DANIEL LAWRENCE CALHOUN
In Situ Monitoring of Suspended Sediments: Development of a Densimetric Instrument
(Under the direction of TODD C. RASMUSSEN)

Sampling methods for determining sediment concentrations can be labor intensive and may not provide sufficient temporal density during stormflow events. Optical and Doppler methods can provide necessary temporal density, but may not be representative of the water column, or of the heterogeneity of the transported material. We present a real-time densimetric technique that meets both the temporal and depth-integration needs of sediment sampling. Fluid density is determined using a precision differential pressure transducer that measures the fluid pressure change between two fixed depths. While small temporal variations in fluid density are induced by changes in temperature and dissolved solids and gasses, much larger variations are induced by suspended materials, primarily mineral sediments with densities greater than water. Laboratory and *in situ* tests demonstrate the principles involved, as well as the utility of the technique. Applications on tributaries to the South Fork of the Broad River in northeast Georgia, USA, show that stormflow suspended sediment concentrations obtained using the densimetric sensor vary with but lack conclusive correlation to depth-integrated observations. We also monitor bedload sediment transport by placing the sensor in a position that tracks fluid density changes in the mobile bed zone. Both suspended sediment and bedload concentrations are coupled with velocity and stage measurements to provide for the potential of real-time measurements of total sediment flux. A densimetric device to provide real-time *in situ* particle-size distributions is another possible application.

INDEX WORDS: Continuous monitoring, Densimeter, Differential pressure transducer, Fluid pressure, *In situ* monitoring, Sediment, Sediment concentration, SSC, Suspended sediment, TMDL, Total suspended solids, TSS, Turbidimeter, Turbidity

IN SITU MONITORING OF SUSPENDED SEDIMENTS:

DEVELOPMENT OF A DENSIMETRIC INSTRUMENT

by

DANIEL LAWRENCE CALHOUN

B.S., Tulane University, 1991

A Thesis Submitted to the Graduate Faculty

of The University of Georgia in Partial Fulfillment

of the

Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2000

IN SITU MONITORING OF SUSPENDED SEDIMENTS:

DEVELOPMENT OF A DENSIMETRIC INSTRUMENT

by

DANIEL LAWRENCE CALHOUN

Approved:

Major Professor: Todd C. Rasmussen

Committee: C. Rhett Jackson
Steven C. McCutcheon
Matthew C. Smith

Electronic Version Approved:

Gordhan L. Patel
Dean of the Graduate School
The University of Georgia
May 2000

DEDICATION

To my parents, Dupre and Manella Calhoun, who have always given me the freedom and support to search this world for my place in it while demonstrating to me that this search can be done thoughtfully and with purpose.

To my petunia, Liesel Potthast, for the last two years of putting up with storm chasing and too many road miles, for never tiring of listening to me blather about hydrology, and for the promise of a future with someone who challenges my being to see the importance of an adventurous, effective and quality life.

To Bill Hilton, Jr. who guided and inspired my early education in the physical and natural sciences, planting a seed that took years to germinate and showing me that you don't have to allow others' view of yourself to steer you away from a true course. I just wish it hadn't taken so long to figure that out.

To "Murphy," though we have never met, I feel like I know your struggles well.

"...the river is everywhere at the same time, at the source and at the mouth, at the waterfall, at the ferry, at the current, in the ocean and in the mountains, everywhere, and that the present only exists for it, not the shadow of the past, nor the shadow of the future..."
Herman Hesse, *Siddhartha*

ACKNOWLEDGMENTS

I cannot fully express my gratitude to Todd Rasmussen for being a living illustration to me of what science and being a scientist can be. If I can capture a fragment of his applied inquisitiveness and constant questioning of the accepted, I will have accomplished something in this life. I have also been delighted to have been mentored and challenged by Rhett Jackson who continually provides his time to students in need of inspiration, academic guidance and the occasional break from the daily grind. Through serving on my committee, Dr. Matthew C. Smith and Dr. Steven C. McCutcheon provided extensive review and corrections for this thesis and I am greatly indebted to them. I look forward to seeing the products of your future work in water resources.

