow of 471 L/s, has a period of time that includes values of *in situ* turbidity that are highly variable. The maximum value of *in situ* turbidity for the water year, 1,631 FBU, occurred during this hydrograph. This hydrograph has two peak flows and *in situ* turbidity data that is highly variable occurs only during the rising limb of the first peak.

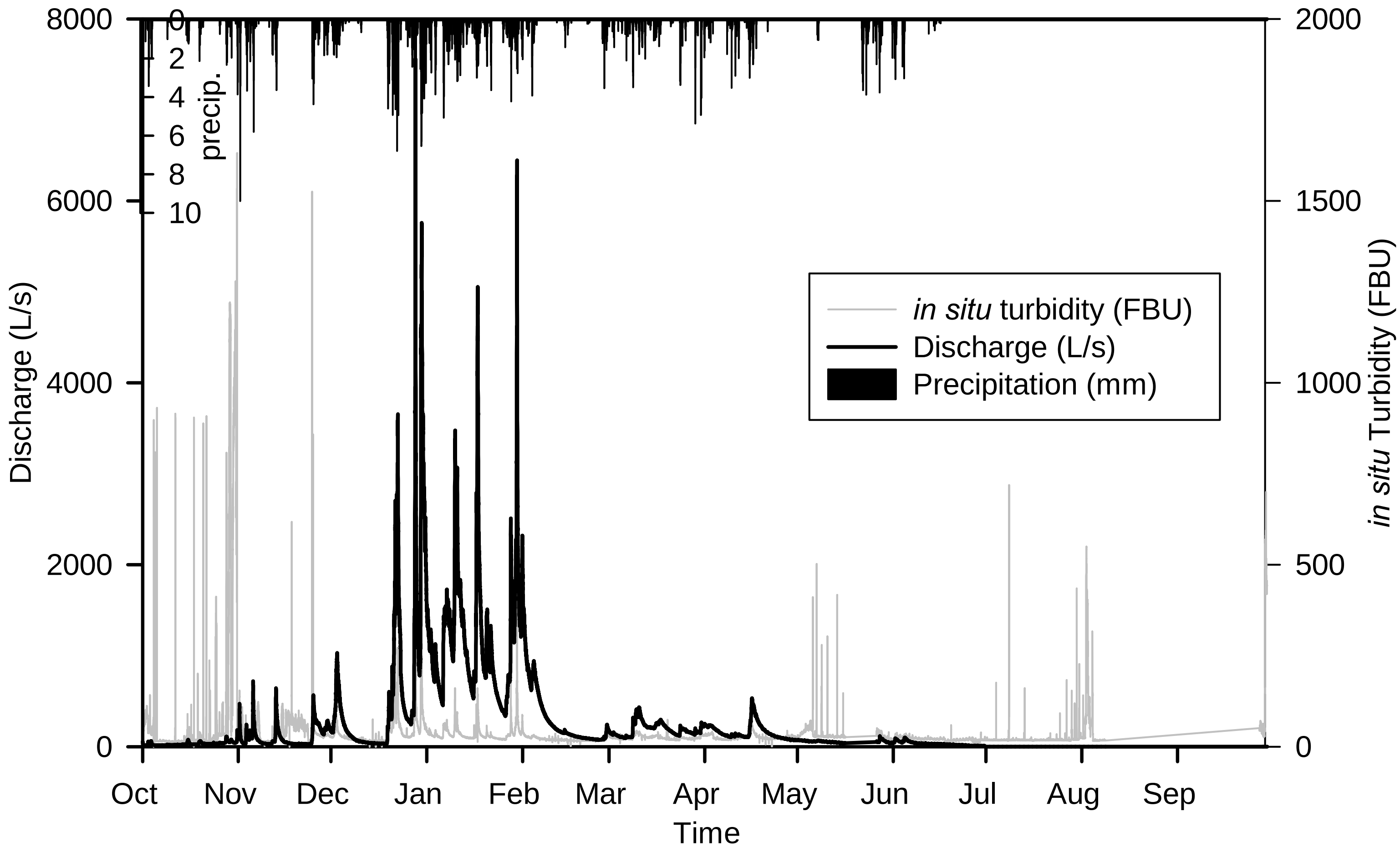


Figure 7. A graph of hourly precipitation, 10-mintue discharge, and 10-minute *in situ* turbidity at Oak Creek for the 2006 water year.

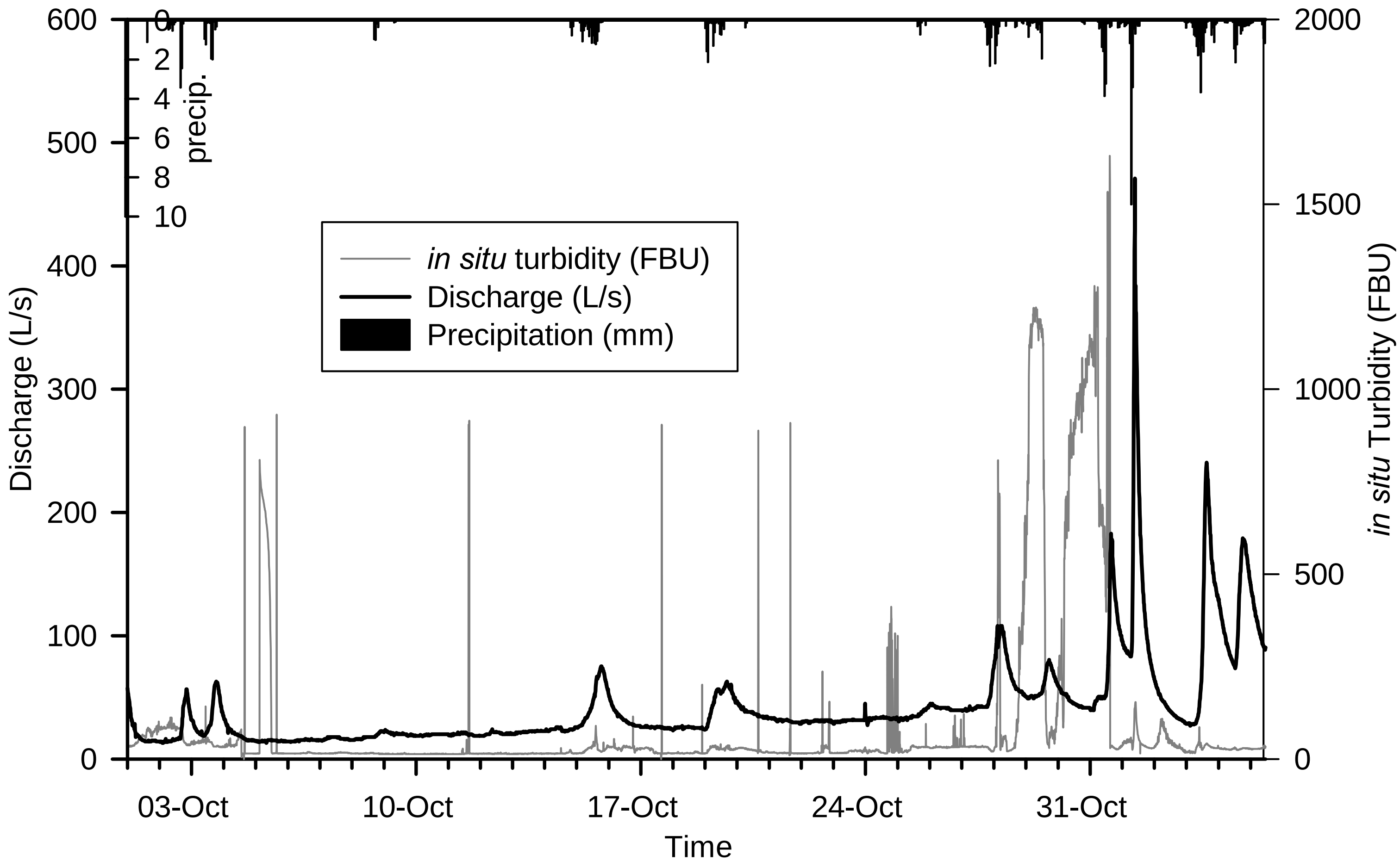


Figure 8. A graph of hourly precipitation, 10-minute discharge, and 10-minute *in situ* turbidity for Oak Creek during the time period that included Storm 1,October 1-November 5, 2005.

In situ turbidity during the period of time that contained the maximum annual peak flow is shown in Figure 9 along with discharge and hourly precipitation. The maximum annual peak flow was 7,561 L/s and the maximum value of *in situ* turbidity during the storm was 673 FBU. Discharge and *in situ* turbidity peaked simultaneously. This period of time did not contain any of the values of *in situ* turbidity that were highly variable and observed during the time period that contained Storm 1.

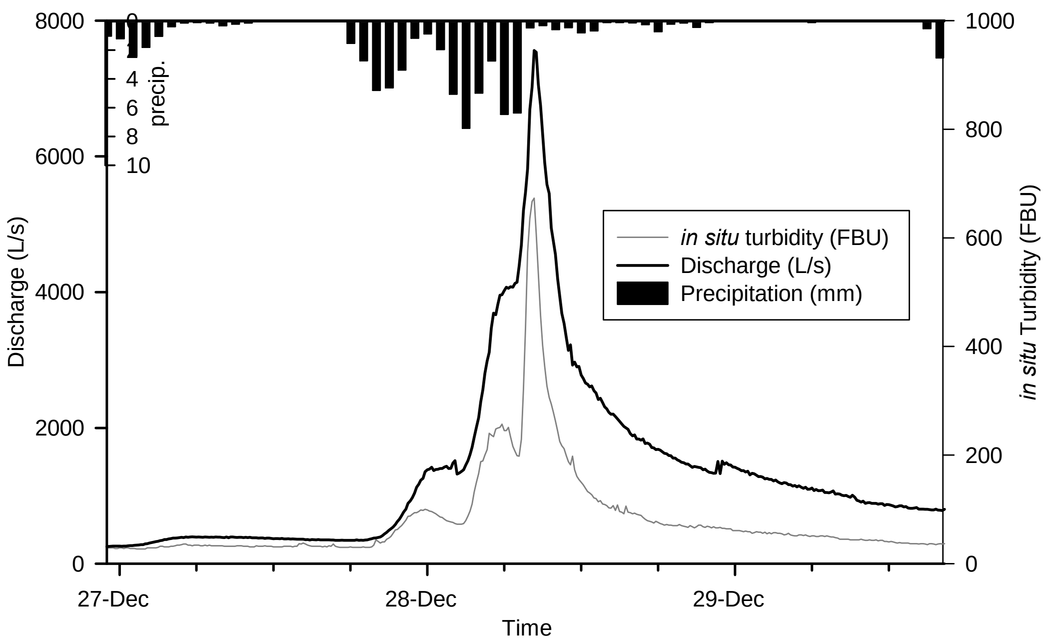


Figure 9. A graph of discharge, *in situ* turbidity, and hourly precipitation for Oak Creek during the December 26 to 29, 2005 time period that included the annual maximum peak flow.

4.1.3 TURBIDITY AND SSC

During the water year 2006, 305 water samples were taken at Oak Creek and analyzed for SSC and turbidity in a laboratory. The distribution of how these samples were collected in time is shown in Figure 10. All of the water samples were taken between October 15, 2005 and February 19, 2006. Suspended sediment concentration of the water samples ranged from 0.4 to 1,835 mg/L. Three water samples had SSC values of 1,135; 1,523; and 1,850 mg/L occurred during the maximum annual peak flow and had laboratory turbidity values that exceeded the sensor maximum (1,000 NTU). Of the 305 water samples collected, 158 water samples were taken during the large winter storms that occurred between December 20, 2005 and February 20, 2006. The water samples that were collected during this winter storm time period occurred at discharges between 100 and 7,061 L/s and the *in situ* turbidity value of the stream water at the time the samples were taken was between 18 and 574 FBU. The range of laboratory turbidity values during the winter storm time period was between 4 and over 1,000 NTU. The SSC of water samples collected during the winter storm period had values between 0.4 and 1,835 mg/L. No water samples were collected after this winter storm time period. Each water sample can be paired with two values of turbidity: the *in situ* turbidity value that corresponds to the time when the water sample was taken and the laboratory turbidity value of the water sample.

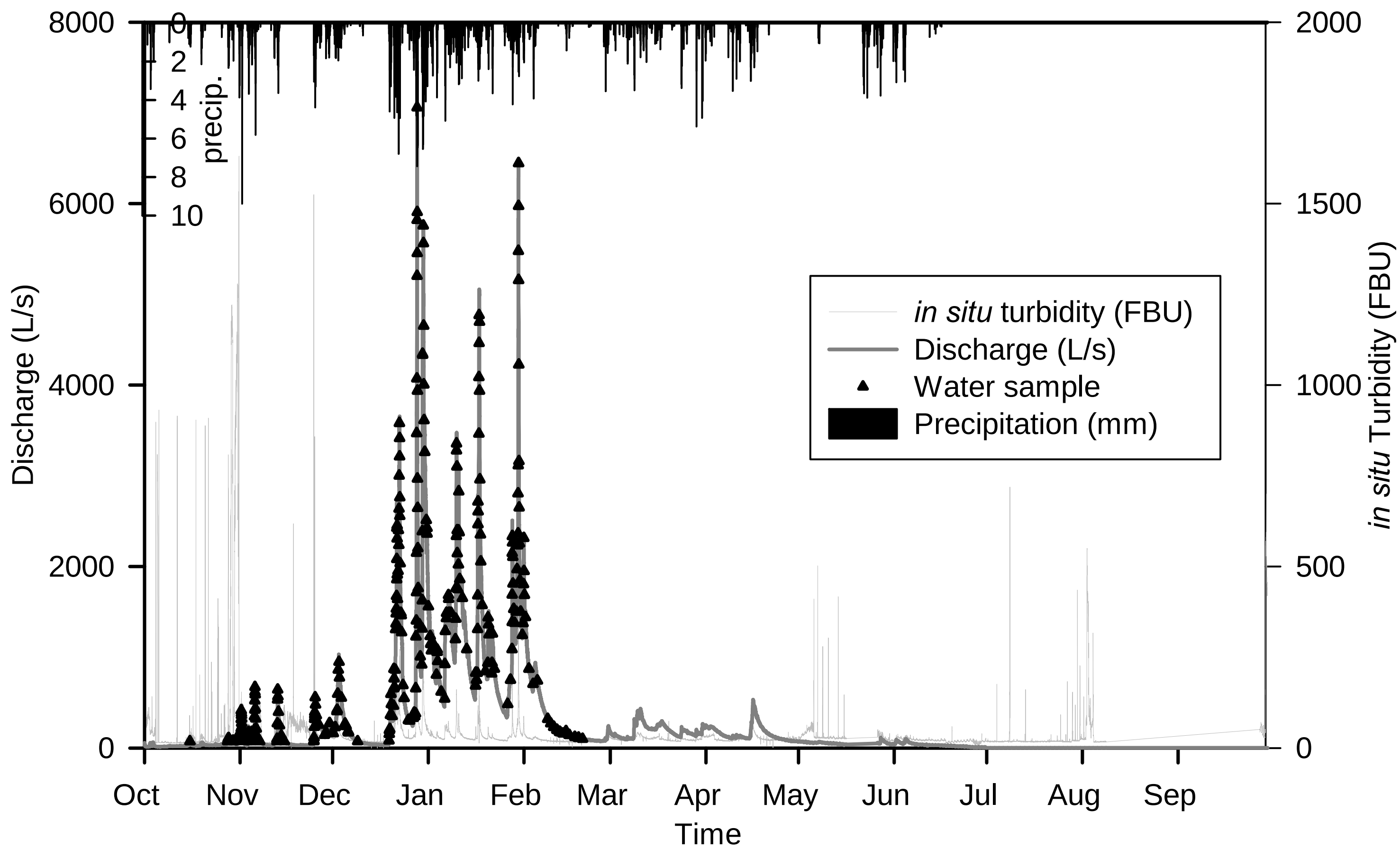


Figure 10. A graph of precipitation, discharge, *in situ* turbidity, and water samples at Oak Creek during water year 2006. Water samples are shown relative to time and discharge during sampling.

4.2 SOUTH FORK HINKLE CREEK

4.2.1 HYDROLOGY

A partial duration frequency analysis of peak flows for South Fork Hinkle Creek was completed that used data from water year's 2004 to 2007. The Gringorten extreme value plotting equation was used to assign a T_R to the peak flows on record (Figure 11). The discharge for the December 30, 2005 peak flow was the largest peak flow in the four year record and it was assigned a T_R of 6.5 years. The four highest peak flows in the four year record occurred during water year 2006. These high peak flows had discharges of 6,061; 9,487; 13,424; and 15,349 L/s, and were assigned recurrence intervals of 1.1, 1.5, 2.5, and 6.5 years, respectively. The next highest peak flow occurred in water year 2005, and had a discharge of 3,512 L/s. This water year 2005 peak flow was assigned a T_R of 0.9 years.

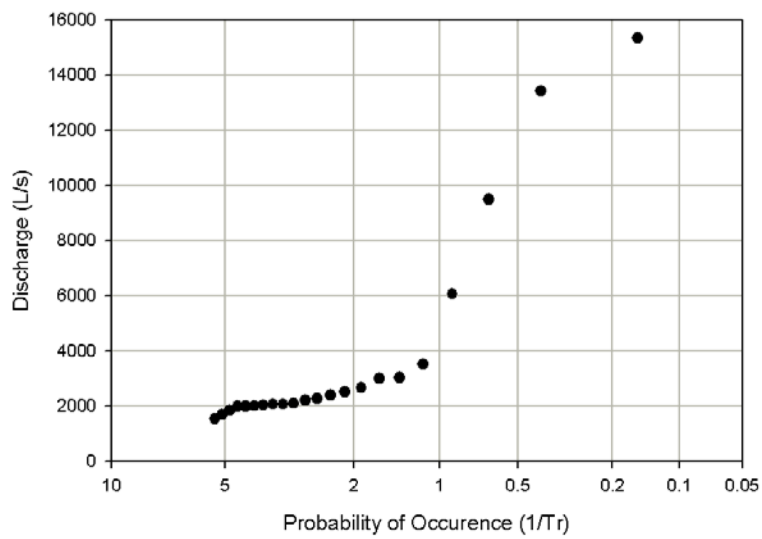


Figure 11. A graph of peak flow discharges and the probability of occurrence (1/ T_R) for South Fork Hinkle Creek water years 2001-2007.

The annual hydrograph was separated into individual storms. The annual hydrograph was separated into seven time periods (Storms), so that storm-specific relationships between *in situ* turbidity and SSC could be developed (Table 2). These time periods contained a maximum instantaneous peak flow or contained multiple instantaneous peak flows, storm shaped hydrographs, and periods of base flow. The magnitude of discharge and turbidity at South Fork Hinkle Creek is seasonal and varies with precipitation. Discharge and turbidity are low and constant during summer and fall low flows but vary greatly with winter storms (Figure 12). Total annual precipitation at South Fork Hinkle Creek for water year 2006 was 1,926 mm. Base flows at South Fork Hinkle Creek rarely exceeded 50 L/s and occurred between July and September. The discharge of the maximum annual peak flow was 15,349 L/s, which occurred on December 30, 2005 (Table 2). There were 162 water samples collected during the 2006 water year. Hourly precipitation and the annual hydrograph for South Fork Hinkle for the 2006 water year are shown in Figure 12. The figure shows the range in magnitude and durations of the storms. Seven time periods result in the collection of SSC and were designated for further analysis. The attributes of these storms are listed in Table 2.

Table 2. A table of annual and separate-storm time periods for South Fork Hinkle Creek: water year 2006.

Storm ID	Start Date	End Date	Peak Discharge (L/s)	Water Samples
Annual	10/1/05 0:00	9/30/06 23:30	15,349	162
1	10/1/05 0:00	12/1/05 0:00	1,020	9
2	12/1/05 0:30	12/27/05 0:00	2,379	13
3	12/27/05 0:30	12/29/05 13:00	5,098	13
4	12/29/05 13:30	1/27/06 20:00	15,349	74
5	1/27/06 20:30	1/31/06 12:30	2,747	10
6	1/31/06 13:00	3/8/06 1:00	2,662	18
7	3/8/06 1:30	9/30/06 23:30	1,614	25

The time period that includes the first storm was the first time period to produce an adequate number of water samples for comparing SSC and *in situ* turbidity. This time period had the smallest peak discharge (1,020 L/s) of all of the time periods. Total precipitation during this time period was 394 mm. The first time period included 10 instantaneous peak hydrographs that occurred between October and December, 2005 (Figure 13). Hydrograph peaks ranged from 65 to 1,020 L/s. The largest peak flow in the time period was preceded by 6 small events with peak discharges less than 500 L/s and was followed by three peaks with discharges less than 850 L/s. From the initial rise of the hydrograph to the peak, discharge increased 0.2 L/s per minute for the peak hydrograph during the Storm 1 time period. For the smaller hydrographs that preceded the maximum peak, the slopes of the rising limbs were between 0.05 and 0.2 L/s per minute. The slopes of rising limbs of the hydrographs that followed the maximum peak were approximately 0.2 L/s per minute. There were nine water samples collected during this time period.

The maximum annual peak flow was 15,349 L/s and it occurred during Storm 4 time period on December 30, 2005. Total precipitation for the time period was 525 mm. The slope of the rising limb of the maximum peak hydrograph was 13.8 L/s per minute. There were three hydrographs that occurred during the Storm 4 time period between December 29, 2005 and January 27, 2006 (Figure 14). The maximum annual peak flow was followed by two smaller peak flows with discharges of 9,487 and 13,424 L/s. The slope of the rising limb these hydrographs were 10.6 and 10.9 L/s per minute, respectively. The three peak flows in the time period that includes Storm 4 are the three highest peak flows during the four-year record at South Fork Hinkle Creek. There were 74 water samples that were taken during this time period.

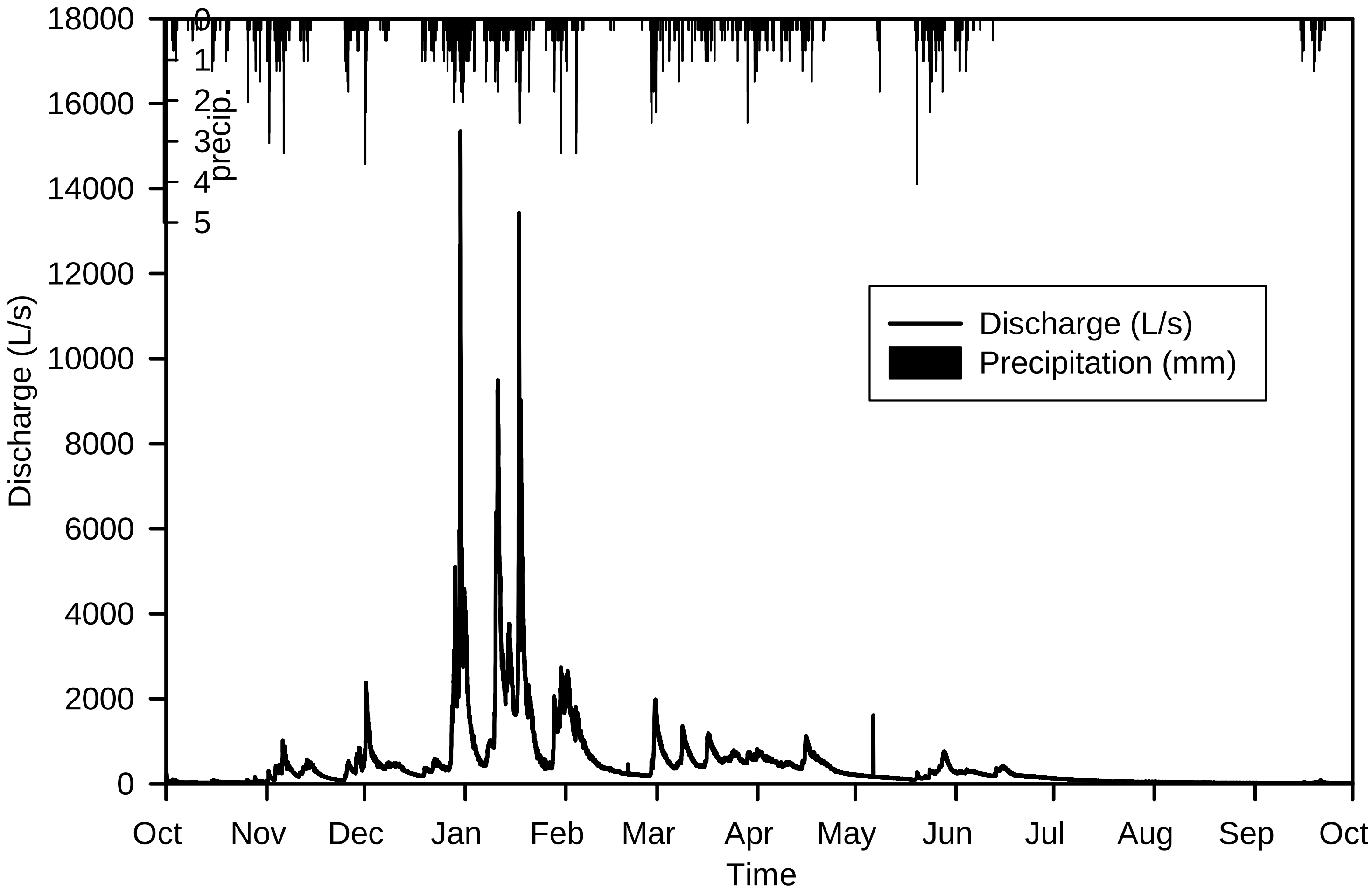


Figure 12. A graph of discharge and hourly precipitation and for South Fork Hinkle Creek during water year 2006.

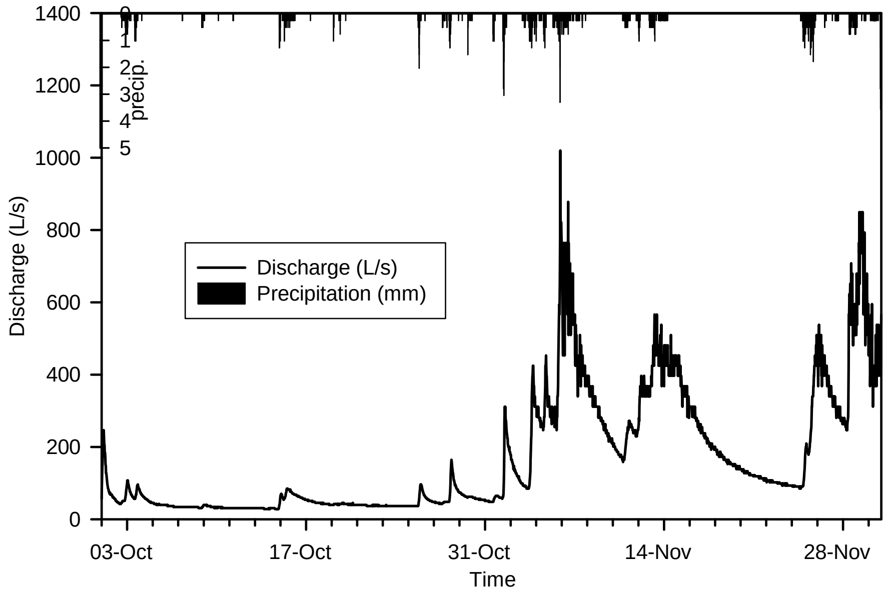


Figure 13. A graph of discharge and hourly precipitation for South Fork Hinkle Creek during the Storm 1 time period, October 1 to December 1, 2005.

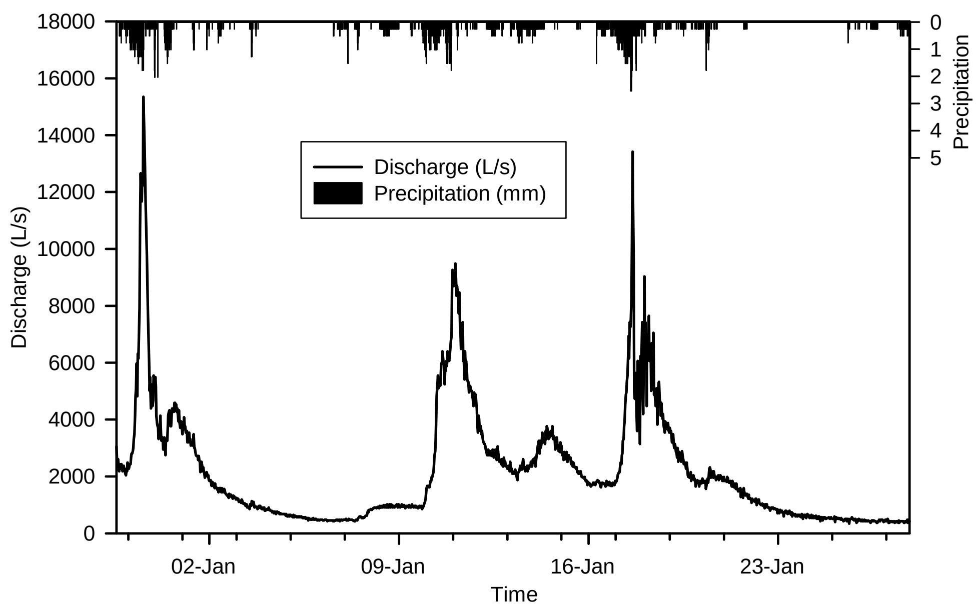


Figure 14. A graph of discharge and hourly precipitation for South Fork Hinkle Creek during the Storm 4 time period, December 29, 2005 to January 27, 2006.

4.2.2 IN SITU TURBIDITY

In situ turbidity at South Fork Hinkle Creek ranged from 8 to 1,326 FBU during water year 2006 (Figure 15). *In situ* turbidity increased during storms and high values of *in situ* turbidity occurred at times not associated with precipitation or a storm hydrograph. Highly variable turbidity data occurs during times of low discharge and during storm hydrographs. The largest values of *in situ* turbidity, 1,326 FBU, occurred in September, 2006 when discharge was at base flow (20 to 30 L/s). Spikes of *in situ* turbidity, between 140 and 590 FBU, occurred between October and early December when discharge rarely exceed 600 L/s. The largest peak flows occurred between late December and February during winter storms and maximum *in situ* turbidity values were between 140 and 750 FBU during those storms.

A graph showing the high variability *in situ* turbidity for the time period that includes Storm 1 is shown in Figure 16. High values of *in situ* turbidity were short-term and persisted for only several observations, or they persisted for longer periods of time. During this first time period steady increases in the value of *in situ* turbidity occur that were followed by sudden decreases back to lower value *in situ* turbidity. The largest of these steady *in situ* turbidity increases occurred between October 14 and 27. *In situ* turbidity during this time period increases steadily from 20 to 82 FBU and is unrelated to discharge. Two hydrographs occurred during this period of increased turbidity, the first hydrograph occurred just after the initial rise in turbidity, and the second occurred near the end. *In situ* turbidity increased from 50 to 82 FBU during the period of heightened *in situ* turbidity as a result of this hydrograph.

In situ turbidity during the time period that contained the maximum annual peak flow is shown in Figure 17 along with discharge and hourly precipitation. The maximum annual peak flow was 15,249 L/s and the maximum value of *in situ* turbidity during the storm was 749 FBU. The hydrograph for the maximum annual peak flow, which occurred December 29, 2005-January 9, 2006, is shown in more detail in Figure 18 along with turbidity and hourly precipitation. During this hydrograph, 38 water samples were collected. There is an instantaneous increase in turbidity that occurs just before the discharge increase followed by three distinct *in situ* turbidity peaks. The first increase of *in situ* turbidity occurred with increases in discharge reaching 677 FBU. This first peak *in situ* turbidity occurred before the peak in discharge, by the time of the peak discharge *in situ* turbidity is less than 100 FBU. The second peak *in situ* turbidity is the largest, lasted approximately 12-hours, and occurred during the recession limb of the hydrograph having a maximum turbidity of 749 FBU. The third peak *in situ* turbidity reached 654 FBU and occurred near the end of the storm. Precipitation that occurred during the recession limb of the hydrograph resulted in both increased discharge and *in situ* turbidity.

The maximum annual peak flow was followed by two peak flows and is shown in Figure 17 along with *in situ* turbidity and hourly precipitation. The hydrograph that occurred January 9-16 immediately follows the annual peak flow and has an instantaneous peak flow discharge of 9,487 L/s (Figure 19). During this hydrograph 32 water samples were collected. This hydrograph is the third largest peak flow in water year 2006 and during the four-year record. Initially, increased values of *in situ* turbidity along with discharge but then *in situ* turbidity becomes highly variable, fluctuating from 70 to 749 FBU for the remainder of the hydrograph. Within two-hours of the peak discharge, values of *in situ* turbidity decrease to base conditions (16-25 FBU).

The third peak flow during the time period that contains the maximum annual peak flow is the second largest peak flow of the year and in the four-year record (Figure 17). This hydrograph occurred January 16-25 and had an instantaneous peak discharge of 13,424 L/s. During this hydrograph five water samples were collected. *In situ* turbidity reached its peak (654 FBU) before discharge. A large increase of *in situ* turbidity occurred during the recession limb of the hydrograph. This increase of *in situ* turbidity reached 574 FBU and persisted for four-hours before returning to base conditions (24 FBU).

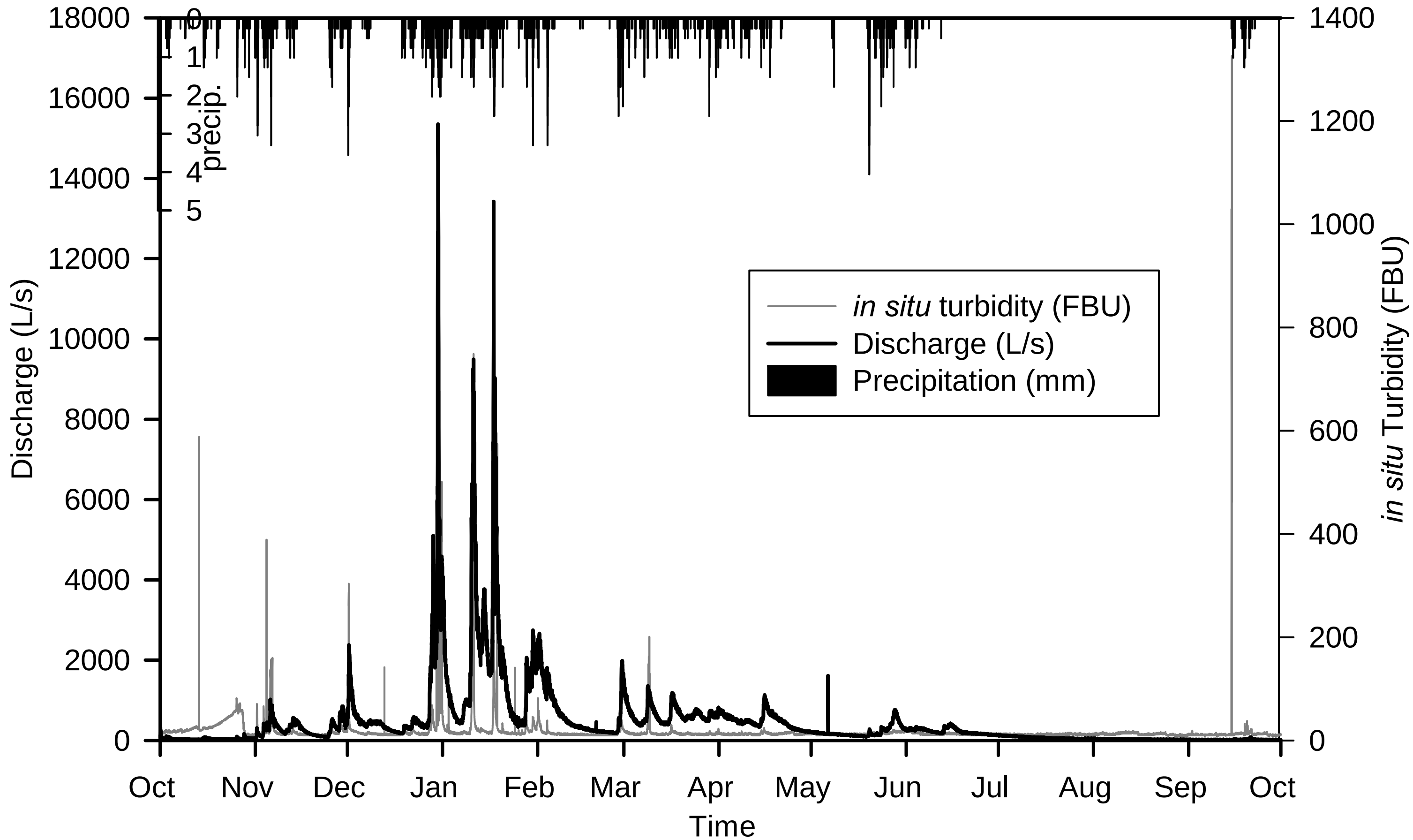


Figure 15. A graph of precipitation, discharge, and *in situ* turbidity at South Fork Hinkle Creek: water year 2006.

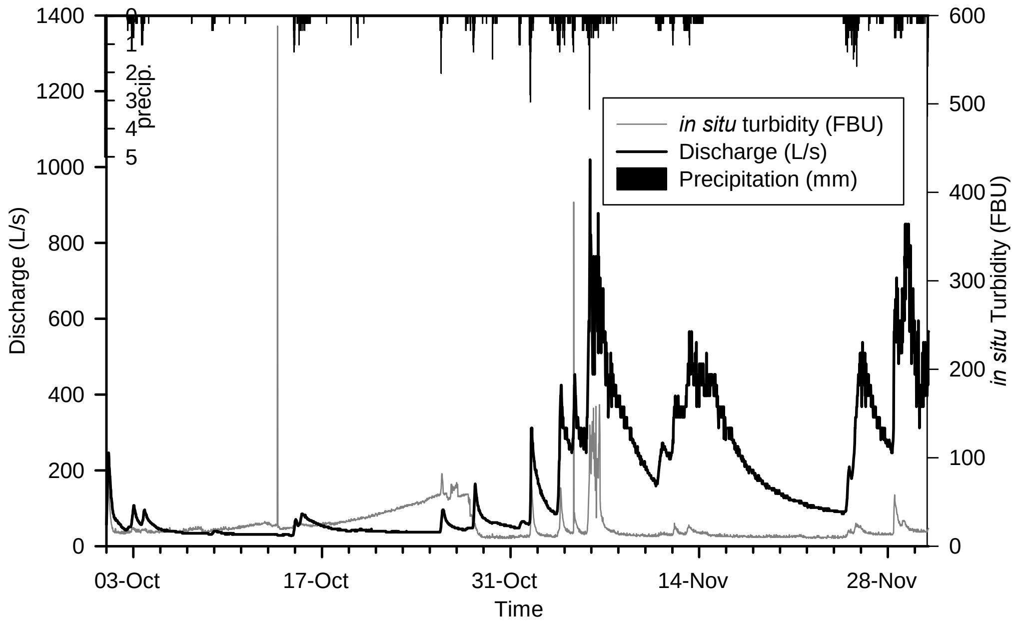


Figure 16. A graph of precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the Storm 1 time period: October 1-December 5 11:10, 2005.

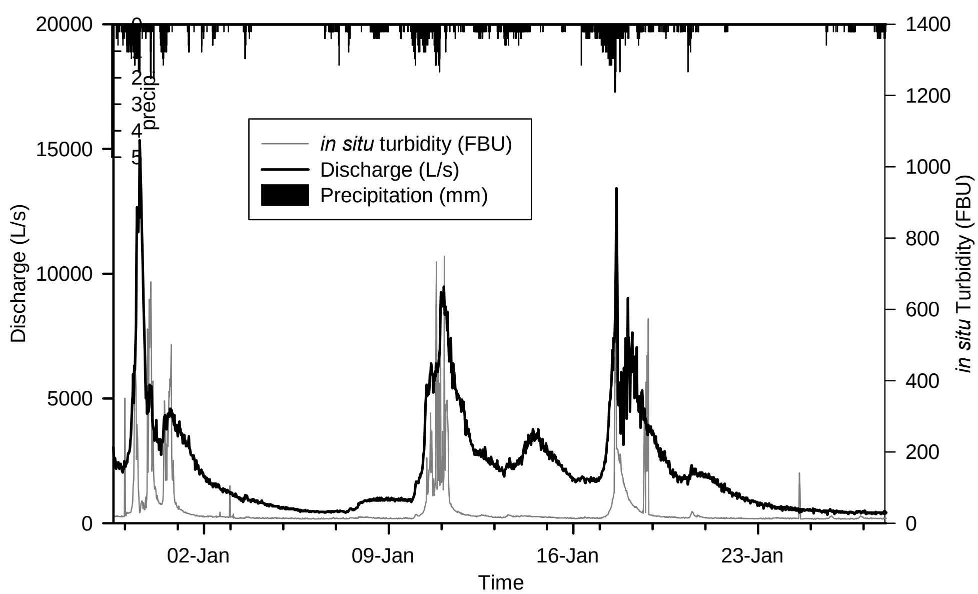


Figure 17. A graph of precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the Storm 4 time period: December 29 13:30, 2005-January 27 20:30, 2006.

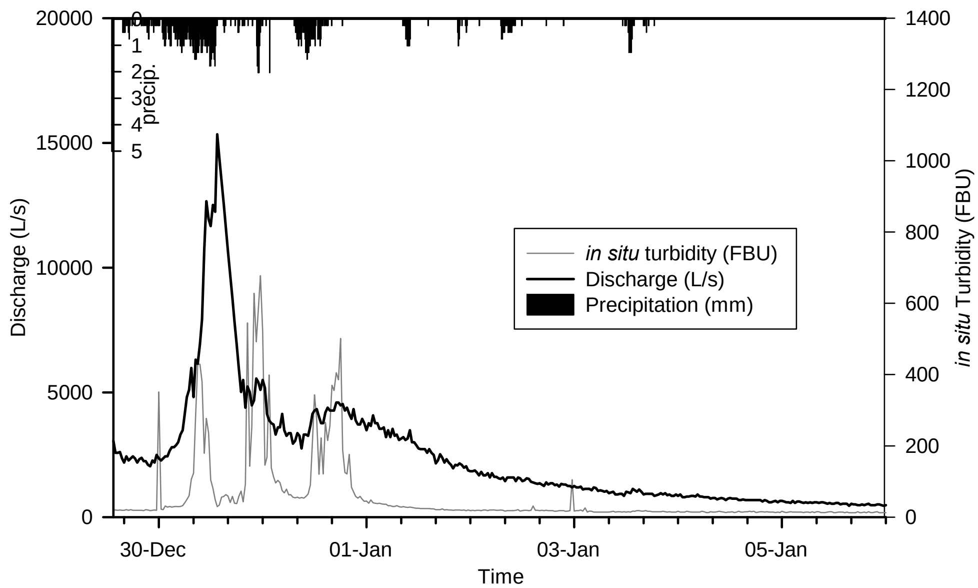


Figure 18. A graph of precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the maximum annual peak flow: December 29 13:30, 2005-January 6, 2006.

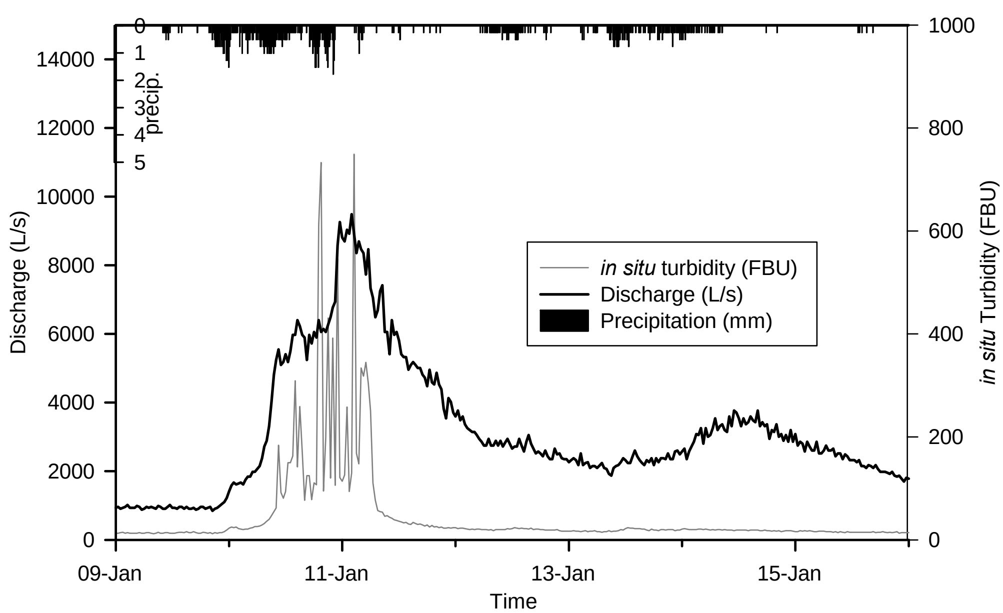


Figure 19. A graph of precipitation, discharge, and *in situ* turbidity for South Fork Hinkle Creek during the Storm 4 time period showing erratic *in situ* turbidity: January 9-January 16, 2006.

4.2.3 TURBIDITY AND SSC

During the 2006 water year, 162 water samples were taken at South Fork Hinkle Creek and analyzed for SSC and turbidity in a laboratory. The distribution of how these samples were collected in time is shown in Figure 20. All of the water samples were taken between November 3, 2005 and March 16, 2006. Suspended sediment concentration of the water samples ranged from 3.7 to 2,533 mg/L. Approximately 23 percent of the water samples contained noticeable amounts of sand, pebbles, or rocks. Of the 162 water samples collected, 115 water samples were taken during the large winter storms that occurred between December 20, 2005 and February 20, 2006. The water samples that were collected during this winter storm time period occurred at discharges between 453 and 11,668 L/s. The *in situ* turbidity value of the stream water at the time these samples were taken ranged between 14 and 516 FBU. The range of laboratory turbidity values during the winter storm time period was between 7 and 335 NTU. The SSC of water samples collected during the winter storm period had values between 6 and 2,533 mg/L. After the winter storm time period, 27 water samples were collected. Each water sample can be paired with two values of turbidity: the *in situ* turbidity value that corresponds to the time when the water sample was taken and the laboratory turbidity value of the water sample.

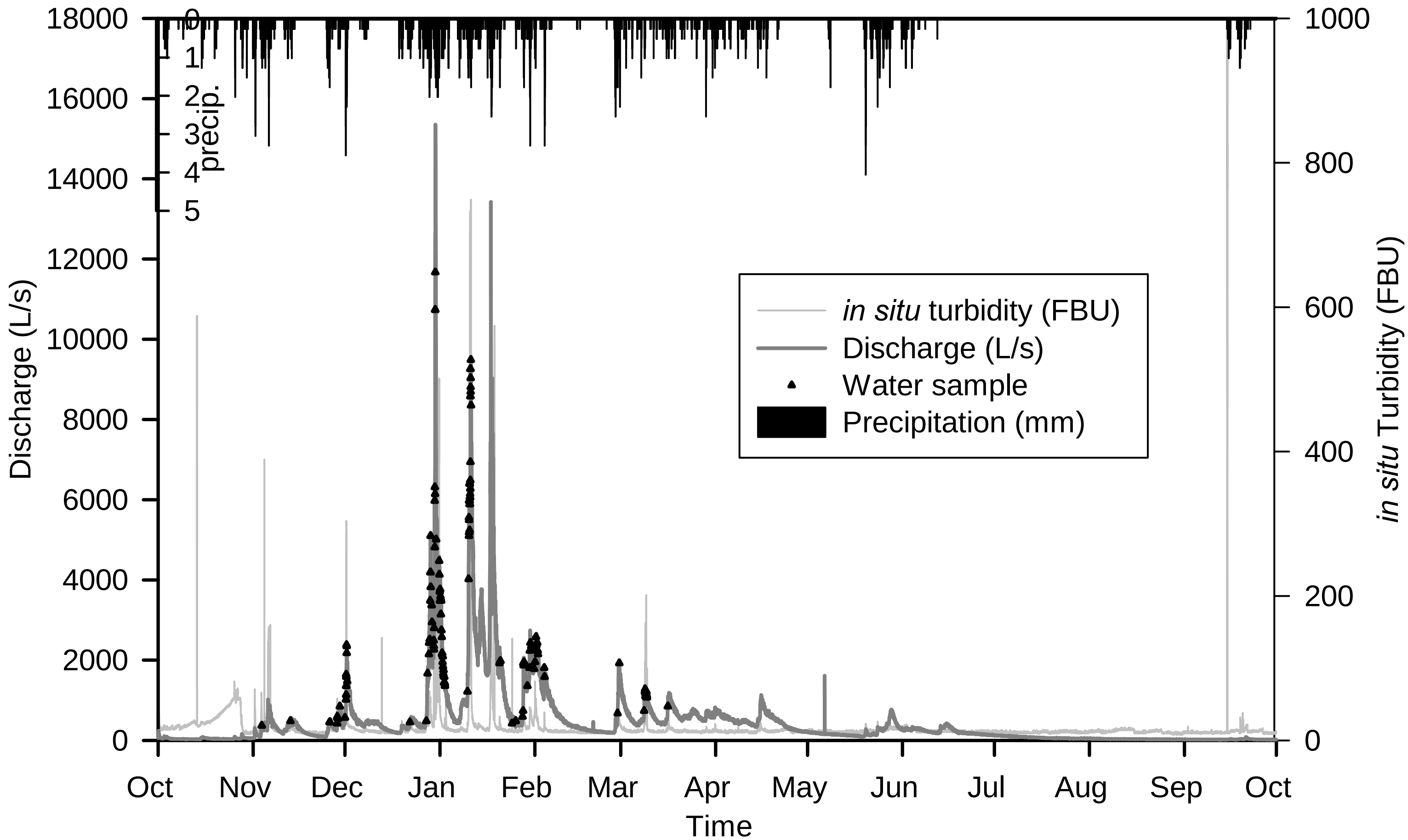


Figure 20. A graph of precipitation, discharge, *in situ* turbidity, and water samples at South Fork Hinkle Creek during water year 2006. Water samples are shown relative to time and discharge during sampling.

4.3 ESTIMATION OF TOTAL SEDIMENT LOAD

The estimation of total sediment load is accomplished, either for a year or for a specific storm, by integrating under the sediment discharge curve. The sediment discharge curve is derived by multiplying the *in situ* turbidity values by an appropriate SSC value that corresponds with the turbidity value. The SSC value is then multiplied by the discharge leaving a curve with units of mg of sediment per second. Then the curve is integrated over time, the result is a mass of sediment for a given length of time.

There are two key steps in the process that affect the accuracy and precision of the estimate of sediment load. The first step is to determine the appropriate value of SSC to assign to each value of *in situ* turbidity in calculating the sediment discharge curve. In general, linear relationships are established between the SSC in the water samples and the *in situ* turbidity measured in the stream at the time the water sample was collected. *In situ* versus SSC relationships can be presented in several ways. These relationships can be developed on an annual basis, on a storm by storm basis, or even for rising or falling limbs of a hydrograph for a single-storm.

The second step of the process to estimate total sediment loads is to correct the *in situ* turbidity values to remove values that are obviously inappropriate. There are several ways to carry out this task. One way is a top-down approach in which high values of *in situ* turbidity are adjusted individually to a more appropriate value. A second way is a bottom-up approach in which the *in situ* turbidity values are adjusted using an automated program that identifies high values of *in situ* turbidity by comparing each value in the turbidity record with the value that directly precedes it.

Total sediment loads were calculated for Oak Creek and South Fork Hinkle Creek using a combination of these two techniques.

4.3.1 IN SITU TURBIDITY AND SSC RELATIONSHIPS

The first step to estimate total sediment loads is to develop the relationships between *in situ* turbidity and SSC concentration for the water samples that were collected. To do this, the value of *in situ* turbidity was determined for the time when the water was collected. Once this was determined, a scatter-plot was made of *in situ* turbidity versus SSC values for the 2006 water year for Oak Creek and South Fork Hinkle Creek (Figures 21 and 22, respectively).

Figure 21 shows the relationship between the SSC of water samples and the *in situ* turbidity of the stream at the time the water samples were collected for water year 2006 at Oak Creek. Out of the 305 samples collected, 276 samples had SSC less than 500 mg/L and only two samples had SSC greater than 1,500 mg/L. There are two distinct sets of data in the scatter-plot. One set of data shows that *in situ* turbidity increases linearly with increases in SSC. In the second set of data, *in situ* turbidity values range from 400 to 1,500 FBU while the corresponding SSC values are less than 100 mg/L.

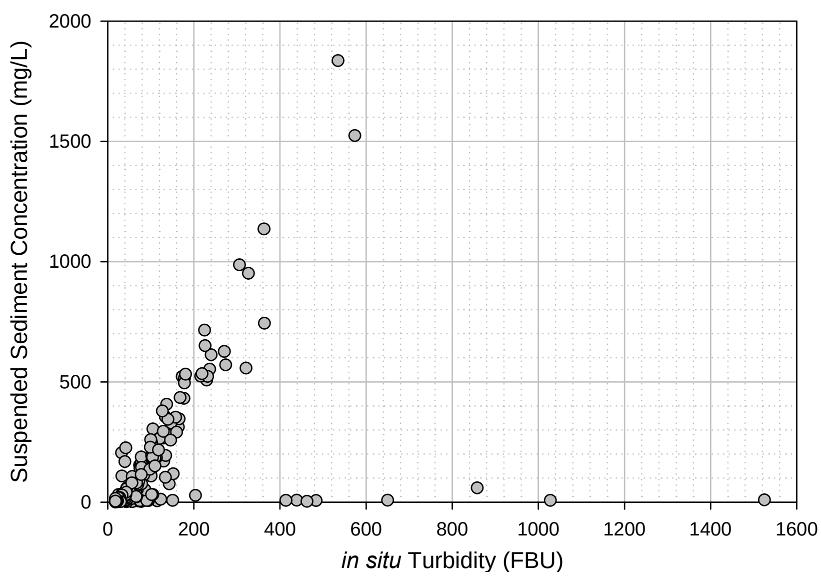


Figure 21. A scatter plot that shows the relationship between SSC of the water samples and *in situ* turbidity of the stream water at the time the water samples were taken for Oak Creek during water year 2006.