Thanks is extended to Dr. Bruce Beck of the Warnell School of Forest Resources and to the Georgia Research Alliance (GRA) which provided the funding for the equipment purchases used for this research. Backing and research support was also provided by Dr. Earl Hayter and Mr. Robert Carousel of the U.S. Environmental Protection Agency (USEPA / NERL / ERD). A third cooperative source was the United States Geological Survey (USGS) which extended support for the later stages of the field work and analysis through the Water Resources Research Program as a part of a larger project to characterize sediment transport in the Georgia Piedmont.

I would like to express my indebtedness to the members of the ACF-NAWQA group of the USGS in Atlanta, GA: Dan Hippe, Betsy Frick, Dave Wangness, Gary Buell, Evelyn Hopkins, Andy Hickey, Brian Gregory, and Gary Holloway for shaping my time at the USGS and my future career.

A special thanks is extended to individuals at the Warnell School of Forest Resources at UGA without whose assistance this work would not have been possible. Individuals of note are Jenny Yearwood, Rosemary Wood, Doris Lord, Chris Miller, and Bo Lawler of the WSFR staff. I send a resounding whoopie to my compatriots in the WSFR Water Resources Group, especially Agent Chris Decker, Jason Ward, and Kirk Martin for continual entertainment, moral support and sweating it out in the field with me. I wish you guys the best of luck in finishing your work and I look forward to working with you in the future. Remember that it is important to bridge the gaps between groups in our field. I have depended on the resourcefulness of the staff at the UGA instrument shop for many projects associated with this work. I would like to extend credit to my brother, Christopher A. Calhoun, for his graphical expertise and constant prodding along the way to ensure completion of this work. Finally, Michael Entrekin and Drummond Sharp had a wonderful knack of showing up in Athens at the right time and bringing with them a twenty year friendship.