Figure 22 shows the relationship between the SSC of water samples and *in situ* turbidity of the stream water at the time the water samples were collected for water year 2006 at South Fork Hinkle Creek. There is no distinct relationship between *in situ* turbidity and the SSC of water samples. *In situ* turbidity ranged from 14 to 516 FBU and the SSC of the water samples ranged from 3.7 to 2,533 mg/L. Out of the 162 samples collected, 136 samples had SSC less than 400 mg/L and *in situ* turbidity less than 200 FBU. Only two samples had *in situ* turbidity values over 500 FBU. When a natural log transformation of *in situ* turbidity and SSC is plotted, the data has a positive trend (Figure 23). The variance in the log-transformed data is high but is uniform throughout the range of data.

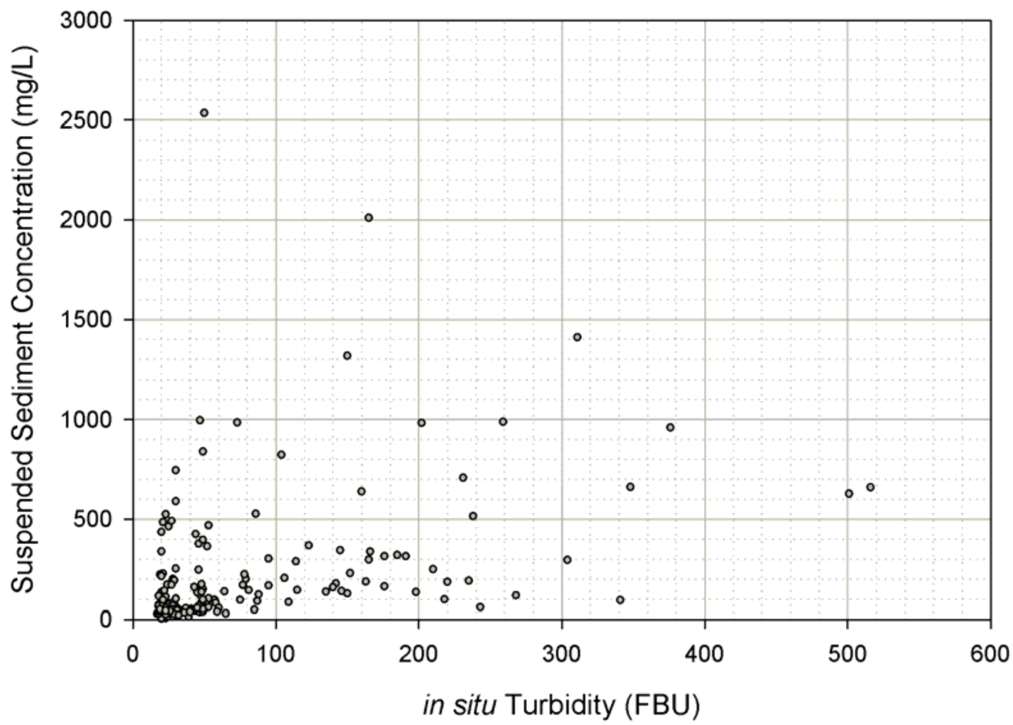


Figure 22. A scatter plot that shows the relationship between SSC of the water samples and *in situ* turbidity of the stream water at the time the water samples were taken for South Fork Hinkle Creek during water year 2006.

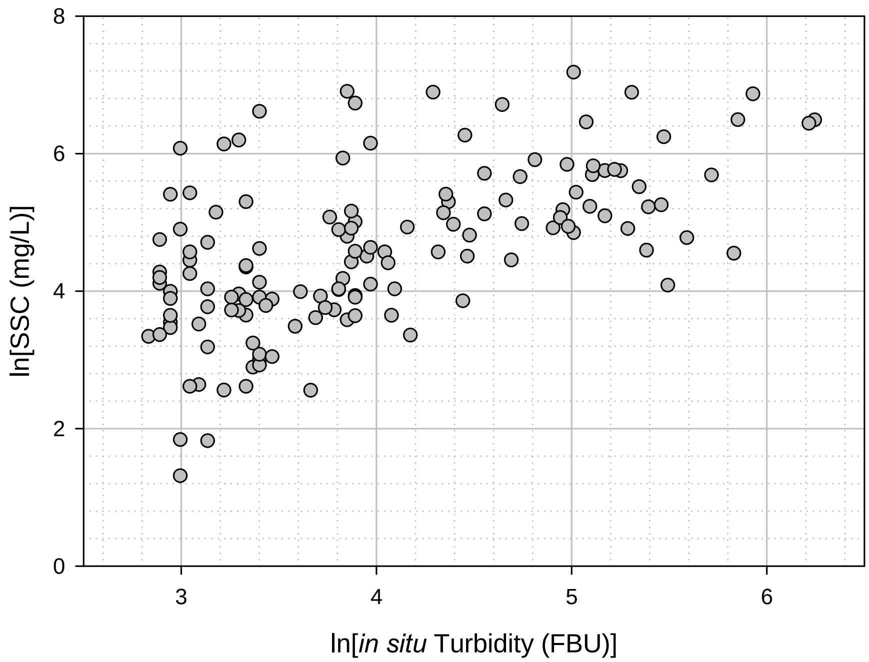


Figure 23. A scatter plot that shows the relationship between ln(SSC) of the water samples and ln(*in situ* turbidity) of the stream water at the time the water samples were taken for South Fork Hinkle Creek during water year 2006.

4.3.2 IDENTIFYING ERRONEOUS TURBIDITY OBSERVATIONS

In the relationship between SSC and *in situ* turbidity, especially in the scatter plot for the Oak Creek data, there are counterintuitive values. Before formal statistical relationships between SSC and *in situ* turbidity are developed, it is necessary to vet these counterintuitive and possibly erroneous values.

For the Oak Creek data during water year 2006 there are two distinct relationships between SSC and *in situ* turbidity (Figure 21). One of these relationships is counterintuitive. This is the relationship where *in situ* turbidity values are highly variable and the SSC values are low and constant. Although turbidity increases with increases in SSC, turbidity also increases with organic matter content, stray light, bubbles, contamination, and interference (Sadar, 2004). Gippel (1995) found that particles composed of organic material could produce turbidity values two to three times greater than turbidity values associated with similar sized mineral particles.

To determine what is going on with these data, SSC values from the water samples were graphed in a scatter plot against the turbidity values for the water samples determined in the laboratory (Figure 24). The variability that is evident in the relationship between the SSC of water samples and the *in situ* turbidity in the stream water is not evident in the relationship between SSC and laboratory turbidity. This appears to eliminate concern regarding high turbidity values caused by organic matter in the stream water. Contamination of water samples also appears unlikely because the laboratory turbidity values appear to be unaffected. Turbidity values that are erroneous and obvious can also occur when field work is carried out in the stream at a time when turbidity is being determined. However, the observations of counterintuitive and possibly erroneous values of *in situ* turbidity at Oak Creek did not occur at times when field work was being carried out at the gauging station.

In order to further understand the nature of the counterintuitive and possibly erroneous values of *in situ* turbidity for Oak Creek data, the date and time that the water samples were collected were plotted on a hydrograph with the trace of *in situ* turbidity for the time that they occurred (Figure 25). It appears that the counterintuitive data points are located on the rising limbs of three hydrographs that occur between October 23 and December 7, 2005. These data points are accompanied by spikes or drastic increases of *in situ* turbidity. These short-term increases of *in situ* turbidity are very rapid spike in turbidity, which means that they are high values of turbidity that do not persist for a very long time. Sometimes they may persist for 1-2 observations or they may persist for longer periods of time. A possible explanation for these observations is debris fouling or interference with the turbidity sensor, which have been seen in other studies (Anonymous, 2006).

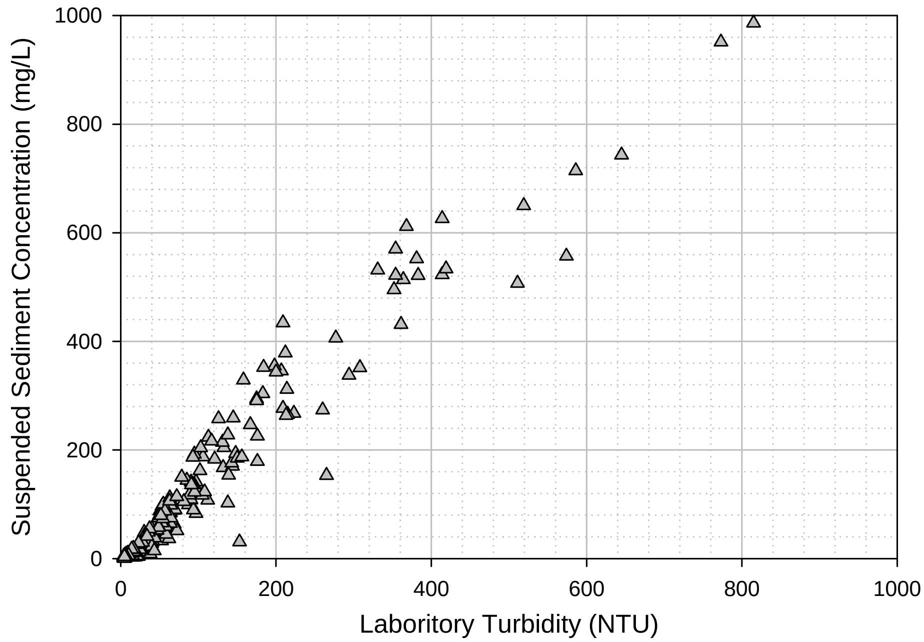


Figure 24. A scatter plot that shows the relationship between SSC of the water samples and the turbidity of the water samples determined in the laboratory for Oak Creek during water year 2006.

Hysteresis loops between discharge and SSC for the three storms that contain the counterintuitive *in situ* turbidity values are shown in Figure 26. The SSC of the water samples collected at the time of the counterintuitive, i.e. high turbidity/low SSC, *in situ* turbidity values are consistent with the hysteretic pattern of discharge and SSC from water samples collected during the storms. This indicates that the counterintuitive values of *in situ* turbidity are the result of errors in the *in situ* turbidity value and not the determination of SSC. These values result from either an error with the *in situ* turbidity sensor or the *in situ* turbidity values are real but simply do not correlate with the SSC of the water (i.e. bubbles in the water, stray light, obstruction, interference, etc.). When these counterintuitive values of *in situ* turbidity were encountered and collateral data did not support their value, they were removed from the data set.

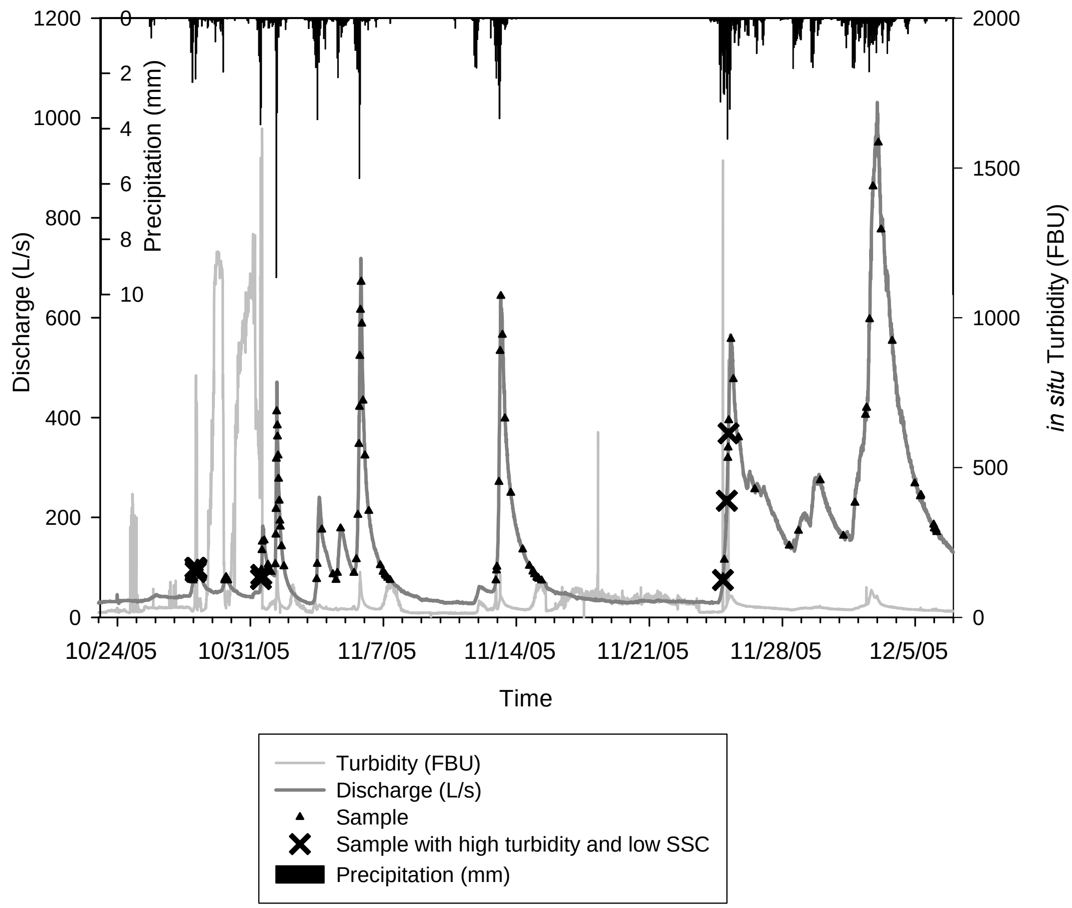
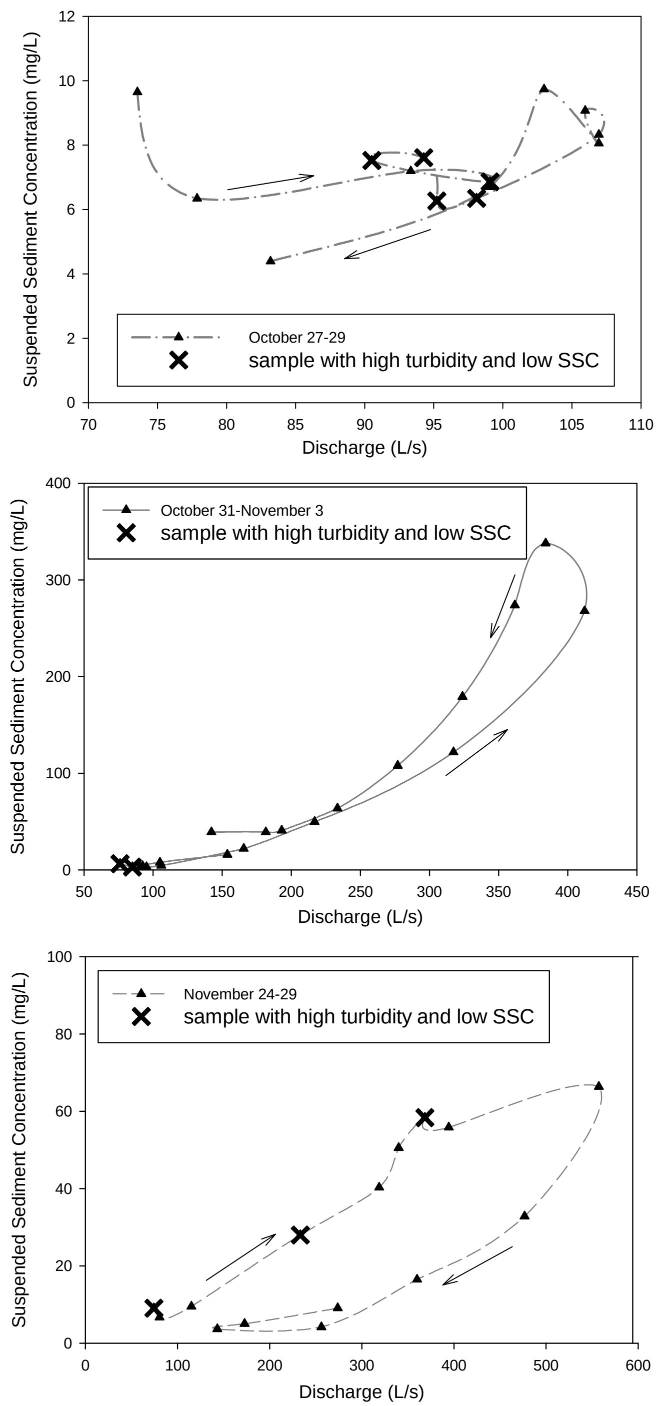


Figure 25. A graph of discharge, precipitation, *in situ* turbidity at Oak Creek for the time period that includes Storm 1, October 23-December 7, 2005. The solid triangles mark when the water samples were taken and the X's mark when water samples were collected in conjunction with counterintuitive *in situ* turbidity values.



Figures 26. Hysteresis loops showing sequential observations of discharge and SSC from water samples collected during three storms in water year 2006 at Oak Creek . Counterintuitive (or erroneous) data points with high *in situ* turbidity and low SSC are delineated by X's.

The relationship between *in situ* turbidity and SSC for discrete water samples collected at South Fork Hinkle Creek during water year 2006 does not have obvious counterintuitive data points (Figures 22 and 23). However, the SSC and *in situ* turbidity data contains a lot of variability for both *in situ* turbidity and SSC. The relationship between SSC and laboratory turbidity of the water samples also has a lot of variability (Figure 27). Approximately 23 percent of the water samples from the South Fork Hinkle Creek contained noticeable amounts of sand, pebbles, or rocks. Materials of sand, pebble, and rock are most likely the cause of the high variability in the SSC and *in situ* turbidity relationship, because the SSC and laboratory turbidity relationships also exhibited the same high variability.

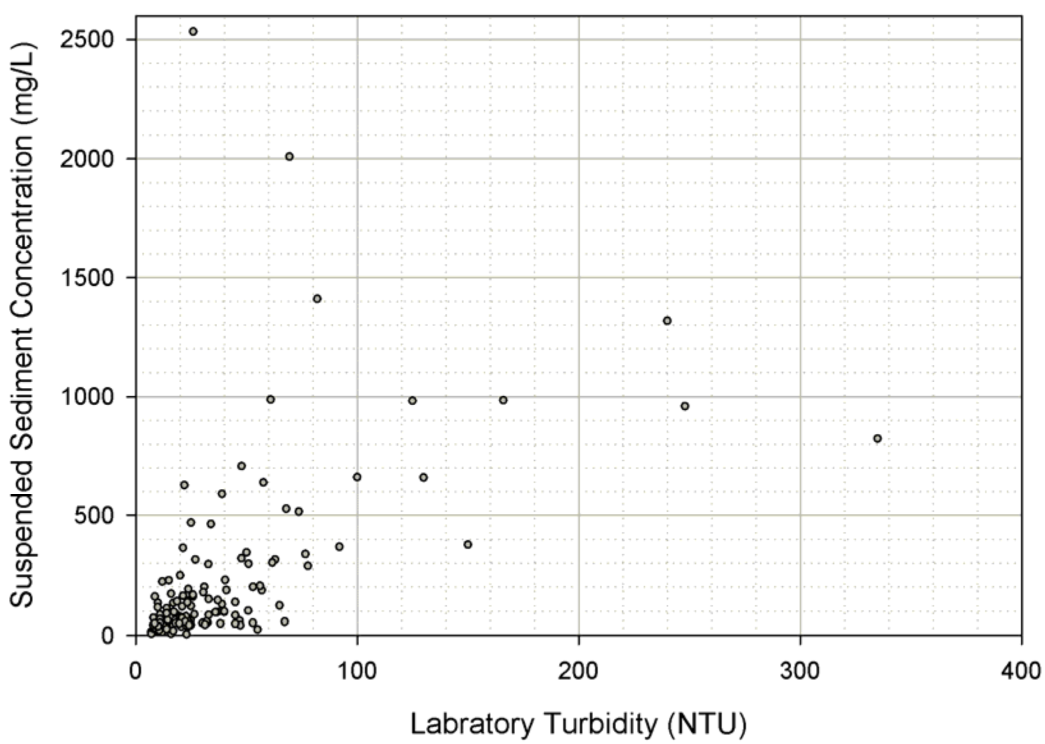


Figure 27. A scatter plot that shows the relationship between SSC of the water samples and the turbidity of the water samples determined in the laboratory for South Fork Hinkle Creek during water year 2006.

At Oak Creek the counterintuitive *in situ* turbidity and SSC data did not occur during the large winter storms. At South Fork Hinkle Creek, values of *in situ* turbidity are erratic during several winter storms (Figure 27). One such event occurred January 10-12, 2006 (Figure 28-A). *In situ* turbidity is erratic during this storm. Observed turbidity during this hydrograph ranges from 20 FBU during base flow conditions and spiking over 700 FBU during the storm. Figure 28 shows the *in situ* turbidity observations that are associated with the SSC of discrete water samples taken during this storm. Samples were only taken on the rising limb of this hydrograph. The SSC of water samples ranges from 90 mg/L at the initial rise of the hydrograph reaching a maximum greater than 2,000 mg/L preceding the peak discharge. Corresponding *in situ* turbidity observations are between 77 and 341 FBU.

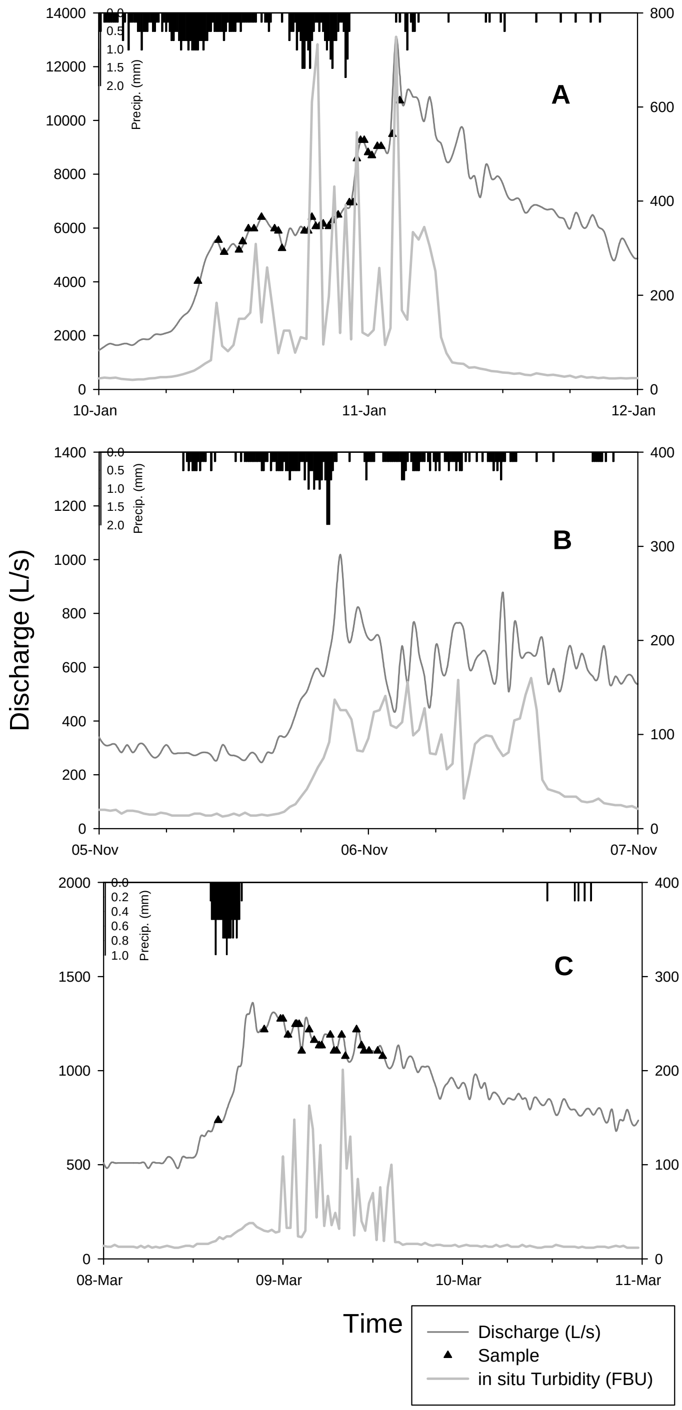


Figure 27. Graphs of discharge, unadjusted *in situ* turbidity, precipitation, and water samples at South Fork Hinkle Creek. A) January 10-12, 2006; B) November 5-11, 2005; C) March 8-10, 2006.

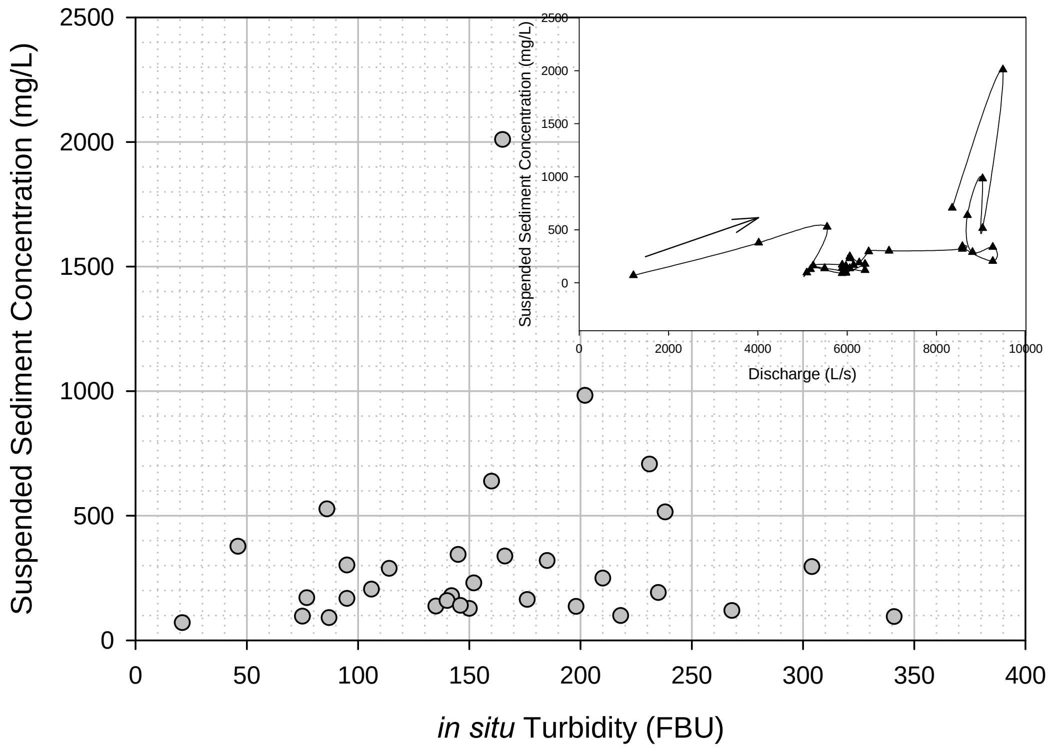


Figure 28. A graph of *in situ* turbidity and SSC at South Fork Hinkle Creek during Storm 4: January 10-12, 2006. Inset: a hysteresis loop of discharge and SSC corresponding to each sequential water sample.

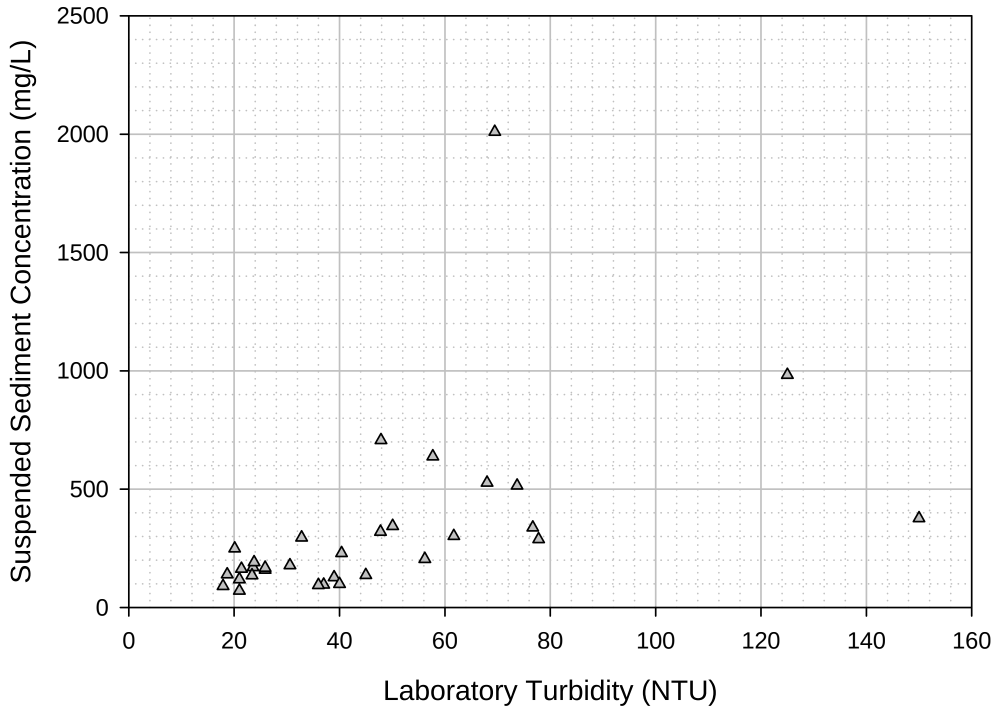


Figure 29. A graph of lab turbidity and SSC at South Fork Hinkle Creek during Storm 4: January 10-12.

Comparing relationships of discharge and laboratory turbidity to the SSC of water samples provides insight to the source of the poor relationship between *in situ* turbidity and SSC for this hydrograph. Inset on Figure 28 is the discharge and SSC corresponding to each water sample, in a time sequential loop. Aside from observation 30 (SSC=2,009 mg/L) which occurred prior to the peak in discharge, the relationship between discharge and SSC is positive and linear. Similarly the relationship between laboratory turbidity and SSC is positive and linear (Figure 29). Observation 30 was also reported to contain pebbles during SSC processing, but the quantity of pebbles is unknown. According to laboratory observation, 36 percent of the water samples that were taken from January 10-12 contained sand, pebbles, or both sand and pebbles. The large proportion of samples that contain non-suspended load is evidence that the intake for the automated sampler is within the saltation zone. However, this does not explain the erratic behavior of the observed *in situ* turbidity. This behavior is most likely a result of some disturbance or interference (Anonymous, 2006). To reduce the variability associated with the *in situ* turbidity observations during this time period, adjustments were made to *in situ* turbidity values corresponding to individual water samples. Adjustments to the *in situ* turbidity values were made by interpolation between surrounding *in situ* turbidity values using the 10-minute record of *in situ* turbidity from the South Fork Hinkle TTS station. Decisions were made based on the relationship between *in situ* turbidity and discharge from adjacent storms, and laboratory turbidity values. This adjustment allowed for the use of these observations in the annual relationship between *in situ* turbidity and SSC, but was not sufficiently to be included in the storm-specific relationship.

Figure 27 shows several storms where turbidity appears to be influenced by streambed interference, air bubbles, or non-submergence (Anonymous, 2006). *In situ* turbidity observations and the SSC of discrete water samples at these times may not be representative of actual sediment transport processes. Laboratory turbidity values and other auxiliary data were used to make adjustments to the turbidity record at times when errors were present in the *in situ* turbidity record. There is a linear relationship between *in situ* turbidity and SSC during Storm 8 that contains an outlier that occurred with the first water sample of the storm (Figure 30). Laboratory turbidity observation of turbidity during Storm 8 are low (<35 NTU) and the first sample of the storm fits the linear pattern between laboratory turbidity and SSC (Figure 31). The hysteresis pattern during Storm 8 is erratic (inset: Figure 30).

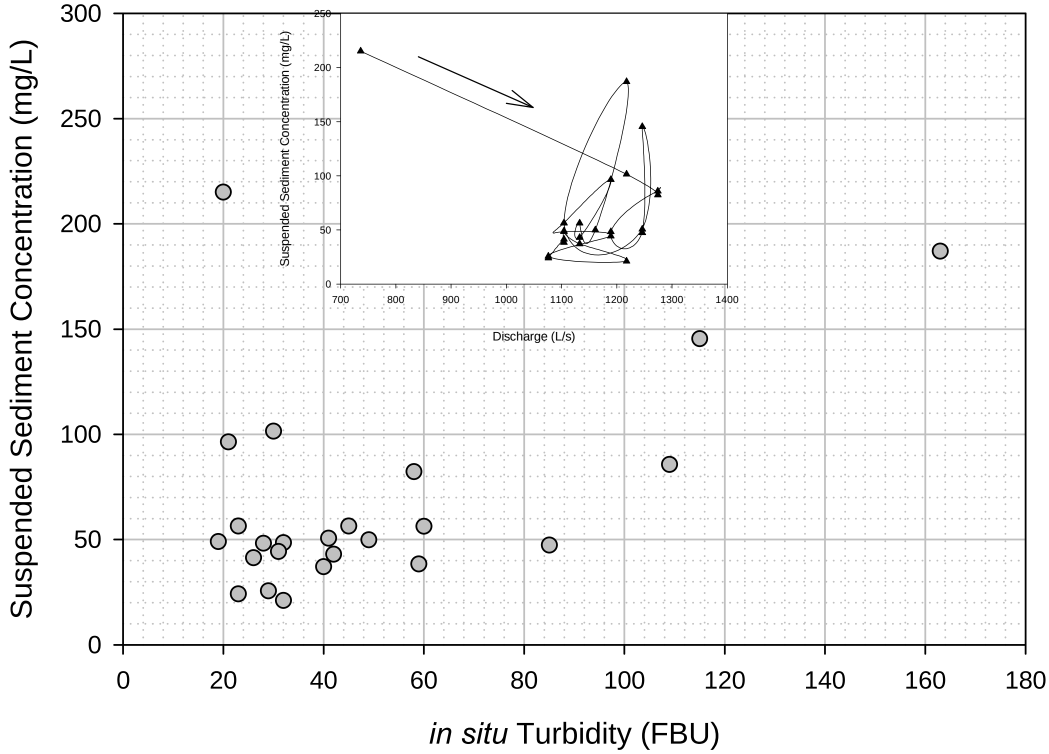


Figure 30. A graph of *in situ* turbidity and SSC at South Fork Hinkle Creek for Storm 8: March 8-10, 2006. Inset: a graph hysteresis loop of discharge and SSC corresponding to each water sample, in a time sequence.

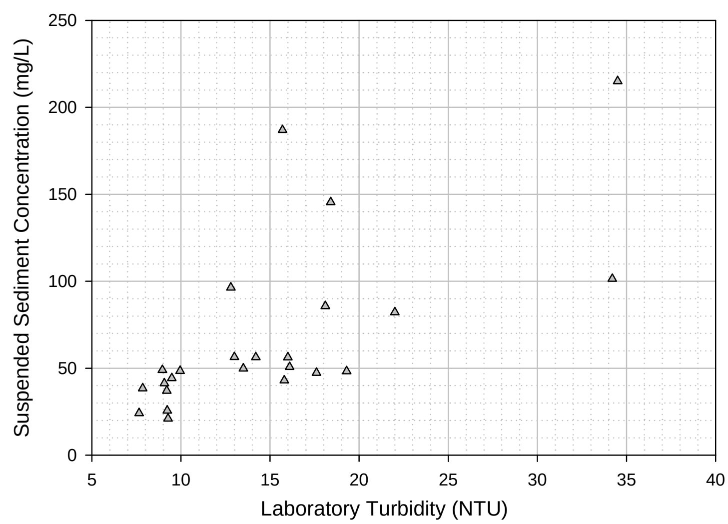


Figure 31. A graph of lab turbidity and SSC at South Fork Hinkle Creek during Storm 8: March 8-10, 2006.

4.3.3 DEVELOPING SSC VS IN SITU RELATIONSHIPS

To calculate the sediment load of a stream, the relationship between *in situ* turbidity and the SSC of water samples can be made for different time scales. In some cases the total annual sediment load is desired, while in other cases the total sediment load for individual storms is desired. Using the annual relationship between *in situ* turbidity and SSC integrates the calibration of the *in situ* turbidity sensor over the entire year. Over the entire year the composition of the suspended sediment that encounters the *in situ* turbidity probe can change and is dependent on the sediment source. Manka (2005) found that total annual sediment load estimates based on individual storm relationships have the potential to increase accuracy over estimates made using the annual relationship between SSC and *in situ* turbidity. Using individual storm relationships can capture the sediment composition variability that occurs during different parts of the year.

Relationships between SSC and *in situ* turbidity are needed to estimate total sediment load for a year or a storm at a gauging station. The relationship between SSC and *in situ* turbidity and SSC is linear and positive. Total sediment load is estimated using *in situ* turbidity by using the linear relationship between SSC and *in situ* turbidity. Linear regression was used to develop all of the SSC and *in situ* turbidity relationships and these regressions were developed with untransformed and transformed data. When necessary, natural-logarithm transformations of the data were made to meet the assumptions of normality and equal variance implicit with the regression models.

Total sediment loads are made by using estimated values of SSC. The estimated values of SSC are calculated using the SSC and *in situ* turbidity relationships. Total sediment load is calculated using the following equation:

$$L = \sum_i t q_i C_i \qquad \textbf{Equation 2}$$

where L is the total suspended sediment load, t is the time in seconds between measurements, q_i is the discharge (L/s) for the ith time period, and C_i is the estimated SSC (mg/L) for the ith time period. The variance of the estimated sediment load is the sum of the variances from each time step of the regression. The mean square error from the regression is used to estimate the variance.

The SSC of the stream for a given time interval (C_i) is calculated using the relationship between *in situ* turbidity and the SSC of the water samples:

$$C_i = \beta_0 + \beta_1 T_i \quad \textbf{Equation 3}$$

where β_o and β_1 are regression parameters and T_i is the *in situ* turbidity (FBU) for the ith time interval. Values of SSC (C_i) that were estimated to be negative were set to zero, because SSC cannot be negative and 0 NTU is equivalent to a SSC of 0 mg/L (Wass and Leeks, 1999). *In situ* turbidity and estimates of sediment discharge are serial correlated, where observations/estimates close in time are more likely to be similar than observations/estimates that are further apart. Discharge and turbidity are correlated at short time lags with strong positive correlations (Lewis, personal communication). Thus, the estimated variance from the regression (s^2), will likely underestimate the variance of sediment load.

When a transformation of SSC and *in situ* turbidity data was needed to fit the assumptions of the linear regression models, the natural-logarithm was used. Estimations made with the subsequent regression equations have to be transformed back into the original space, which introduces bias (Koch and Smillie, 1986). A quasi-maximum likelihood estimator (QMLE) was used to correct for the bias (Cohn *et al.*, 1989). The natural-logarithm of SSC for a given time interval ($C_{LN\text{-}i}$) can be calculated using the relationship between *in situ* turbidity and the SSC of water samples:

$$C_{LN_I} = \beta_0 + \beta_1 T_{LN_i} \quad \textbf{Equation 4}$$

where β_0 and β_1 are estimated regression parameters and $T_{LN\text{-}i}$ is the instantaneous *in situ* turbidity (*ln*[FBU]) for the ith time interval. A retransformation of C_{LNi} into SSC, using the QMLE bias correction factor is

$$C_{QMLE_i} = e^{0.5s^2 + C_{LN_i}}$$ **Equation 5**

where C_{QMLEi} is the bias corrected estimate of stream water SSC (mg/L) for the i^{th} time interval. The variance (V_{QMLE}) of the sediment load estimation is estimated from the mean square error of sums of the regression (s^2).

4.3.4 OAK CREEK ANNUAL RELATIONSHIP

The relationship between *in situ* turbidity and the SSC of the water samples for Oak Creek during water year 2006 is shown in Figure 32. The parameter values associated with the annual relationship between *in situ* turbidity and SSC are given in Table 3. Of the 305 water samples taken, 294 SSC values were used in the correlation of *in situ* turbidity and SSC for Oak Creek in water year 2006. The relationship was used to estimate SSC of the stream at ten-minute time steps using Equation 3. An *in situ* turbidity increase of 10 FBU results in a SSC increase of 27.4 mg/L (r^2=0.89, SE=4.25, n=294). The estimate of SSC in the stream was multiplied by the discharge for the corresponding time step. This product was multiplied by the length of the time interval, in seconds, and that product is summed over the year to estimate the sediment load for Oak Creek during water year 2006 (Equation 2).

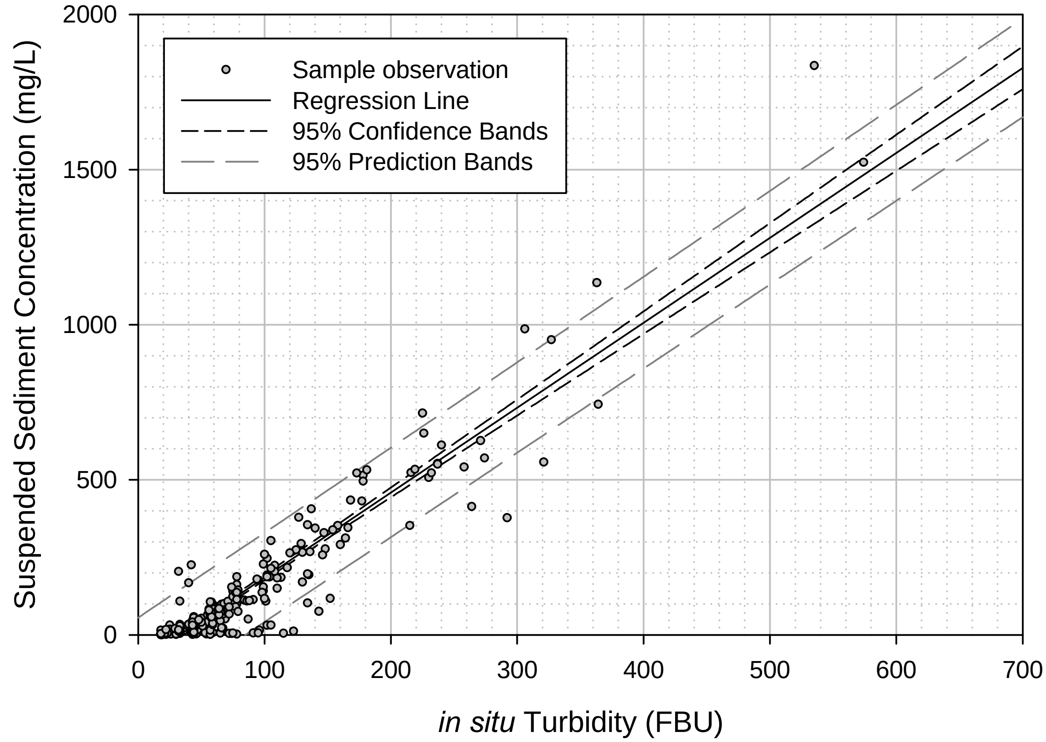


Figure 32. The relationship between *in situ* turbidity and SSC for the times when the water samples were collected in Oak Creek for water year 2006

Table 3. A table of annual and separate-storm turbidity-SSC relationships and regression parameter estimates for each storm period at Oak Creek during water year 2006.

Storm ID	Start Date	End Date	Peak Discharge (L/s)	β_1	β_0	SE	r^2	Transformation	n
Annual	10/1/2005 0:00	9/30/06 23:50	6,445	2.74	-88.60	4.25	0.89	-	294
1	10/1/05 0:00	11/5/05 11:00	471	2.54	-64.06	3.59	0.99	-	15
2	11/5/05 11:10	11/20/05 0:00	719	1.39	-2.56	0.29	0.40	log-log	11
3	11/20/05 0:10	12/1/05 8:10	566	2.16	-5.29	0.12	0.85	log-log	13
4	12/1/05 8:10	12/19/05 0:00	1,031	2.57	-6.81	0.12	0.83	log-log	16
5	12/19/05 0:10	12/21/05 3:10	883	3.30	-9.88	0.16	0.82	log-log	8
6	12/21/05 3:20	12/26/05 22:50	3,656	1.65	-2.80	0.06	0.89	log-log	38
7	12/26/05 23:00	12/29/05 16:10	7,561	1.72	-3.12	0.10	0.92	log-log	22
8	12/29/05 16:20	1/3/06 9:40	5,758	2.94	-74.04	8.51	0.97	-	22
9	1/3/06 9:50	1/6/06 5:00	1,128	1.41	-26.74	1.45	0.93	-	5
10	1/6/06 5:10	1/9/06 12:00	1,727	2.16	-46.92	2.70	0.93	-	9
11	1/9/06 12:10	1/10/06 14:10	3,476	3.08	-91.86	8.12	0.96	-	10
12	1/10/06 14:20	1/16/06 3:00	3,068	2.25	-42.49	4.33	0.94	-	7
13	1/16/06 3:10	1/20/06 4:00	5,055	2.26	-72.11	3.60	0.98	-	19
14	1/20/06 4:00	1/31/06 12:20	6,445	1.68	-2.89	0.06	0.93	log-log	35
15	1/31/06 12:20	9/30/06 23:50	2,321	1.77	-32.44	1.54	0.94	-	25

4.3.5 OAK CREEK STORM-SPECIFIC RELATIONSHIPS

Regressions of *in situ* turbidity and SSC for time periods that contained specific storms were also developed for Oak Creek during water year 2006. If there is sufficient data to develop storm-specific relationships, the resulting estimates of sediment load may be more accurate (Manka, 2005). A relationship between *in situ* turbidity and SSC of the water samples was developed for the water samples that were collected during a specific time period that contained a labeled storm. For the most part, the water samples were collected during the storm featured in that time period. Each time period-specific or storm-specific relationship was used to estimate SSC for each 10-mintue time interval (Equations 3 and 4). Storm-specific, *in situ* turbidity-SSC relationships are shown in Figure 33. Those relationships that required a natural-logarithm transformation to meet model assumptions are listed in Table 3, along with estimates of regression parameters, regression standard errors, r^2, and sample size.

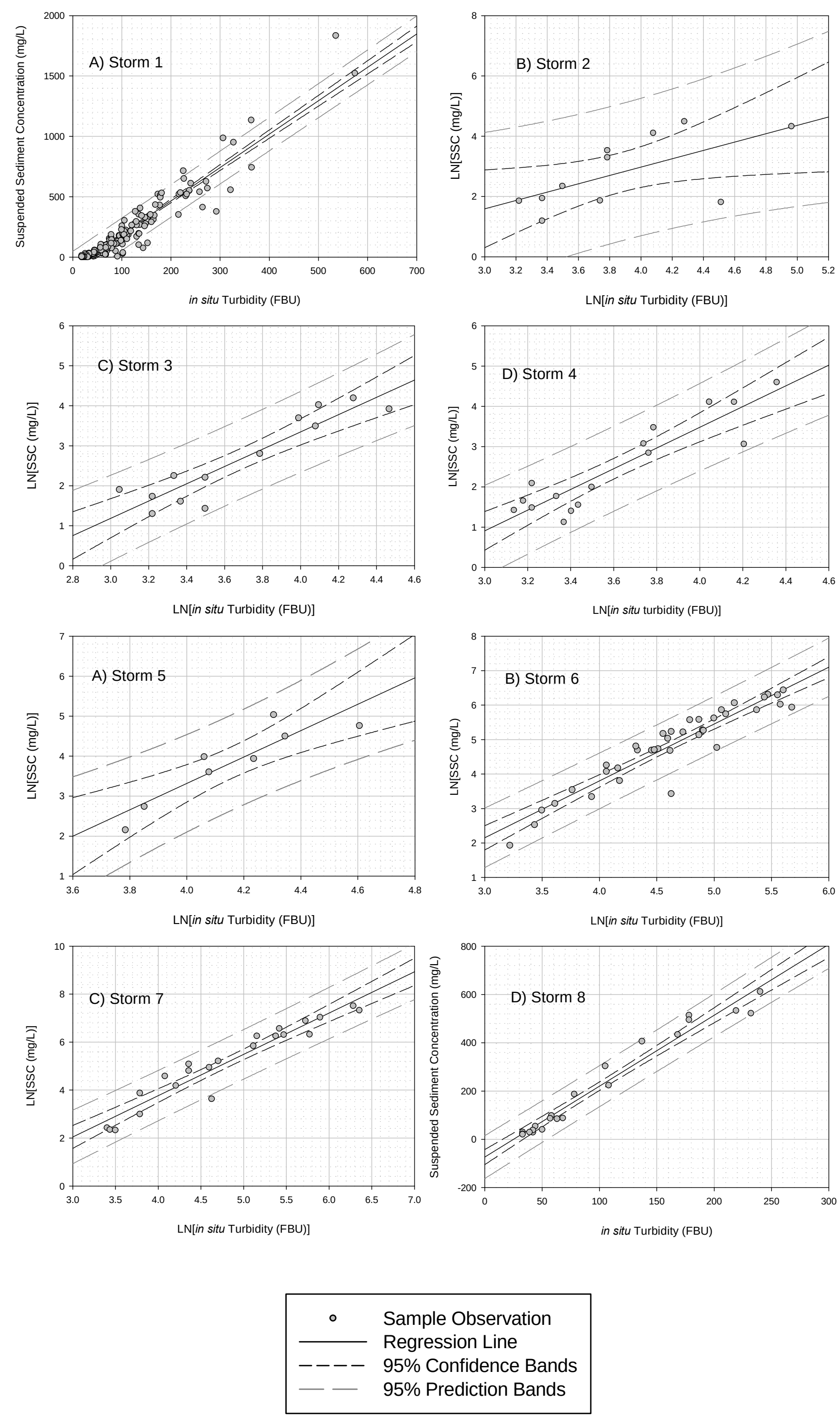


Figure 33. The relationship between the SSC of water samples and *in situ* turbidity at Oak Creek during water year 2006 for Storms 1-8. Regression parameters for each time period are shown in Table 3.

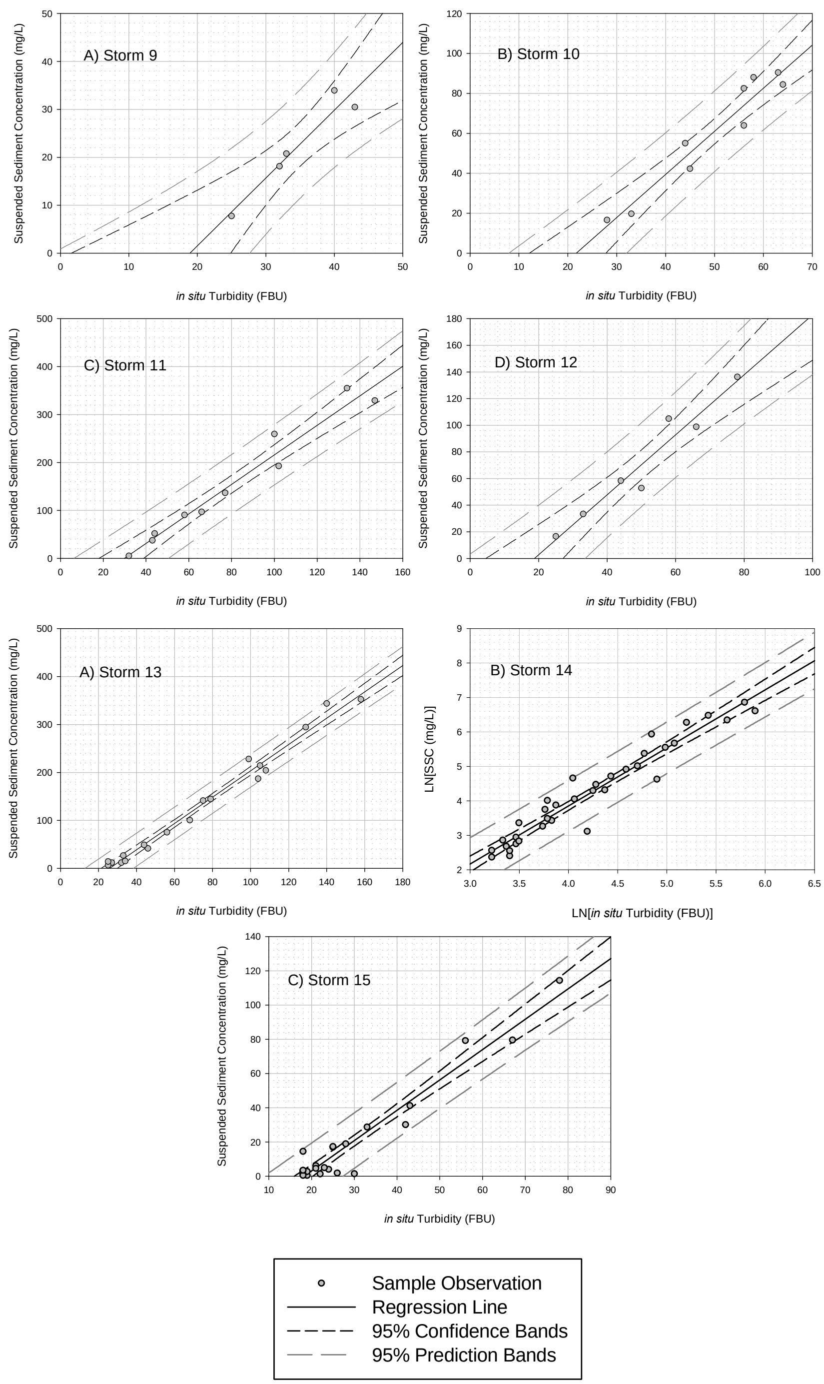


Figure 33 continued. The relationship between the SSC of water samples and *in situ* turbidity at Oak Creek during water year 2006 for Storms 9-15. Regression parameters for each time period are shown in Table 3.