TABLE OF CONTENTS

ACKNOWLEDGMENTS . . . v

LIST OF TABLES . . . ix

LIST OF FIGURES . . . x

1. INTRODUCTION . . . 1

1.1. Objectives . . . 2

1.2. Motivation . . . 3

2. LITERATURE REVIEW . . . 6

2.1. Effects of Stream Sediments . . . 6

2.2. Existing Suspended Sediment Monitoring Techniques . . . 8

2.3. Previous Studies Utilizing a Densimetric Method . . . 12

2.3.1. Oscillating U-tube . . . 12

2.3.2. Pressure measurements for bedload transport . . . 13

2.3.3 Pressure measurements for suspended sediment . . . 14

3. LABORATORY TESTS . . . 19

3.1. Design . . . 19

3.2. Results . . . 19

3.3 Conclusions . . . 21

4. FIELD EXPERIMENTS . . . 22

4.1. Site Description . . . 22

4.2. Installation Description . . . 22

4.3. Results . . . 24

4.4. Conclusions . . . 28

5. EQUIPMENT COSTS 29

6. CONCLUSIONS 30

7. RECOMMENDATIONS 32

REFERENCES 33

APPENDICES 70

LIST OF TABLES

Table Page

1. Sample datalogger program for laboratory applications 67

2. Sample datalogger program for field applications 68

LIST OF FIGURES

Figure Page

2.1 Sources of error in the velocity component of fluid density 38

3.1 Schematic of the proposed densimeter applications 39

3.2 Laboratory arrangement of the densimeter 40

3.3 Densimetric response to 0.3 grams of 360 μm beads 41

3.4 Densimetric response to 1.0 grams of 360 μm beads 42

3.5 Densimetric response to 10 grams of 360 μm beads 43

3.6 The relationship between the derived and expected concentrations 44

3.7 Densimetric response to 50 grams of 360 μm beads 45

4.1 Field placement at Brushy Creek 46

4.2 Densimetric response to the 9/20/1999 storm 47

4.3 Stream temperature response to the 9/20/1999 storm 48

4.4 Specific conductance response to the 9/20/1999 storm 49

4.5 Flow velocity response to the 9/20/1999 storm 50

4.6 The relationship between manual samples and the densimetric response 51

4.7 Densimetric response to the 1/10/2000 52

4.8 Stream temperature response to the 1/10/2000 53

4.9 Specific conductance response to the 1/10/2000 54

4.10 Flow velocity response to the 1/10/2000 55

4.11 Densimetric record from December 1999 to April 2000 56

4.12 Stream temperature record from December 1999 to April 2000 57

4.13 Stream conductance record from December 1999 to April 2000 58

4.14 Flow velocity record from December 1999 to April 2000 59
4.15 Densimetric response to the March 2000 event 60
4.16 Stream temperature response to the March 2000 event 61
4.17 Stream conductance to the March 2000 event 62
4.18 Flow velocity to the March 2000 event 63
4.19 Densimetric record at Clouds Creek from February 2000 to April 2000 64
4.20 Stream temperature record at Clouds Creek from February 2000 to April 2000 65
4.21 Stream conductance record at Clouds Creek from February 2000 to April 2000 66

1. INTRODUCTION

Erosion, sediment transport, and sediment deposition in freshwater and saltwater aquatic systems have been studied worldwide. There is growing evidence that research must continue in many disciplines before these processes can be effectively understood. The earliest quantitative contributions were made in the nineteenth century by Navier (1822), Saint-Venant (1843), Stokes (1845), Dupuit (1848), Mulvaney (1851), Lechlas (1871), and Duboys (1879) (dates of fundamental works in parenthesis). These researchers investigated the physical characteristics of viscous flow, sediment transport and relations to hydraulics establishing the theoretical foundations of the science (Rouse and Ince, 1957). Early studies were followed by findings from within the engineering field by researchers such as H.A. Einstein. Einstein (1971) played a pivotal role by introducing theories stating that stream equilibrium is a complex interaction between sediment supply, stream discharge, streambank stability and bed sediment properties such as particle size and sorting.

The difficulty in quantifying the sediment volumes transported through natural systems has always impeded understanding of sediment. Sampling and analytical techniques including computer technology are only recently being able to further propel the science from the theoretical to the applied (Wolman, 1977; White, 1998). Much of what Wolman (1977) states about the research needs in the field of fluvial sediment could be repeated today, however some of this should be achieved through the dissemination and application of existing knowledge (Yang, 1977). The present study advances a new method for monitoring suspended sediments in fluvial systems that addresses limitations in existing techniques. Many of the concerns and challenges that are expressed by contemporary sediment researchers is discussed and it is concluded that after further design and analytic modifications, the described technique would be a viable alternative to methods that are currently relied upon.

1.1. Objectives

The primary goal of this thesis is to determine the effectiveness of a densimetric method for monitoring sediment concentration in a field setting. The instrument determines a change in the fluid density across a known vertical distance in the water column. The material flowing through water that changes the density of the column is the total suspended solids (TSS), however this term is often associated with wastewater facilities because of the high concentrations of organic material found in various processes of treatment. Because organic material has nearly the same density as the water that transports it and its overall concentration should be negligible in relation to the inorganic material in the fluvial systems studied, the instrument should not be measurably affected by the material. An assessment of the ability of this instrument to measure high concentrations of organic rich sediments was not possible for this study. Therefore, for the purposes of this research, the measured parameter attributed to this instrument will be referred to as suspended sediment concentration (SSC and C_s) or total sediment concentration (TSC). In order for this instrument to be useful for resource management, the goal was to achieve the 10-milligram per liter accuracy of suspended sediment determination established by earlier laboratory trials (Lewis and Rasmussen, 1999).

A secondary goal is to evaluate the cost that it takes to build the instrument to determine if the application tested in this study will be economically justifiable and available to a sufficient range of potential users. A tertiary goal of this research is to explore alternative designs for additional applications of these densimetric measurements. Stream sampling for suspended sediment will be the initial application, but measurements of organic-rich sediment in wastewater treatment plants, wetlands, lakes and coastal waters is a long term goal. Analyses of sediment particle sizes and of water levels deep in groundwater wells where errors are commonly made based on density effects have also been envisioned. Variations of densimetric monitoring for these additional applications will require alterations in the instrument design and outside of the bounds of this study from other than a theoretical review.