4.3.6 SOUTH FORK HINKLE CREEK ANNUAL RELATIONSHIP

The linear relationship between *in situ* turbidity and SSC of the water samples for South Fork Hinkle Creek during water year 2006 is shown in Figure 34. Given the high variability in the data, a natural-logarithm transformation was carried out before the linear regression was developed. The parameter values associated with the annual relationship between *in situ* turbidity and SSC are given in Table 4. Of the 162 water samples taken, 138 SSC values were used in the correlation of *in situ* turbidity and SSC for South Fork Hinkle Creek in water year 2006. The relationship between *in situ* turbidity and the SSC of water samples for the whole year was used to estimate the sediment load of South Fork Hinkle Creek at 30-minute intervals (Equations 3 and 4). An *in situ* turbidity increase of 10 FBU results in a SSC increase of 26.4 mg/L (r^2=0.34, SE=0.08, n=138). The estimated value of SSC was multiplied by the discharge of the time interval and the length of the time interval to get an estimate of the sediment load for that time interval. These values were summed to get an estimate of the annual sediment load for South Fork Hinkle Creek (Equation 2).

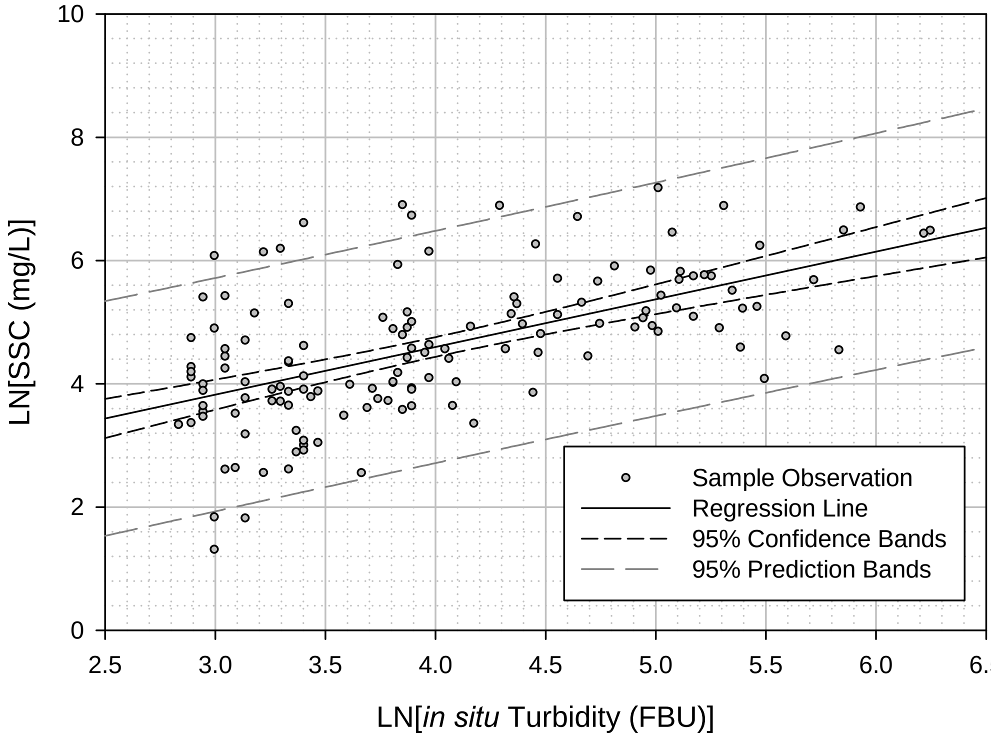


Figure 34. The annual relationship between the natural-logarithm of *in situ* turbidity and the natural-logarithm of SSC for South Fork Hinkle water year 2006.

Table 4. Annual and separate-storm turbidity-SSC relationships for each storm period and regression parameter estimates for South Fork Hinkle Creek during water year 2006.

Storm ID	Start Date	End Date	Peak Discharge (L/s)	β_1	β_0	SE	r^2	Transformation	n
Annual	10/1/05 0:00	9/30/06 23:30	15,349	0.77	1.50	0.08	0.34	log-log	138
1	10/1/05 0:00	12/1/05 0:00	1,020	2.67	-6.17	0.15	0.83	log-log	8
2	12/1/05 0:30	12/27/05 0:00	2,379	0.84	94.43	27.00	0.42	-	9
3	12/27/05 0:30	12/29/05 13:00	5,098	1.56	-1.76	0.15	0.35	log-log	10
4*	12/29/05 13:30	1/27/06 20:00	15,349	0.89	1.29	0.16	0.46	log-log	38
5	1/27/06 20:30	1/31/06 12:30	2,747	0.85	3.53	0.07	0.85	log-log	5
6	1/31/06 13:00	3/8/06 1:00	2,662	2.40	0.55	10.51	0.63	-	12
7	3/8/06 1:30	9/30/06 23:30	1,614	0.51	2.09	0.09	0.32	log-log	24

*Two *in situ* turbidity-SSC relationships were used during the Storm 4 time period. The Annual relationship was used between January 9-13 and the Storm 4 relationship was used for the remainder of the time.

4.3.7 SOUTH FORK HINKLE CREEK STORM-SPECIFIC RELATIONSHIPS

The regressions for the relationships between *in situ* turbidity and the SSC of water samples were made for seven delineated periods of time that combined specific and labeled storms (Figure 35). These relationships were used to make estimates of SSC for 30-mintue time intervals. Seven periods of time had storms that contained a sufficient number of water samples that they produced decent relationships between *in situ* turbidity and SSC for the 2006 water year data. The storms that occurred during the delineated time periods varied in magnitude and duration (Table 4). The storm-specific, relationships between *in situ* turbidity and SSC were linear or exponential. When the data from individual storms did not meet the necessary assumptions, natural-logarithm transformations of the data were used. Estimates of SSC for time periods when a storm-specific relationship was not available were made with *in situ* turbidity-SSC relationships from adjacent time periods (Table 4). At South Fork Hinkle Creek, the relationship between *in situ* turbidity and SCC is better for individual storms compared with the annual relationship.

Only three properly labeled water samples were taken during the second largest storm of the year, which occurred January 16th to 27th and had a peak discharge of 13,424 L/s. This small number of samples was not sufficient to produce a relationship between *in situ* turbidity and SSC. A relationship between *in situ* turbidity and the SSC could not be made for the third largest event of the year, which occurred January 9th to13th and had a peak discharge of 9,487 L/s. During the January 9th storm, 32 water samples were collected. The relationship between *in situ* turbidity and SSC for the January 9th to 13th storm is shown in Figure 36, with the linear regression and confidence bands. Using the January 9th relationship, an *in situ* turbidity increase of 10 FBU would result in an SSC increase of 2 mg/L, this increase is not significantly different than no increase ($p=0.70$, $df=28$). Because the January 9th relationship between *in situ* turbidity and SSC is not adequate the annual *in situ* turbidity-SSC relationship was used to make the sediment load estimate. The sediment load estimates for the January 16th portion of the time period that includes Storm 4 was made using the relationship between *in situ* turbidity and the SSC of water samples from the annual peak hydrograph, which occurred from December 29-January 6 and had a peak discharge of 15,349 L/s. Although samples from the January 9th and 16th storms were not used to make individual regression relationships between *in situ* turbidity and SSC, they were used in the annual relationship between *in situ* turbidity and SSC.

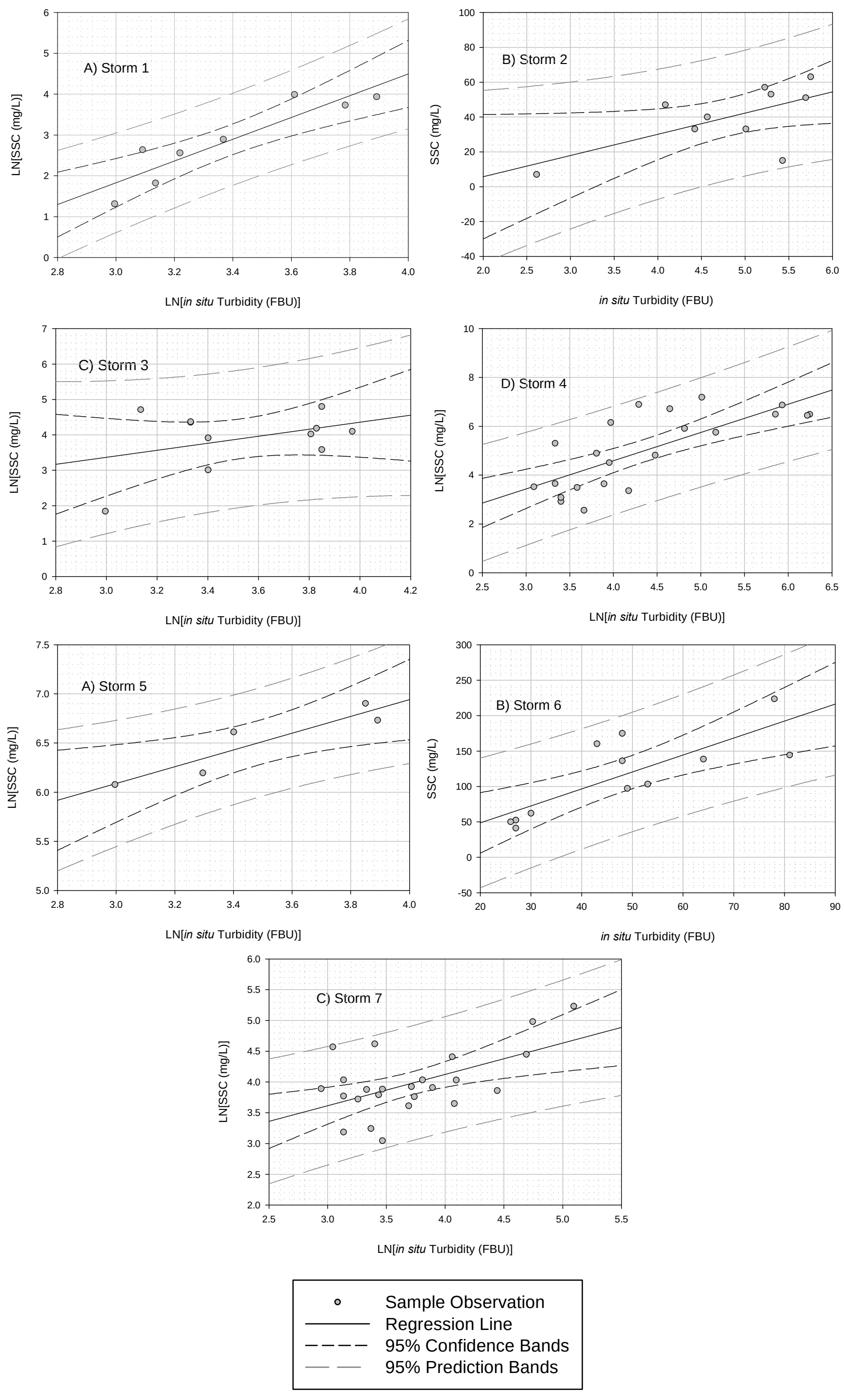


Figure 35. The relationships between the SSC of water samples and *in situ* turbidity at South Fork Hinkle Creek for separate storms during water year 2006. Regression parameters for each time period are shown in Table 4.

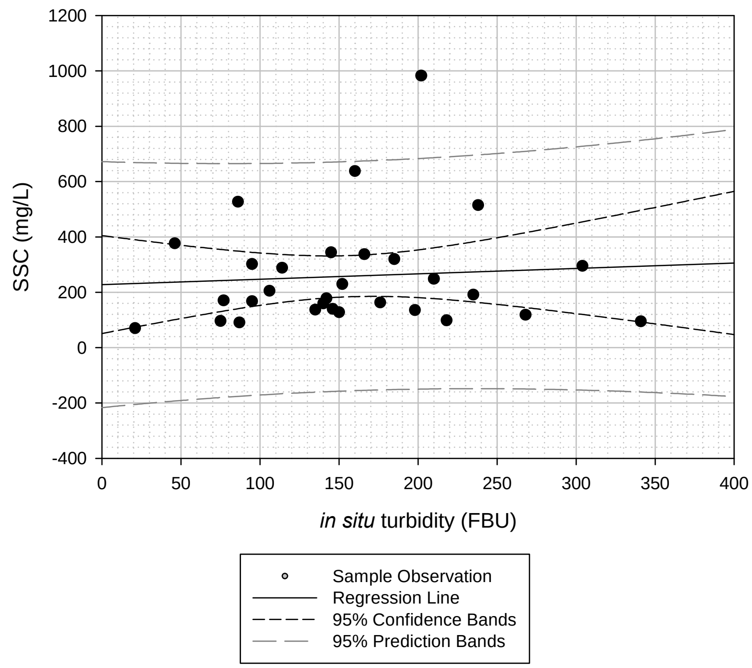


Figure 36. The relationship between the SSC of water samples and *in situ* turbidity at South Fork Hinkle Creek for the January 9th to 13th, 2006 storm.

4.3.8 IN SITU TURBIDITY ADJUSTMENT

The second step in the process to estimate sediment loads is to convert the real-time *in situ* turbidity time series data to real-time estimates of *in situ* SSC using the relationships between *in situ* turbidity and SSC. As discussed in Section 4.3.2, counterintuitive values of *in situ* turbidity were observed and they were determined to be truly in error. Thus, it is not appropriate to make estimates of sediment load without correcting the erroneous *in situ* turbidity in the real-time turbidity record.

Two approaches were taken to correct the erroneous values of *in situ* turbidity in the real-time record: a top-down approach and a bottom-up approach. These approaches are techniques that are intended to correct erroneous values of *in situ* turbidity and reduce the “noise” in the real-time data base.

The top-down approach is a qualitative method that lowers high values for *in situ* turbidity or the turbidity spikes and other perceived erroneous values to values that are presumably correct. The bottom-up approach uses a threshold change of *in situ* turbidity to detect perceived erroneous values and adjusts them to presumably correct values.

The top-down adjustment approach uses the TTS-Adjuster program developed by the U.S. Forest Service (U.S. Forest Service Southwest Research Station, 2007). The TTS-adjuster program provides an efficient way to manipulate raw *in situ* turbidity and discharge data and works well for top-down adjustments. Anomalies in turbidity that have the greatest potential to influence estimates of sediment load are from high values of *in situ* turbidity or turbidity spikes. Very large increases of *in situ* turbidity over short periods of time, or turbidity spikes, occur frequently during certain times of the year (Figure 8). Turbidity increases also occur over longer periods of time. The TTS-adjuster is a qualitative approach where auxiliary data and field records are used to manually manipulate the *in situ* turbidity record. In general, turbidity spikes or very high values of *in situ* turbidity are manually adjusted down to the presumably correct value. This presumption of correctness is based on adjacent values of *in situ* turbidity and other supporting data (i.e. precipitation, discharge, laboratory turbidity, and field notes).

The bottom-up approach is based on the observation that traces of real-time, *in situ* turbidity are characterized by a clearly defined line of minimum threshold values as seen in Figure 8. The data is also characterized by high variability and, at times, spikes in turbidity that extend above this clearly defined line of minimum values. The goal of this approach was to develop an automated method that would define the line that constitutes the minimum threshold values and use that line as the de facto data set for *in situ* turbidity. This method has to distinguish between increases of *in situ* turbidity that result from increases in SSC and increases of *in situ* turbidity that result from leaves, needles branches, twigs, bubbles, and algae growth. The former are characterized by small, steady, and constant increases and decreases in turbidity over time while the latter are characterized by very large increases and decreases in time, defined as turbidity spikes.

This bottom-up approach uses a turbidity-threshold macro (TTM) to find and correct potentially erroneous values of *in situ* turbidity in the real-time record. Potentially erroneous values are identified by comparing each value in the turbidity record with the value that directly precedes it. If the change in turbidity between the two records exceeds a user defined maximum percent change (ΔT_{MAX}), then that value is flagged. The flagged observations are then compared to the expected *in situ* turbidity value, which is based on the relationship between discharge and *in situ* turbidity for the stream during the entire water year. If a flagged observation is not within the 95 percent confidence limits of that estimate, then the observation is considered erroneous. Each erroneous *in situ* turbidity value (T_i) is replaced with the previous turbidity value (T_{i-1}) when the percent change in turbidity (ΔT) is greater than ΔT_{MAX}:

$$\Delta T = \left(T_i - T_{i-1}\right) / T_{i-1} \qquad \textbf{Equation 6}$$

The relationship between discharge and turbidity were made for Oak Creek and South Fork Hinkle Creek. Figure 37 shows the relationship between discharge and the natural-logarithm of *in situ* turbidity at Oak Creek during water year 2006. A total of 305 observations of *in situ* turbidity and discharge were used in this relationship, which occurred at times that the TTS protocol attempted to sample the stream water at Oak Creek. Figure 38 shows the relationship between discharge and the natural-logarithm of *in situ* turbidity at South Fork Hinkle Creek during water year 2006. A total of 163 observations of *in situ* turbidity and discharge were used in this relationship, which occurred at times that the TTS protocol attempted to sample the stream water at South Fork Hinkle Creek.

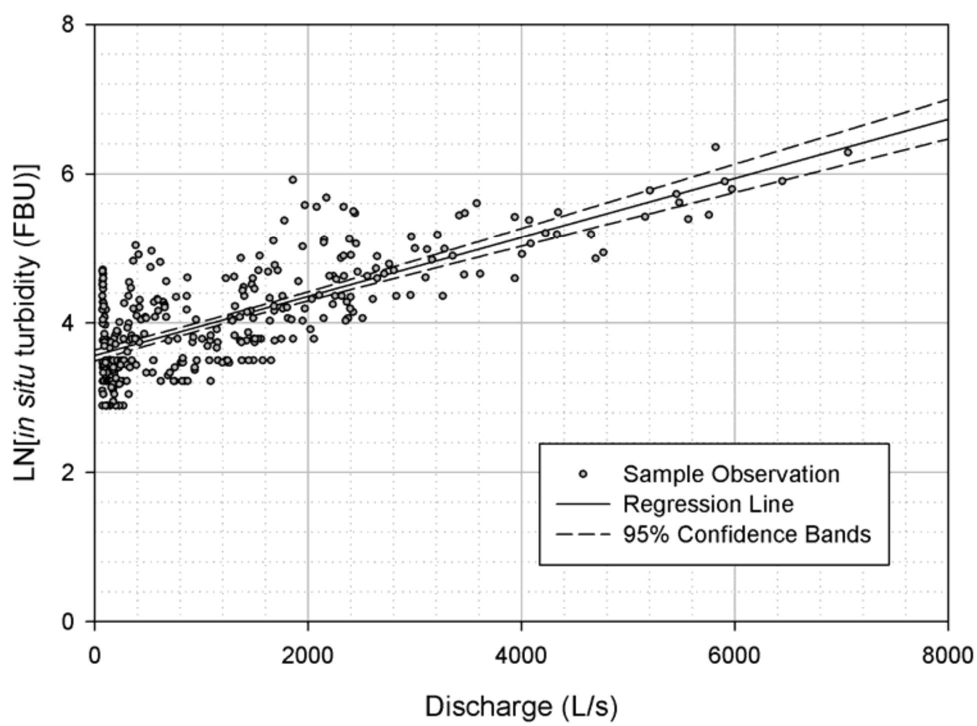


Figure 37. The relationship between discharge and ln[*in situ* turbidity], showing 95% confidence limits, at Oak Creek during water year 2006. SE=0.489, n=324, r^2=0.5563, β_1=0.00004, β_0=3.5647

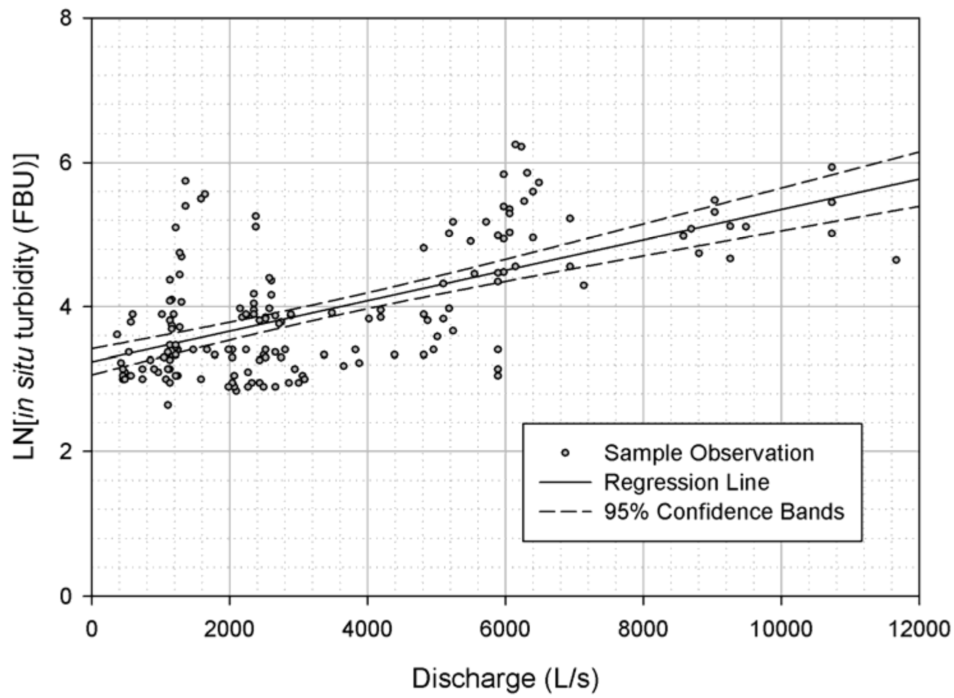


Figure 38. The relationship between discharge and ln[*in situ* turbidity], showing 95% confidence limits, at South Fork Hinkle Creek during water year 2006. SE=0.6973, n=163, r^2=0.6143, β_1=0.0002, β_0=3.2398

The actual sediment load in the stream is unknown. The use of techniques to adjust *in situ* turbidity values are an attempt to get the most accurate possible estimate of the sediment load. The TTS method is time consuming, adjustment is carried out on individual data points, and defined by the user where personal judgment is required to accept or adjust every data point in the turbidity record. Each time that turbidity is adjusted using this method a unique estimate of sediment load could result. The quality of the output from the adjusted turbidity record is affected by overall data quality, experience of the data manager, and the level of acceptance of fluctuations in turbidity.

The TTM adjustment macro is qualitative and crude but is designed to reduce the time required to make estimates of sediment load and to standardize how *in situ* turbidity data are vetted among users. In this analysis, by definition, the estimates of sediment load determined with the TTS approach are the true sediment load in the stream. Estimates of sediment load determined with the TTM approach are compared with the TTS estimates to determine the efficacy of the TTM approach.

4.4 SEDIMENT LOAD ESTIMATES

4.4.1 OAK CREEK SEDIMENT LOAD ESTIMATES

The real-time, *in situ* turbidity record for Oak Creek during water year 2006 was adjusted using the TTS adjuster (see Figure 39). This record was also adjusted using the TTM method. Nine values of ΔT_{MAX} that ranged from 0.3 to 0.9 were used to investigate an appropriate value that remove turbidity spikes but leave the traces of turbidity during storms intact. The annual sediment loads for Oak Creek were estimated from the *in situ* turbidity record adjusted by the TTM approach with different values of ΔT_{MAX}. The estimates of the annual sediment load calculated using the different ΔT_{MAX} are listed in Table 5 and shown in Figure 40. Several features were evaluated to determine the value of ΔT_{MAX}: that was most effective at adjusting the *in situ* turbidity data with the TTM adjuster. These features include 1) the ability to correct the obviously erroneous values of *in situ* turbidity, and 2) preservation of the *in situ* turbidity trace during the winter storms that are most critical to annual sediment load calculation. The ΔT_{MAX} that was chosen for Oak Creek is 0.71. Adjustments to the *in situ* turbidity record result from turbidity values greater than 71% of the preceding turbidity value being adjusted. Figure 39 shows traces of *in situ* turbidity for Oak Creek for water year 2006 adjusted with the TTM approach with a value of ΔT_{MAX} of 0.71 and with the TTS adjustor. A visual comparison of the differences in the resulting traces between these two methods can be observed in Figure 39.

Table 5. Estimates of annual sediment loads for Oak Creek, water year 2006, using the TTM-adjustment with specified thresholds (ΔT_{MAX}).

Threshold [ΔT_{MAX} (%)]	**Sediment Load (tonnes)**
30	543.58
50	557.55
60	561.63
70	566.23
71	564.94
72	564.91
73	564.91
80	565.17
90	580.03

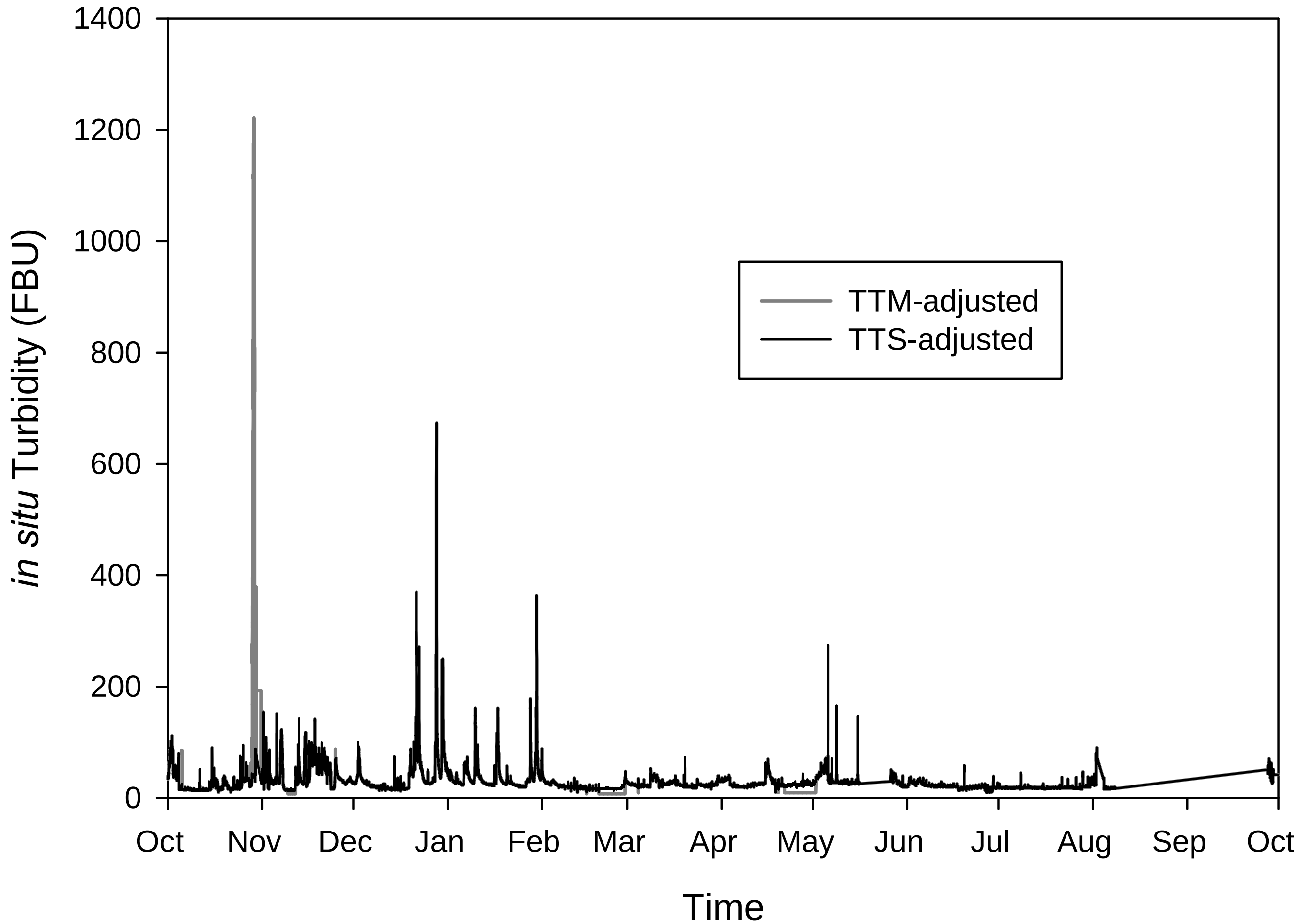


Figure 39. Two curves showing the adjusted values of *in situ* turbidity for Oak Creek during water year 2006, a ΔT_{MAX} of 0.71 was used for the TTM-adjustment.

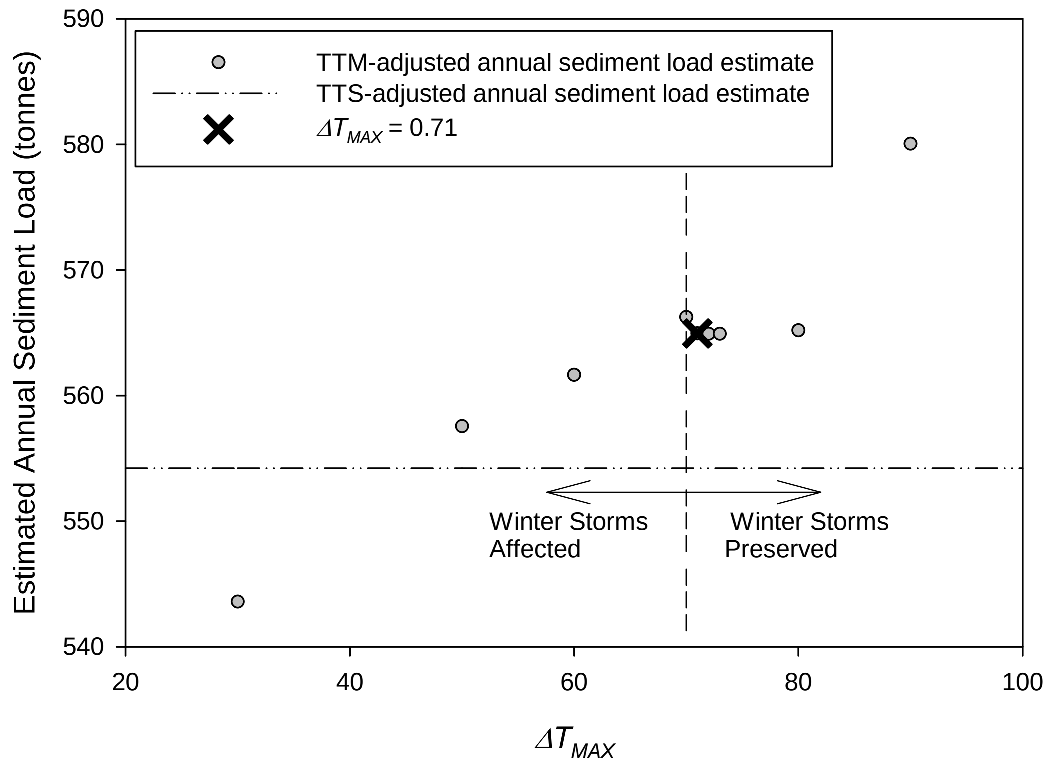


Figure 40. A graph of estimated annual sediment load at Oak Creek vs. ΔT_{MAX} for TTM adjustment for Oak Creek during water year 2006.

Estimates of the annual sediment load using a ΔT_{MAX} of 0.71 in the TTM-adjustment method were within 11 tonnes of the estimates of annual sediment load using the TTS adjustment method (Table 6). Most of the *in situ* turbidity values recorded between December and February were preserved and only one large spike in turbidity remained after the record was adjusted using the TTM-adjustment method. There are several time periods between February and June that have TTM-adjusted turbidity values that are lower than the TTS-adjusted turbidity values. This had minimal effect on estimates of sediment load because of the low turbidity (<25 FBU) and the low discharge (<50 L/s) at these times. The remaining large spike of *in situ* turbidity that remained in the record after TTM-adjustment occurred on October 28-29 (Figure 36). When using separate-storm relationships between *in situ* turbidity and SSC this turbidity spike occurs during the time period that contains Storm 1 and accounts for the majority of the difference between estimates of total annual sediment load between the two adjustment techniques (Table 7). This time period accounts for 2.2 percent of the annual sediment load when using the TTM-adjustment, compared to 0.6 percent of the annual sediment load when using the TTS-adjustment.

Table 6. Estimates of annual sediment load and 95 percent confidence intervals for the estimates for TTS and TTM adjusted *in situ* turbidity data using total annual and separate-storm *in situ* turbidity SSC relationships at Oak Creek during water year 2006.

Turbidity-SSC Relationship	**Sediment Load [tonnes (95% confidence interval)]**	
	TTS-adjust	**TTM-adjust**
Annual	554.7 (524.0, 589.9)	564.9 (534.3, 600.1)
Separate-storm	652.3 (558.0, 762.2)	660.9 (567.1, 770.1)

Table 7 shows the estimated sediment loads for the 15 time periods, with estimates of sediment load made using separate-storm relationships between *in situ* turbidity and the SSC of water samples. The first time period of the year, from October 1-November 5, accounts for most of the difference in the estimates of sediment load between the two turbidity adjustment methods. During this time period a large spike of *in situ* turbidity, which occurred on October 28-29, remained after TTM-adjustment (Figure 39). Storms 7 and 8 were the largest contributors to the annual sediment load with 27 and 23 percent of the annual sediment load, respectively. The largest storm of the year, Storm 7, had a peak discharge of 7,561 L/s and the duration was 1 percent of the time covered by the data set (Table 7). Storm 8 was the third largest storm of the year, the peak discharge was 5,758 L/s and it’s duration was approximately 2 percent of the time covered by the data set. The third largest contributor to the annual sediment load was from Storm 14, which was the second largest storm of the year, which had a peak discharge of 6,445 L/s, accounted for 15 percent of the sediment load, and approximately 3 percent of the time covered by the data set. Storms 7, 8, and 14 combined account for approximately 64 percent of the annual sediment load and only 6 percent of the time covered by the data set.

Table 7. A table of annual and separate-storm sediment load estimates for Oak Creek during water year 2006.

Storm ID	Start Date	End Date	Peak Discharge (L/s)	Sediment Load [tonnes (% of annual load)]	
				TTS-adjust	TTM-adjust
Annual	10/1/2005 0:00	9/30/06 23:50	6,445	554.7 (100)	564.9 (100)
1	10/1/05 0:00	11/5/05 11:00	471	3.6 (0.6)	14.5 (2.2)
2	11/5/05 11:10	11/20/05 0:00	719	3.3 (0.5)	3.3 (0.5)
3	11/20/05 0:10	12/1/05 8:10	566	2.3 (0.4)	2.3 (0.4)
4	12/1/05 8:10	12/19/05 0:00	1,031	4.6 (0.7)	4.5 (0.7)
5	12/19/05 0:10	12/21/05 3:10	883	4.1 (0.6)	4.1 (0.6)
6	12/21/05 3:20	12/26/05 22:50	3,656	79.5 (12.2)	78.5 (11.9)
7	12/26/05 23:00	12/29/05 16:10	7,561	171.9 (26.4)	171.9 (26.0)
8	12/29/05 16:20	1/3/06 9:40	5,758	147.2 (22.6)	147.2 (22.3)
9	1/3/06 9:50	1/6/06 5:00	1,128	2.4 (0.4)	2.4 (0.4)
10	1/6/06 5:10	1/9/06 12:00	1,727	17.3 (2.7)	17.3 (2.6)
11	1/9/06 12:10	1/10/06 14:10	3,476	24.5 (3.8)	24.5 (3.7)
12	1/10/06 14:20	1/16/06 3:00	3,068	22.0 (3.4)	22.0 (3.3)
13	1/16/06 3:10	1/20/06 4:00	5,055	40.1 (6.2)	40.1 (6.1)
14	1/20/06 4:00	1/31/06 12:20	6,445	96.9 (14.9)	96.9 (14.7)
15	1/31/06 12:20	9/30/06 23:50	2,321	32.7 (5.0)	31.4 (4.8)
Annual Sum*	10/1/05 0:00	9/30/06 23:30	7561	652.3 (100)	660.9 (100)

*The Annual Sum is the sum of the estimated sediment loads using separate storm relationships between *in situ* turbidity and SSC. This value is used to calculate the percentages for the separate-storm sediment load estimates.

The annual relationship between *in situ* turbidity and SSC resulted in the lowest estimated sediment load at Oak Creek for the TTS- and TTM-adjusted data sets with 555 and 565 tonnes of sediment, respectively (Figure 41). Storm-specific relationships between *in situ* turbidity and the SSC of water samples resulted in the highest estimated sediment loads for the TTS- and TTM-adjusted data sets with 652 and 661 tonnes, respectively (Figure 42). Storm-specific estimates of annual sediment load are approximately 96 tonnes higher than estimates annual sediment load using an annual relationship between *in situ* turbidity and SSC.

Cumulative sediment load (CSL) curves show the sediment load throughout the year expressed as a percentage. CSL curves created using the annual relationship between *in situ* turbidity and SSC were dependant on adjustment method (Figure 43). The CSL during the low flow period is lower for the TTS adjusted data set. Similarly the TTS adjusted values are also lower during the low flow period for the separate-storm estimate (Figure 44). Figures 45 and 46 respectively show the CSL curves for the TTS and TTM adjusted data. The annual and storm-specific estimates are similar before the winter storms. During the winter peak flows the CSL curves show the largest differences.

There is more variability in the annual sediment load estimate when using separate-storm relationships instead of an annual relationship for Oak Creek. When using the separate-storm relationships the confidence interval range is similar, respectively 202 and 201 tonnes. The narrowest confidence interval range is for the annual relationship, respectively 66 and 62 tonnes (Table 6).

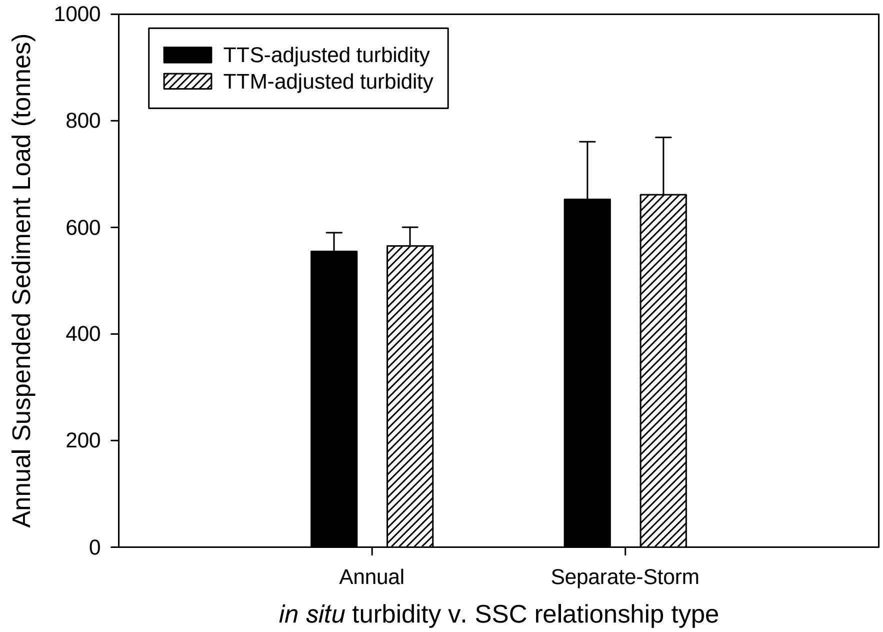


Figure 41. A graph of estimated annual sediment load calculated by annual and separate-storm relationships between *in situ* turbidity vs. SSC and TTS and TTM adjustment of the *in situ* turbidity record for Oak Creek during water year 2006.

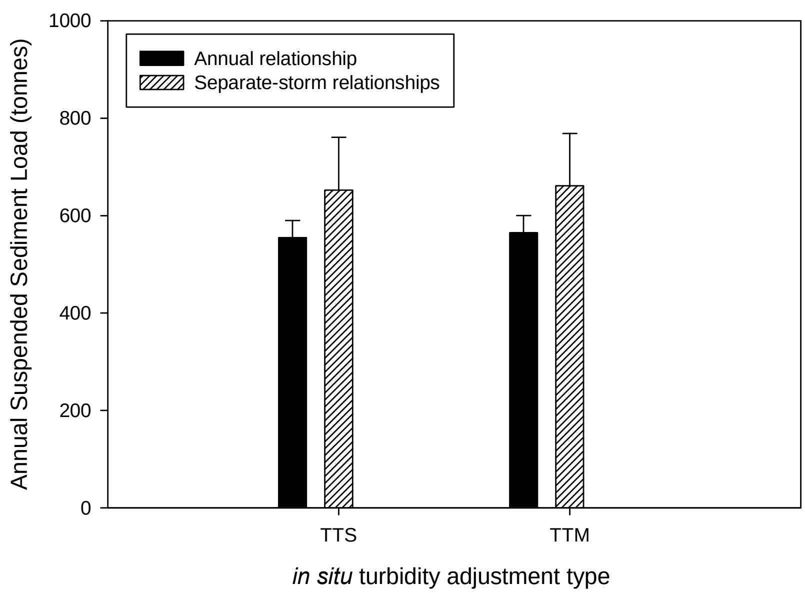


Figure 42. A graph of annual sediment load by *in situ* turbidity adjustment type for Oak Creek: water year 2006.

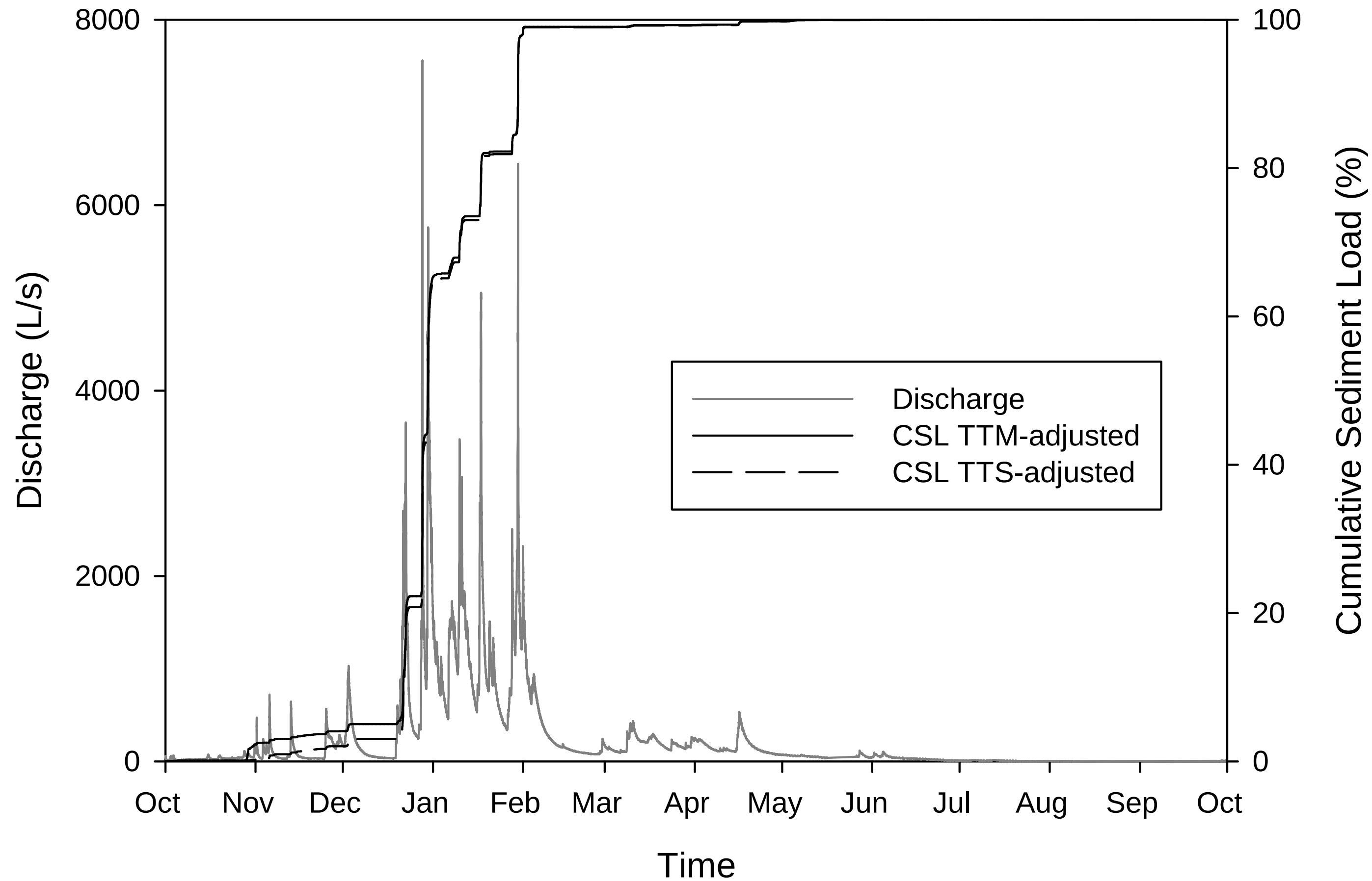


Figure 43. Cumulative sediment load (CSL) as a percent for annual estimate at Oak Creek during water year 2006: Turbidity adjusted using the TTM and TTS-adjustment approaches.

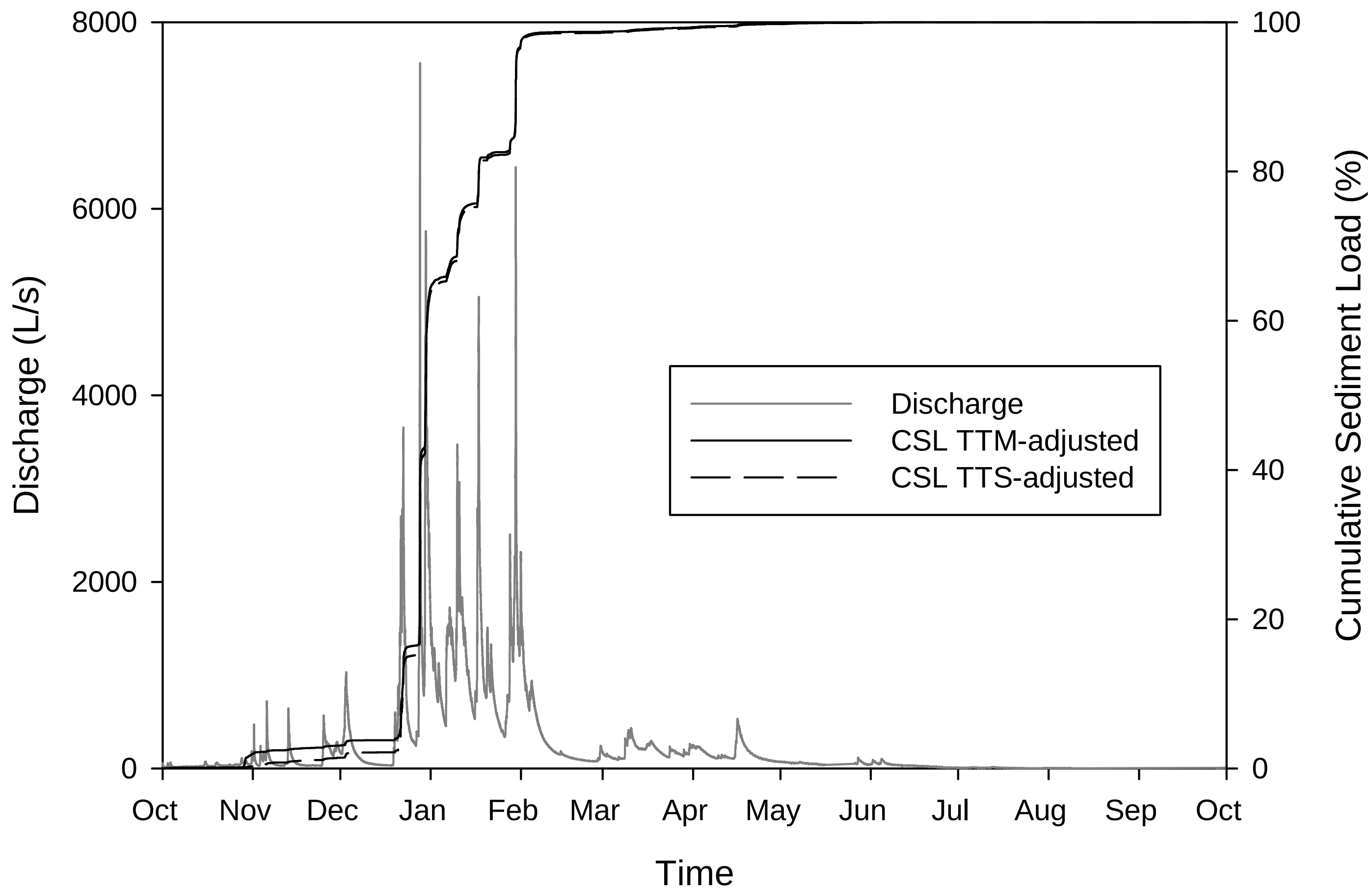


Figure 44. Cumulative sediment load (CSL) as a percent for storm-specific estimate at Oak Creek during water year 2006: Turbidity adjusted using the TTM and TTS-adjustment approaches.

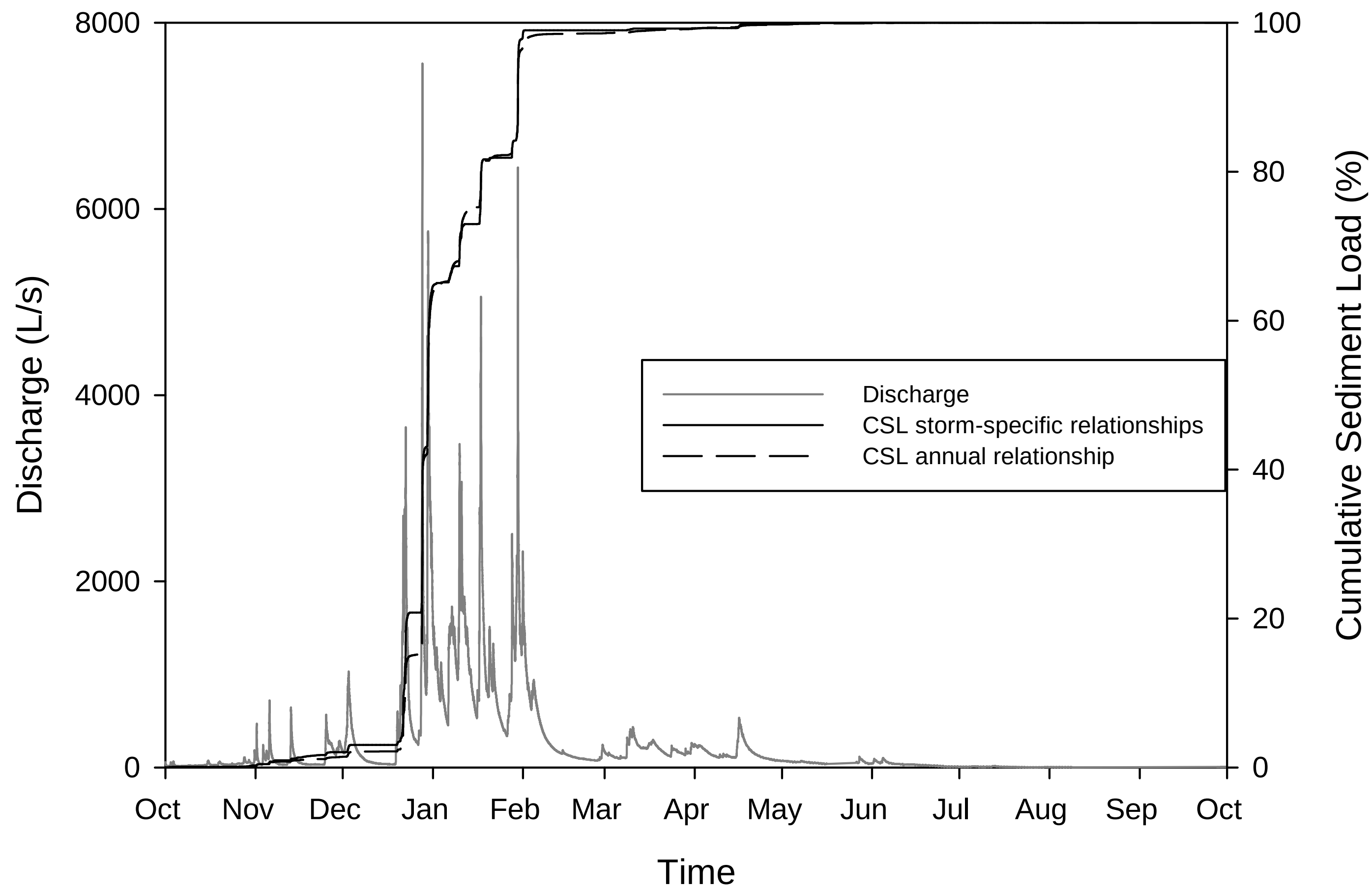


Figure 45. Cumulative sediment load (CSL) as a percent for TTS-adjusted *in situ* turbidity at Oak Creek during water year 2006: Annual and separate storm relationships between turbidity and SSC.

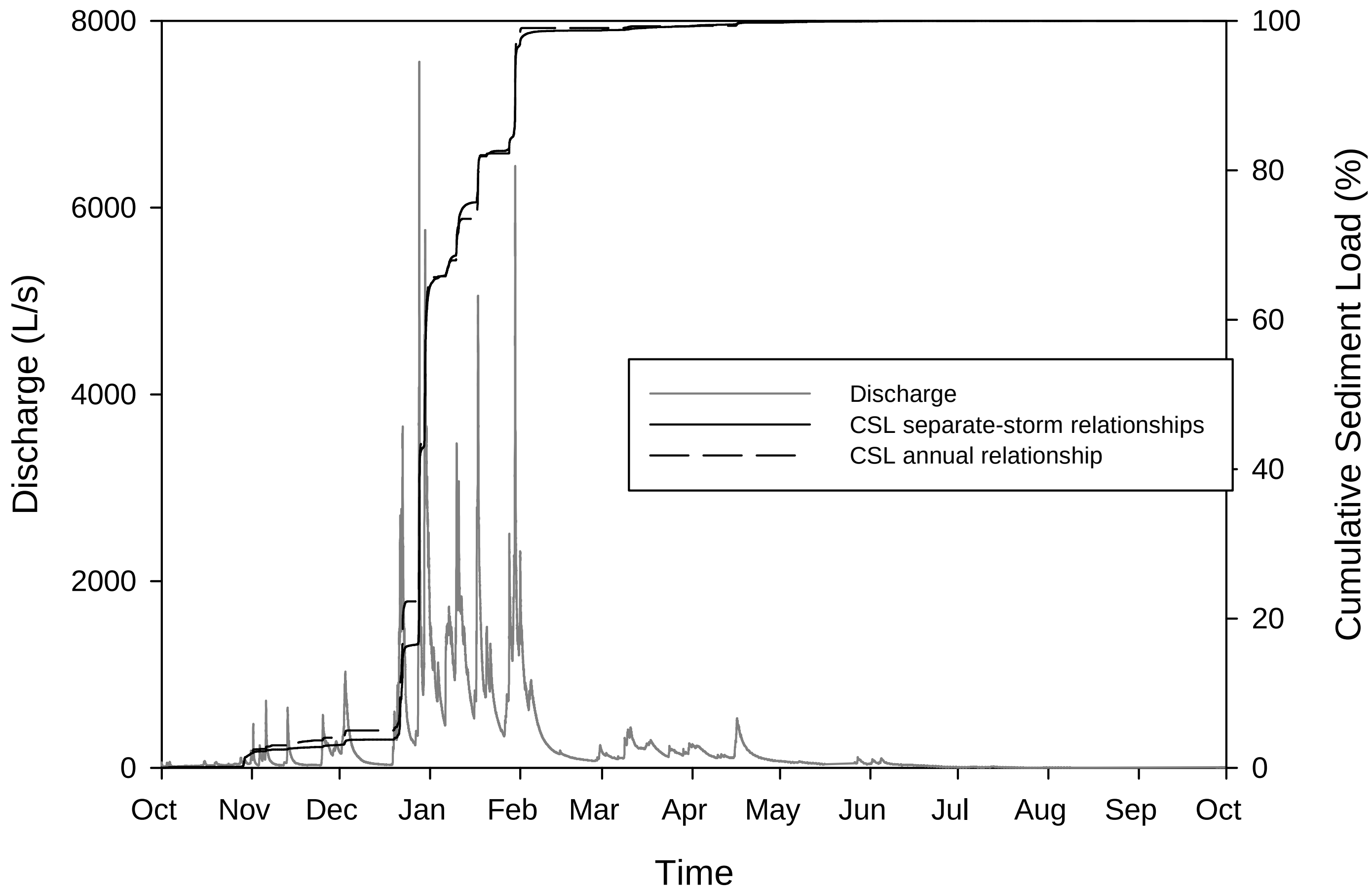


Figure 46. Cumulative sediment load (CSL) as a percent for TTM-adjusted *in situ* turbidity at Oak Creek during water year 2006: Annual and storm-specific relationships between turbidity and SSC.

4.4.2 SOUTH FORK HINKLE CREEK SEDIMENT LOAD ESTIMATES

The real-time, *in situ* turbidity record for South Fork Hinkle Creek for water year 2006 was adjusted using the TTS adjuster (Figure 47). This record was also adjusted using the TTM method. Nine values of ΔT_{MAX} that ranged from 0.7 to 0.98 were used to investigate an appropriate value that would remove turbidity spikes but leave traces of turbidity during storms intact. The annual sediment loads for South Fork Hinkle Creek were estimated from the *in situ* turbidity record adjusted by the TTM approach with different values of ΔT_{MAX}. The estimates of the annual sediment load calculated using the different ΔT_{MAX} are listed in Table 8 and shown in Figure 48. Several features were evaluated to determine the value of ΔT_{MAX}: that was most effective at adjusting the *in situ* turbidity data with the TTM adjuster. These features include 1) the ability to correct the obviously erroneous values of *in situ* turbidity, and 2) preservation of the *in situ* turbidity trace during the winter storms that are most critical to annual sediment load calculation. The ΔT_{MAX} that was chosen for South Fork Hinkle Creek is 0.93. Adjustments to the *in situ* turbidity record result from turbidity values greater than 93% of the preceding turbidity value being adjusted. Figure 47 shows traces of *in situ* turbidity for South Fork Hinkle Creek for water year 2006 adjusted with the TTM approach with a value of ΔT_{MAX} of 0.93 and with the TTS adjustor. A visual comparison of the differences in the resulting traces between these two methods can be observed in Figure 47.

Table 8. Estimates of annual sediment loads for South Fork Hinkle Creek, water year 2006, using the TTM-adjustment with specified thresholds (*ΔT_{MAX}*).

Threshold [Delta-T (%)]	**Sediment load (tonnes)**
70	2,521.44
80	2,195.47
87	1,930.93
88	1,923.51
89	1,923.51
90	1,926.01
93	1,926.17
95	1,926.17
98	1,950.39

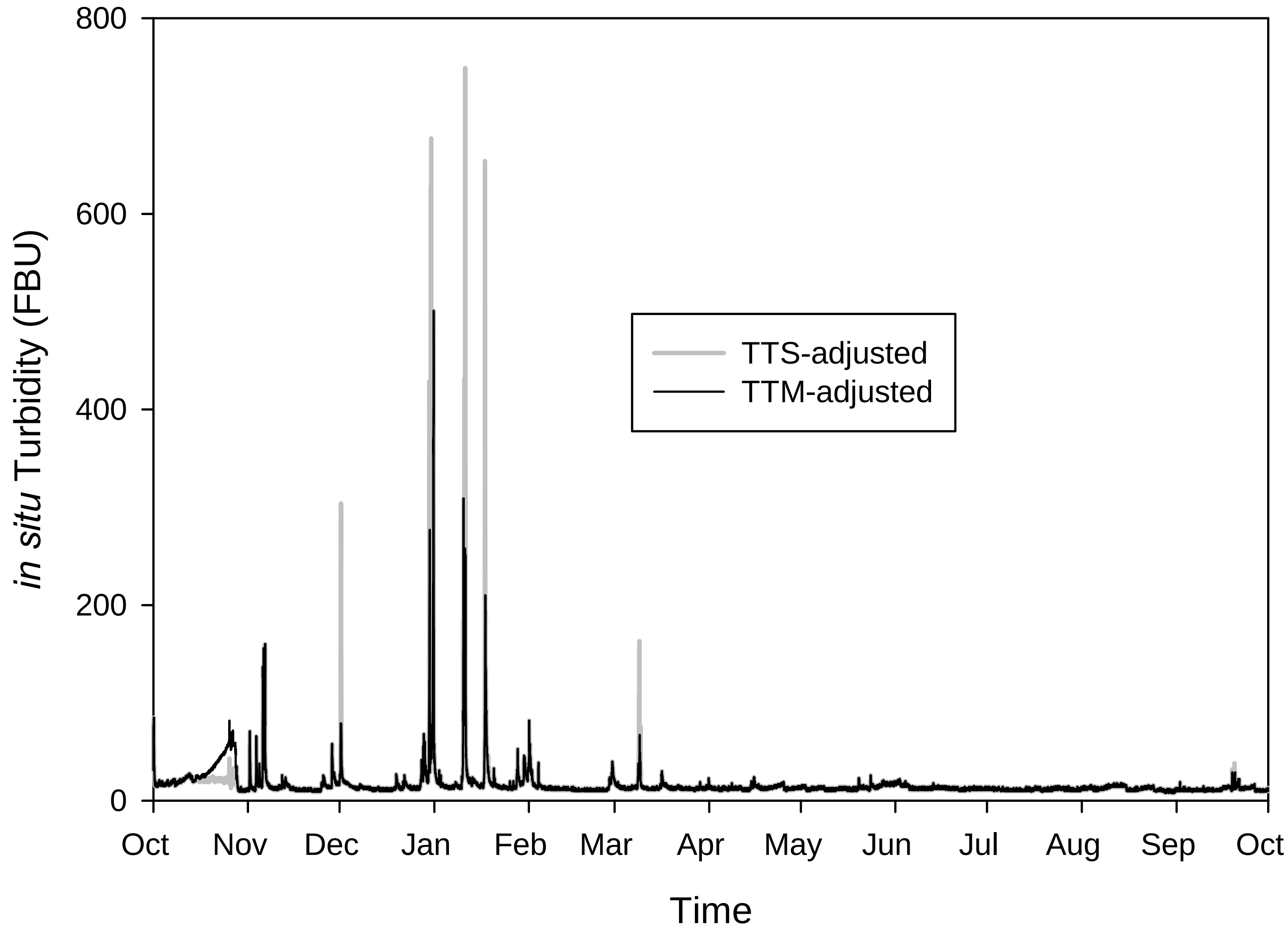


Figure 47. Adjusted *in situ* turbidity values for South Fork Hinkle Creek during water year 2006, TTM and TTS-adjusted (ΔT_{MAX}=0.93).

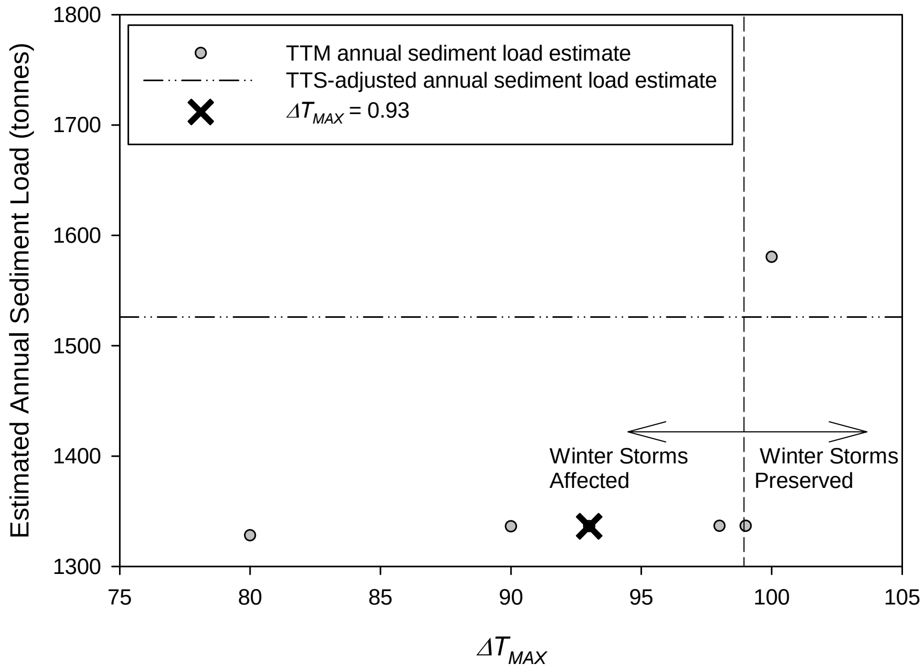


Figure 48. A graph of estimated annual sediment load determination to determine ΔT_{MAX} for TTM adjustment at South Fork Hinkle Creek: water year 2006.

Estimates of the annual sediment load using a ΔT_{MAX} of 0.93 in the TTM-adjustment method were within 200 tonnes of estimates of annual sediment load using the TTS-adjusted method (Table 9). Figure 47 shows the TTM-adjusted *in situ* turbidity record overlaying the TTS-adjusted *in situ* turbidity record. There is progressive fouling of the *in situ* turbidity sensor recorded from October 15-28 (Figure 47). This fouling was adjusted in the TTS-adjusted *in situ* turbidity record, but not in the TTM-adjusted *in situ* turbidity record. This fouling was not adjusted by the TTM because the gradual change of *in situ* turbidity never exceeded the 0.93 ΔT_{MAX}. The low discharge (<100 L/s) and *in situ* turbidity (<70 FBU) during this time period resulted in a 0.1 tonne difference in the estimate annual sediment load between the TTM and TTS adjusted *in situ* turbidity records (Table 10).

In situ turbidity at South Fork Hinkle Creek can be flashy during storms, with drastic changes occurring in short, 30-minute, time periods. These drastic changes are most likely real during high discharge when ΔT_{MAX} can be easily exceeded over the 30-minute integration time. Other studies have reported similar rapid increases of *in situ* turbidity while using a 30-minute integration time (Nistor and Church, 2005). Several storms between December and March have turbidity observations that were inappropriately reduced by the TTM-adjuster. One instance occurred during the largest storm of the year, Storm 4, which was the largest contributor to the annual sediment load. The reduction of *in situ* turbidity values by the TTM-adjuster during Storm 4 accounted for a majority (61%) of the difference between estimated annual sediment loads when compared to the TTS-adjusted *in situ* turbidity data set (Table 10).

Table 9. Annual sediment load estimates and 95% confidence intervals for TTS and TTM-adjustments using Annual and Separate-storm turbidity-SSC relationships at South Fork Hinkle Creek: water year 2006.

Turbidity-SSC Relationship	Sediment load [tonnes/year (95% confidence interval)]	
	TTS-adjust	**TTM-adjust**
Annual	1,525.9 (1,300.0; 1,790.9)	1,336.3 (1,138.6; 1,568.5)
Separate-storm	715.2 (502.3; 1,001.9)	597.4 (420.6; 831.8)

Table 10 shows the estimated sediment loads for 7 time periods, with estimates of sediment load made using separate-storm relationships between *in situ* turbidity and the SSC of water samples. The first time period of the data set, from October 1-December 1, had a 0.1 tonne difference in estimated sediment load, which resulted from the progressive fouling of *in situ* turbidity that was not adjusted by the TTM. The largest contributor to the annual sediment load, the Storm 4 time period, accounted for approximately 61 and 67 percent for TTM and TTS adjusted *in situ* turbidity records, respectively (Table 10). This time period contained the three largest discharge events of the year. The largest event of the year occurred on December 29, with a peak discharge of 15,349 L/s, during which 38 water samples were taken. The third largest event of the year occurred on

January 9, with a peak discharge of 9,487 L/s. The SSC of samples taken during this storm had no usable pattern or relationship between *in situ* or laboratory turbidity. The third peak that occurred in the Storm 4 time period was the second largest event of the year, with a peak discharge of 13,424 L/s. No water samples were taken during this hydrograph. In total the duration of these three storms accounted for 8 percent of data record.

Table 10. Annual and separate-storm sediment load estimates for South Fork Hinkle Creek during for water year 2006.

Storm ID	Start Date	End Date	Peak Discharge (L/s)	Sediment Load [tonnes/time (% of annual load)]	
				TTS-adjust	TTM-adjust
Annual	10/1/05 0:00	9/30/06 23:30	15,349	1,526 (100)	1,336 (100)
1	10/1/05 0:00	12/1/05 0:00	1,020	12.5 (1.7)	12.6 (2.1)
2	12/1/05 0:30	12/27/05 0:00	2,379	37.7 (5.3)	36.6 (6.1)
3	12/27/05 0:30	12/29/05 13:00	5,098	7.6 (1.1)	7.6 (1.2)
4	12/29/05 13:30	1/27/06 20:00	15,349	481.7 (67.4)	365.1 (61.1)
6	1/27/06 20:30	1/31/06 12:30	2,747	100.3 (14.0)	100.3 (16.8)
7	1/31/06 13:00	3/8/06 1:00	2,662	29.6 (4.1)	29.6 (5.0)
8	3/8/06 1:30	9/30/06 23:30	1,614	45.8 (6.4)	45.7 (7.6)
Annual Sum*	10/1/05 0:00	9/30/06 23:30	15349	715.2 (100)	597.4 (100)

*The Annual Sum is the sum of the estimated sediment loads using separate storm relationships between *in situ* turbidity and SSC. This value is used to calulate the percentages for the separate-storm sediment load estimates.

The annual relationship between *in situ* turbidity and SSC resulted in the highest estimated sediment load at South Fork Hinkle Creek for the TTS- and TTM-adjusted data sets with 1,526 and 1,336 tonnes of sediment, respectively (Figure 49). Storm-specific relationships between *in situ* turbidity and the SSC of water samples resulted in the lowest estimated sediment loads for the TTS- and TTM-adjusted data sets with 715 and 597 tonnes, respectively (Figure 49). Estimated annual sediment load using annual relationships between *in situ* turbidity and the SSC of water samples were more than two-times the estimated annual sediment loads made using storm-specific relationships for TTS and TTM-adjusted data sets (Figure 50). The confidence interval range around the estimated annual sediment loads is similar for the annual and separate-storm relationships, 411 to 500 tonnes (Table 9).

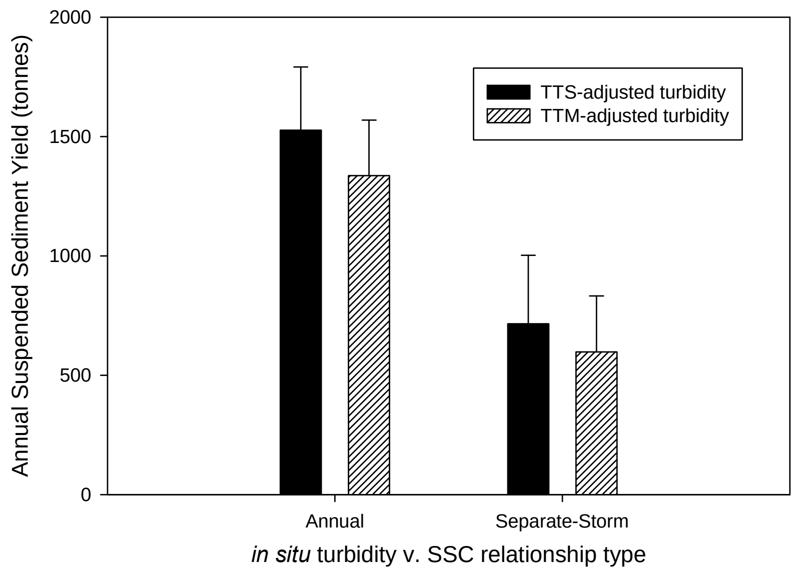


Figure 49. A graph of annual sediment load by *in situ* turbidity vs. SSC relationship type for South Fork Hinkle Creek: water year 2006.

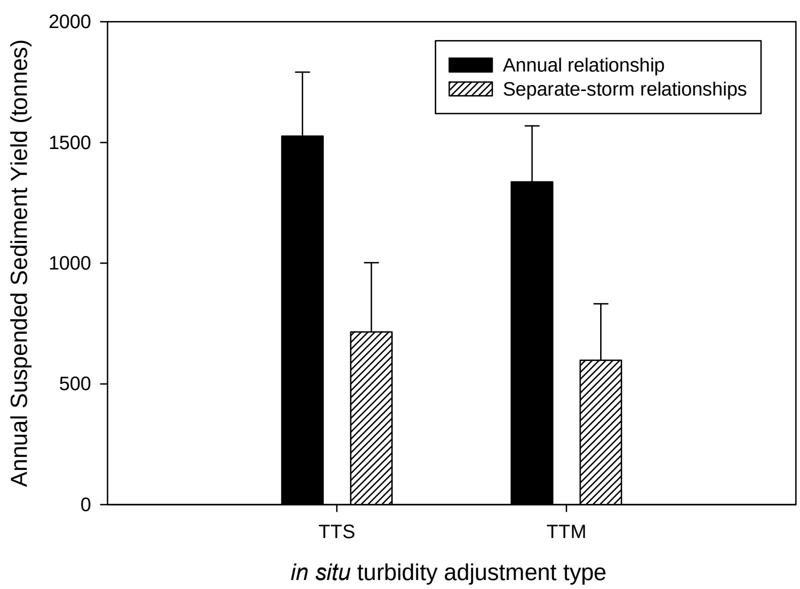


Figure 50. A graph of annual sediment load by *in situ* turbidity adjustment type for South Fork Hinkle Creek: water year 2006.

Using the annual relationship, the estimated annual sediment load is between 1,300 and 1,791 tonnes for the TTS-adjusted turbidity, and between 1,137 and 1,569 tonnes for the TTM-adjusted turbidity (Table 9). Using the storm-specific relationship, the estimated annual sediment load is between 502 and 1,002 tonnes for the TTS-adjusted turbidity, and between 421 and 832 tonnes for the TTM-adjusted turbidity.

Cumulative sediment load (CSL) curves for South Fork Hinkle Creek show the sediment load throughout the year expressed as a percentage. CSL curves created using the annual relationship between *in situ* turbidity and SSC shows that 80 percent of the sediment load is transported before March, 2006 (Figure 51). From February through September the CSL curve has a positive trend, accounting for 20 percent of the estimated annual suspended load. The estimated CSL using storm-specific relationships between *in situ* turbidity and SSC shows that a larger proportion of the estimated annual sediment load is transported during winter storms, accounting for roughly 90 percent of the estimated annual sediment load (Figure 52). From February through September the cumulative sediment load has a more gradual positive trend, accounting for only 10 percent of the estimated annual sediment load. The correlation between *in situ* turbidity and the SSC of discrete water samples varies for the different storm periods (Table 4). When using the annual relationship, the correlation between *in situ* turbidity and SSC is poor (r^2=0.34). Most of the sediment load is transported during a short time period, during winter storms. Separate-storm relationships between *in situ* turbidity and SSC are more highly correlated. Only one time period has a correlation as low as the annual relationship, Storm 8, which accounts for less than 7 percent of the annual sediment load (Table 10).

The CSL curve for at South Fork Hinkle Creek using the annual relationship between *in situ* turbidity and SSC is shown in Figure 51. The CSL curve shows that both TTM and TTS adjusted turbidity records produce similar results throughout the year. The TTS adjusted data set produces a higher percent of the annual sediment load during the winter storms. This difference is dependant on the amount of alteration done to the turbidity record by the TTM-adjustment. Similarly Figure 52 shows that the TTS-adjusted turbidity record loads a higher percentage of the total annual sediment load during the winter storm period. Figures 53 and 54 show the CSL curves for TTS and TTM adjusted sediment load estimates and shows the difference between annual and separate-storm relationships. Before January the annual relationship estimates higher sediment load than separate-storm estimates. After the largest peak flows, the annual relationship estimate is much lower than the separate-storm relationship estimate. This results in a larger proportion of the annual sediment load to be attributed to the storms that follow the large winter peaks.

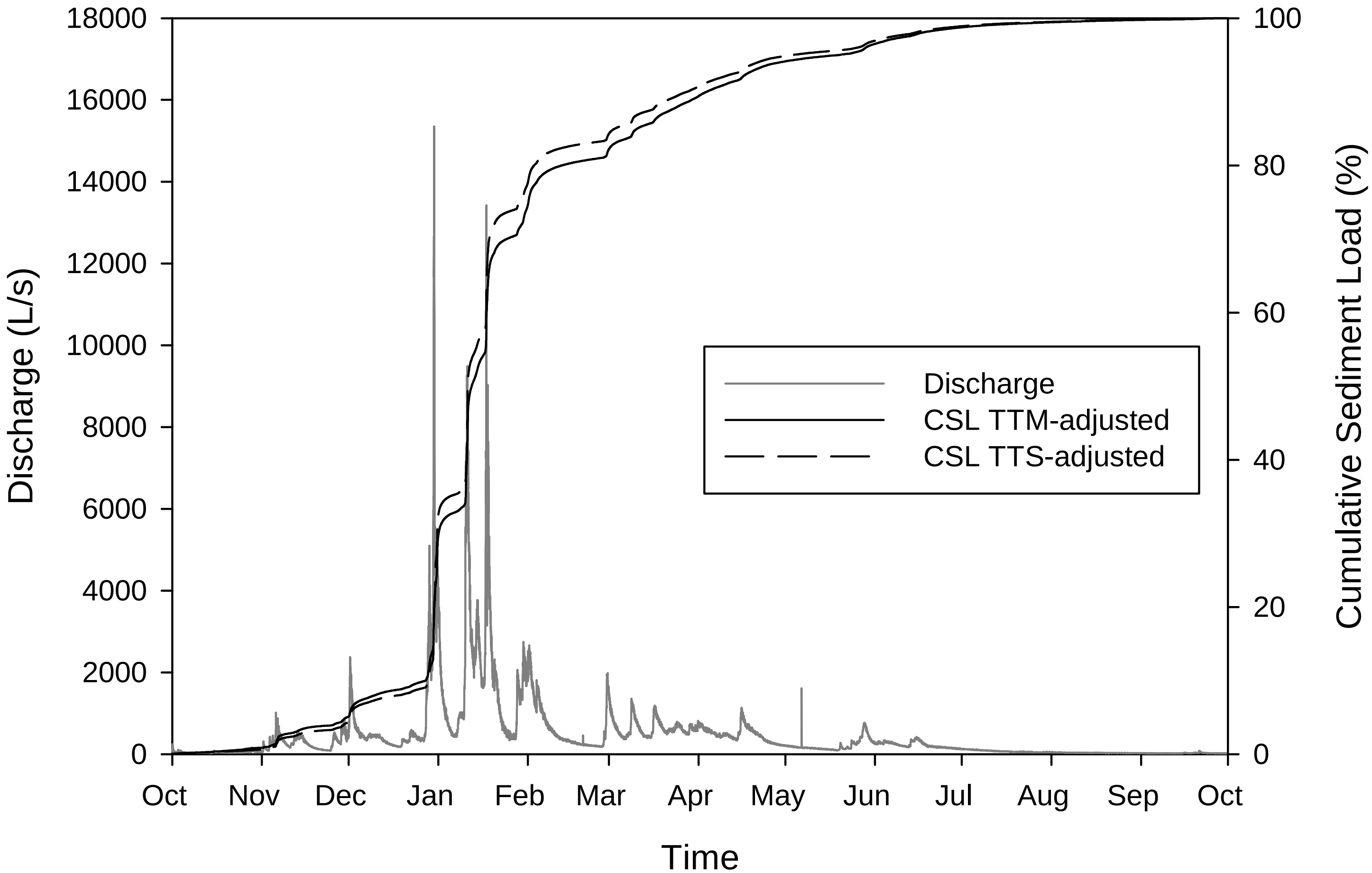


Figure 51. Cumulative sediment load (CSL) as a percent for annual estimate at South Fork Hinkle Creek during water year 2006: Turbidity adjusted using the TTM and TTS-adjustment approaches.

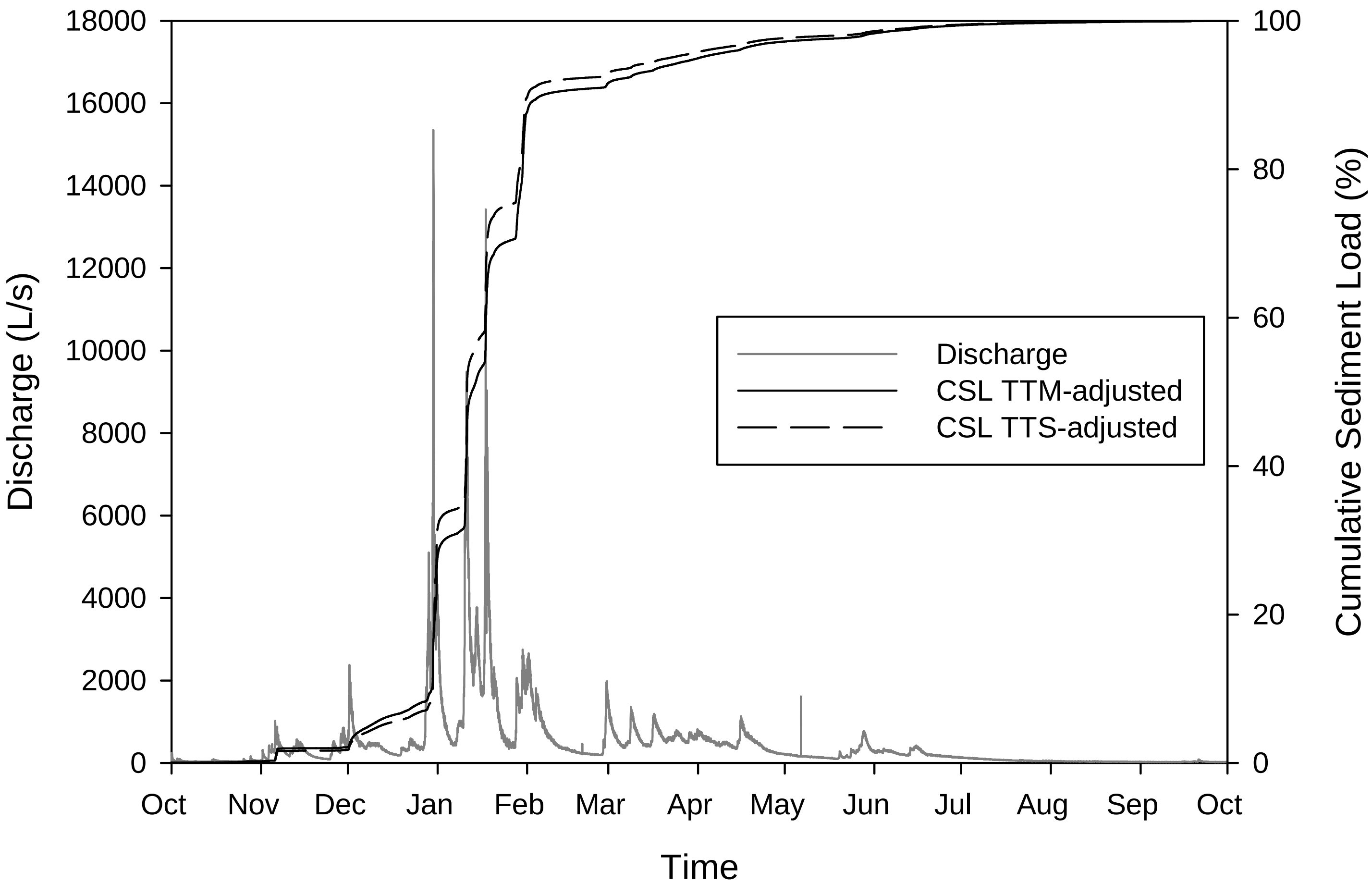


Figure 52. Cumulative sediment load (CSL) as a percent for storm-specific estimate at South Fork Hinkle Creek during water year 2006: Turbidity adjusted using the TTM and TTS-adjustment approaches.

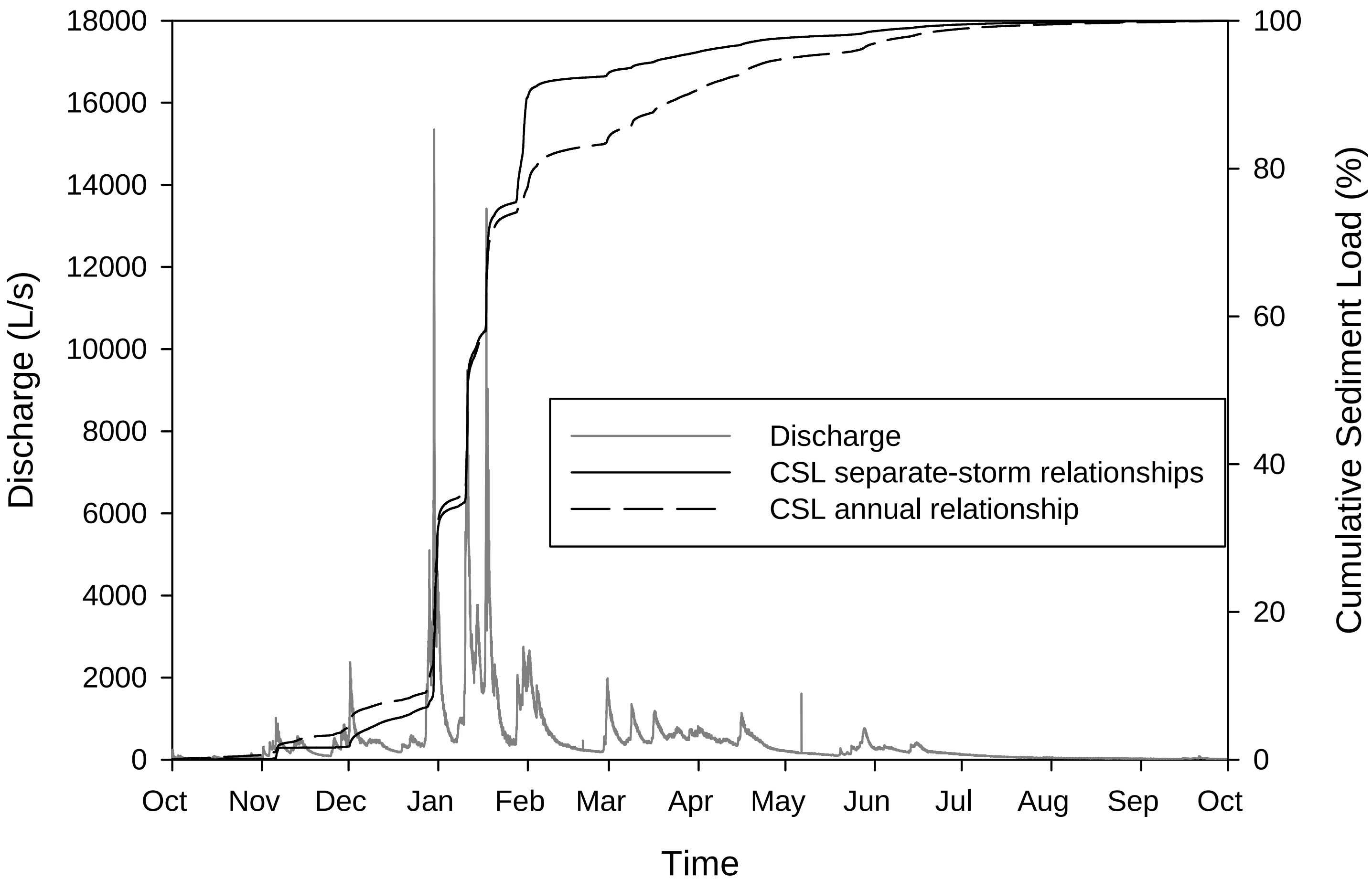


Figure 53. Cumulative sediment load (CSL) as a percent for TTS-adjusted *in situ* turbidity at South Fork Hinkle Creek during water year 2006: Annual and storm-specific relationships between turbidity and SSC.

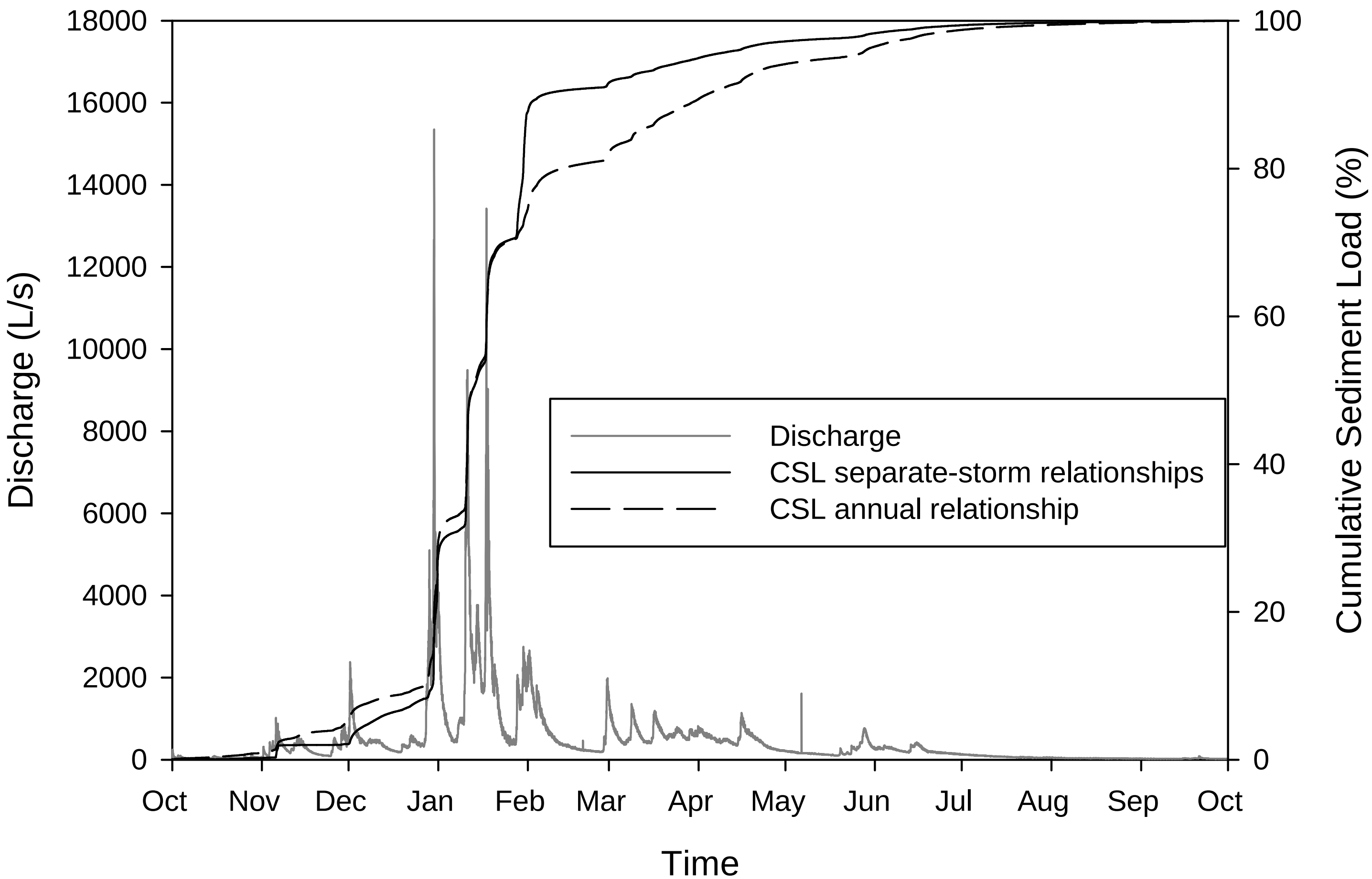


Figure 54. Cumulative sediment load (CSL) as a percent for TTM-adjusted *in situ* turbidity at South Fork Hinkle Creek during water year 2006: Annual and storm-specific relationships between turbidity and SSC.

5. DISCUSSION

5.1 ERRONEOUS OBSERVATIONS

There were observations of *in situ* turbidity that were erroneous at Oak Creek and South Fork Hinkle Creek during the 2006 water year. The development of a turbidity adjustment tool like the TTS-adjuster program is evidence that erroneous measurements of *in situ* turbidity are routinely collected.

The submergence of the optical sensor that makes up the turbidimeter is a major factor that controls the quality of *in situ* turbidity data. Only the water that the turbidity measurement is desired for should be observed by the sensor. Observations of the water surface, bubbles, organic debris in the stream, or the stream bottom will result in erroneous observations of *in situ* turbidity. Placement of the optical sensor for the turbidimeter should allow for the measurement of *in situ* turbidity during large events, when most of the sediment transport occurs, but also allow for the measurement of *in situ* turbidity during low flows and small storms. The characteristics of the stream should be considered when the location of the turbidity probe is selected so that the turbidity of low flows can be measured with minimal erroneous values. At South Fork Hinkle Creek, the turbidimeter is located on a boom suspended in a pool where observation of *in situ* turbidity during high and low flows is optimal. At Oak Creek, the turbidimeter is located on a boom suspended in a riffle. The depth of the water in at the Oak Creek gauging location commonly reaches 0.6 meters during winter storms but gets down to less than 0.05 meters during the summer. The summer low flows at Oak Creek may not be ideal for year-round *in situ* turbidity monitoring.

Fouling and interference of the optical sensor during storms can cause erroneous observations of *in situ* turbidity. This is evident at South Fork Hinkle Creek where erratic values of *in situ* turbidity during several storms are obvious (Figure 27). During Storm A, January 10-12, discharge increased from less than 1,500 to approximately 13,500 L/s. Then there were minor fluctuations in discharge while *in situ* turbidity fluctuated between 100 and 750 FBU. Some of the fluctuations of *in situ* turbidity were associated with fluctuations in discharge, but some large spikes of *in situ* turbidity are not correlated with discharge or precipitation. During Storm B, November 5 – 7, there are erratic values of *in situ* turbidity that appear to be erroneous but precipitation and discharge do appear to fluctuate in a pattern that is similar to the storm. A lack of water samples makes it impossible to compare *in situ* turbidity to laboratory turbidity and SSC during this time. During Storm C, March 8-11, a burst of precipitation caused the discharge at SOUTH FORK Hinkle Creek to increase from 500 to 1,400 L/s. The *in situ* turbidity, however, increased only slightly, from 13 to 38 FBU, as a result of the peak discharge. After the peak in discharge, the *in situ* turbidity was erratic and fluctuate over 200 FBU for the next 16 hours.

The *in situ* turbidity at South Fork Hinkle Creek was erratic at times. A hypothesis for this behavior could be that the movement of suspended sediment in South Fork Hinkle Creek may be similar to the movement of bedload. The movement of bedload can be highly variable and erratic (Beschta, 1987). Observation of the sediment discharge record at Oak Creek and South Fork Hinkle Creek indicates that these watersheds may have different sediment transport regimes even though they have similar geology. The soils in the Oak Creek watershed are grassland soils that developed in an oak-savannah and have high clay content. The soils at Hinkle Creek are forest soils that have much lower clay content. The lack of colloidal material in the water at South Fork Hinkle Creek may explain the erratic observations of *in situ* turbidity.

In undisturbed stream channels, turbidity and SSC should be associated with changes in discharge, available sediment, and natural erosion processes (creep, dry ravel, bank scour, etc). At Oak Creek the highest *in situ* turbidity occurred at times when there was little or no increase in discharge (Figure 25). These increases in turbidity would peak at values twice as high as turbidity values that occurred during the largest storms of the year. The annual sediment load for Oak Creek is 5 percent higher when these erroneous values of *in situ* turbidity are included in the estimate of the annual sediment load.

Increased SSC is the result of increased discharge (Stott and Grove, 2001). However, SSC can increase in the absence of increased discharge due to stream bank and bed disturbance (Lewis, 1998). An increase of *in situ* turbidity that was not associated with an increase in discharge was observed at Oak Creek during the 2005 water year (Figure 55), several spikes of *in situ* turbidity occurred before the hydrograph peak. After the hydrograph peak, the discharge returned to base flow but an increase of *in situ* turbidity started on December 16th and that was not associated with increased discharge. The increased sediment load was, presumably, real. The stream bed was disturbed during this time by the installation of several wells into the streambed as a part of a separate study. The automated sampling system did not collect a water sample during the time period of elevated *in situ* turbidity.

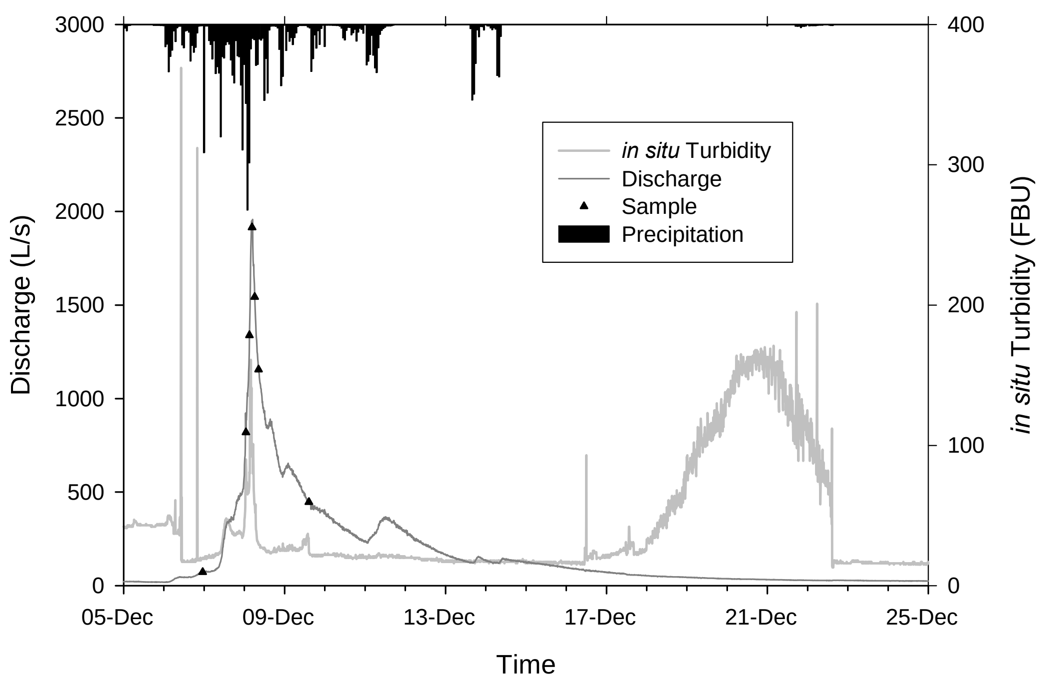


Figure 55. A graph of discharge, precipitation, un-adjusted *in situ* turbidity, and water samples at Oak Creek: December 5-25, 2004.

5.2 EFFICACY OF TTM-ADJUSTMENT

Results from Oak Creek and South Fork Hinkle Creek show that estimates of the annual sediment load with a TTM-adjusted *in situ* turbidity record are similar to estimates of the annual sediment load made with a TTS-adjusted *in situ* turbidity record (Tables 6 and 9). Annual sediment loads estimated with a TTM-adjusted record of *in situ* turbidity for Oak and South Fork Hinkle Creeks were 2 and 16 percent greater, respectively, than annual sediment loads estimated with a TTS-adjusted record of *in situ* turbidity.

Comparison of *in situ* turbidity records that were edited with TTM- and TTS-adjustments can be used to determine the applicability of the TTM-adjustment (Figures 39 and 47). The TTM-adjuster worked well for turbidity records that contained large spikes in turbidity. The Oak Creek record of *in situ* turbidity contains few instances of erratic turbidity and most of the observations of erroneous *in situ* turbidity were short-term spikes. The TTM-adjuster was able to remove all but one of these turbidity spikes from the Oak Creek *in situ* turbidity record. The record of *in situ* turbidity from South Fork Hinkle Creek also contains short-term spikes of *in situ* turbidity, but also contains several instances where *in situ* turbidity shows a slow, steady increase and episodes of erratic *in situ* turbidity. The TTM-adjuster was not able to detect and correct the time periods with erratic *in situ* turbidity at South Fork Hinkle Creek.

In general, the use of a tool like the TTM-adjuster was satisfactory. The TTM-adjuster was able to produce records of adjusted *in situ* turbidity that tracked the records of TTS-adjusted *in situ* turbidity quite well. For Oak Creek the TTM-adjuster was not able to handle some of the large spikes of *in situ* turbidity. For the South Fork Hinkle Creek the TTM-adjuster had trouble with the long, slow, increases of *in situ* turbidity and struggled with the erratic values during big storms. But, estimated values of total annual sediment load between the two methods was remarkably similar given the other sources of error inherent in the process.

The problems encountered with the TTM-adjuster were easily identified by simply observing the adjusted record. The large spikes of turbidity at Oak Creek during low fall flows were easily observable as was the period of slow increase in turbidity in South Fork Hinkle Creek. These observations suggest that a hybrid approach to adjustment of *in situ* turbidity might be of value. An initial step would be to run the TTM-adjuster and get an adjusted record of *in situ* turbidity then that record can be evaluated by eye and individual, erroneous values could adjusted using the TTS-adjuster. This approach will reduce the time and effort currently spent adjusting *in situ* turbidity records.

The problem with this approach is that assigning a threshold adjustment value for the TTM-adjuster requires an estimate of the total sediment load be known. Thus, to some degree, to solve the problem you already need to know the answer. The calibration of the TTM threshold value was not a part of this research. Thus, while a bottom-up, TTM-adjuster program to edit and adjust records of *in situ* turbidity appears to be viable, the details of the method are not perfected and it remains a work in progress. A method to calibrate an *in situ* turbidity record for the threshold adjustment value remains to be worked out.

5.3 EFFICACY OF ANNUAL AND STORM-SPECIFIC RELATIONSHIPS

Results from Oak Creek and South Fork Hinkle Creek show that estimates of the annual sediment load can be made with annual or storm-specific relationships between the *in situ* turbidity and SSC of water samples. However, for the 2006 water year, these estimates for South Fork Hinkle Creek are different and depend on the type of relationship used.

The annual relationship between *in situ* turbidity and the SSC of water samples at Oak Creek is linear and strongly correlated (Table 3, Figure 32). Estimates of total annual sediment load with the storm-specific relationships between *in situ* turbidity and SSC were within 100 tonnes (17 percent) of the sediment load estimated with the annual relationship between *in situ* turbidity and SSC.

The annual relationship between *in situ* turbidity and SSC of water samples at South Fork Hinkle Creek is not linear and a natural-log transformation of the independent and dependant variables was carried out to make the relationship more linear (Figure 22 and 34). The storm-specific relationships between the *in situ* turbidity and the SSC of water samples were either linear or were transformed with a natural-log function to make the relationship more linear (Figure 35). For all of the relationships except one the strength of the correlations (r^2) between *in situ* turbidity and SSC improved for the storm-specific relationship compared to the annual relationship between *in situ* turbidity and SSC (Table 4). The *in situ* turbidity data for South Fork Hinkle Creek were highly variable during the largest peak flows of the year (Figure 17). The total annual sediment load estimated with the annual relationship between *in situ* turbidity and SSC was more than double the estimate of total annual sediment load made with the storm specific relationships.

Results from Oak and South Fork Hinkle Creeks were different for the use of annual versus storm-specific *in situ* turbidity/SSC relationships to estimate total annual sediment load. For Oak Creek the estimate of total annual sediment load was slightly larger (17 percent) for the storm specific relationships. For South Fork Hinkle Creek, the estimate of total annual sediment load was quite a bit smaller (53 percent). It is unclear why this difference exists. Oak Creek had more data (294 samples) and the data were much better behaved. For South Fork Hinkle Creek there was less data (138 samples) and the data was highly variable and poorly behaved.

One problem with storm-specific data is that it is routine for the range of *in situ* turbidity values for a storm to be larger than the range for the SSC data. Thus, a storm-specific relationship will almost always be required to extrapolate beyond its range. This is less of a problem if an annual relationship is used. In the absence of high quality and robust data it is probably best to stay with an annual relationship between *in situ* turbidity and SSC. If there is a critical mass of high quality data then perhaps breaking the data into storms will work.

5.4 RELEVANCE TO HYDROLOGIC STUDIES

Forest road construction and timber harvest can alter sediment loads as a result of hydrologic changes and with accelerated erosion and sediment transport (Beschta, 1978; Lewis, 1998; Troendle and King, 1985). Forest watershed studies are designed to help us identify how to reduce negative impacts that result from forest practices. Recently, hydrologic studies have used *in situ* turbidity as a surrogate for SSC. Several studies were initiated in the western United States to evaluate contemporary management practices and harvesting techniques. Hinkle Creek, Trask, Mica Creek, and the Alsea Revisited watershed studies use *in situ* turbidity monitoring coupled with water samples. Annual sediment loads are compared before and after treatments, or a comparison is made between harvested and un-harvested basins.

Preliminary results from Mica Creek show that no significant increases in sediment load were detected in harvested catchments compared with the control watersheds (Karwan *et al*., 2007). Similar to South Fork Hinkle Creek, sediment loads were calculated at 30-minute time intervals using *in situ* turbidity as a surrogate for SSC. Sediment loads were aggregated monthly and annually. There is no mention of the type of relationship between *in situ* turbidity and SSC used to estimate sediment load. There is also no mention of *in situ* turbidity adjustment, or discussion of erroneous observations.

Results from the South Fork Hinkle Creek analysis show that estimated sediment loads depend on the relationship between *in situ* turbidity and SSC that is used (Figures 49 and 50). The estimate of the annual sediment load for South Fork Hinkle Creek with an annual relationship between *in situ* turbidity and SSC is more than twice estimate of annual sediment load made with storm specific relationships. The methods used to estimate sediment load should also be clearly stated, since analysis methods can lead to different estimates of sediment load estimates.

It is important to be consistent when relationships are developed to estimate sediment load for streams when these sediment loads are going to be compared. At

South Fork Hinkle Creek, the estimated annual sediment load varied and depended on how the sediment load was calculated. If a comparison of sediment loads from two streams is made these results show that detecting a difference in sediment load due to land management can be a function of the sediment load estimation technique and not land management. Care needs to be made when estimating stream sediment loads at research study sites, especially since results help evaluate and determine best management practices, as well as land management regulation.

6. CONCLUSION

Total annual sediment loads were estimated for two watersheds, Oak Creek and South Fork Hinkle Creek, for the 2006 water year. The sediment loads were estimated using real time *in situ* turbidity as a surrogate for SSC. *In situ* turbidity data can be highly variable and tools have been developed to help edit sets of turbidity data that have erroneous values. For this project, two tools were used to edit *in situ* turbidity records; a top down TTS-adjuster and a bottom up TTM-adjuster. The TTS-adjuster can edit data manually, one record at a time. The TTM-adjuster is a macro that can edit data automatically. This project evaluated the efficacy of these two *in situ* turbidity adjusters. This project also looked at the efficacy of different relationships between *in situ* turbidity and SSC; a total annual relationship and storm-specific relationships.

The TTM method for adjusting *in situ* turbidity records was useful to remove spikes of *in situ* turbidity. In the case of Oak Creek, the TTM-adjuster worked satisfactorily. However, in the case of South Fork Hinkle Creek, the TTM-adjuster did not work as well. For neither stream was the TTM-adjuster able to recreate the record that resulted from the TTS-adjuster. A TTM-adjuster appears to be able to work well but it would be best used in conjunction with a final adjustment using the TTS-adjuster. Thus, a hybrid approach that uses the strengths of both approaches might be the best approach. The TTM-adjuster as presented in this thesis is not a finished product. No method was developed to calibrate a data set to a TTM threshold value. Thus, while a bottom-up, TTM-adjuster program to edit and adjust records of *in situ* turbidity appears to be viable, the details of the method are not perfected and it remains a work in progress.

Both annual and storm-specific relationships between *in situ* turbidity and SSC can be used to estimate sediment loads in streams. The record of success for these two methods depended on the stream. Oak Creek had a lot of samples (294) and the data was well-behaved. For that stream both approaches seemed to work well. However, South Fork Hinkle Creek had fewer samples (138) and the data was not as well behaved. It is probably best to use annual relationships when data is sparse or poorly behaved. Also, annual data alleviates the problem, to a degree, of extrapolating beyond the range of data that could be a problem for storm-specific relationships.

In situ turbidity values are a proven surrogate to use to predict sediment loads in streams. However, *in situ* turbidity data can be highly variable and erratic. Automated methods to edit *in situ* turbidity records are a viable way to reduce the time and effort needed to edit highly variable *in situ* turbidity data. While the method shows promise it is not perfected yet. Research should continue to work on this problem.

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