This research is being conducted in partnership with the Environmental Protection Agency (EPA) National Exposure Research Laboratory (NERL). The NERL will use the results of this study to assist in the data collection for testing computer models to be used in TMDL protocols, including unit stream power methods. The intention of this modeling effort is to provide the ability to predict the non-point source pollution resulting from land use in a particular watershed.

1.2. Motivation

Early understandings of the physical properties of sediment transport and deposition occurred simultaneously with the realization that sediment loading in natural systems is altered by human activity. This understanding has been furthered by the finding that natural geomorphic processes resulting from geologic activity also play an important role in limiting the human and biological utilization of waterways. Stream alterations resulting from human activities such as reservoir construction and land use change in a watershed are seen as important antecedents to an ultimate change in the profile of a given stream reach or segment (Einstein, 1971). In recent decades, advances in stream ecology have shown that stream alterations have measurable effects on the biological integrity of streams (Waters, 1995). That stream alterations have been occurring for some time became apparent as major shifts in species composition were followed by the extinction of some aquatic species.

Modifications to traditional agricultural and silvicultural practices, as well as in patterns of urbanization, are certain to be required if the biotic integrity of landscapes and waterways are to be maintained. This need for improved management can be noted through lawsuits brought by interests within 34 U.S. states (as of August 1999) (USEPA TMDL website, http://www.epa.gov/owow/tmdl/tptmdl2.html). These lawsuits are based on the failure of the Environmental Protection Agency to enforce the Total Maximum Daily Load (TMDL) requirements of the Clean Water Act. The Act states that a maximum allowable limit per-day of non-point source pollutant loads, such as sediments, must be established for the impaired waters of the U.S. This law was enacted to protect the waters of the U.S. from pollution that would render these waters unsuitable for aquatic habitat and for human use.

Compliance with and enforcement of existing laws are predicted to increase in the future (Patterson and others, 1993). However, a consistent and more affordable method for the quantifying of suspended sediment concentration (SSC) or of the bedload sediment concentration in a water body, such as a stream, appears absent from ongoing research and development of cost-effective measurement techniques. Consequently, little success is being achieved in the accurate monitoring of total sediment movement through impaired fluvial systems.

In the effort to complete TMDL assessments for the multitude of sediment (and associated pollutant) impaired stream segments, a reliance on sediment rating curves is expected. This practice has been shown to be problematic from a predictive standpoint for a host of reasons and the extension of these curves to characterize unmeasured or streams out of the characterized basin may be even less justifiable (Walling, 1977; Stevens and Yang, 1989; Campbell and Doeg, 1989). The successful extension of these and other strategies, such as more frequent water sampling, to pollutant load estimates can be highly varied based on the scale of the system studied. Statistically, however, characterizing large basins that respond more slowly to changing flow conditions is simpler (Phillips and others, 1999). Early reports of success with sediment rating curves to calculate loads are tempered with the later findings that serious departures from established flow relationships occur during seasonal and annual fluctuations of runoff and must be adjusted for through the use of high quality data and through utilizing periodic rather than single curves for a given site (Miller, 1951; Walling, 1977).

Attempts have been made to statistically justify the use of empirical load estimations through taking into account more of the variability that exists in natural systems (Cohn and others, 1989). However, mechanistic approaches to the problem of sediment load estimation may hold more promise than regressions (Stevens and Yang, 1989). Many mechanistic equations exist, however many of these have not been fully validated within multiple settings. One approach that has been widely validated is the use of unit stream power or the product of the energy slope and the flow velocity, derived from the second law of thermodynamics. Along with associated sediment and hydraulic properties, unit stream power has proved effective in estimating total sediment discharge (Yang, 1973; Yang, 1978). Until a universal principle is fully derived for all applications in the study of sediment in water bodies, the use of reliable semi-empirical methodologies will be required for the full assessments that are presently mandated under the Clean Water Act. To ensure that the fundamental and semi-empirical methods are fully tested on scales ranging from catchments to river basins in differing physiographic regions with a variety of land disturbances, much more intense sediment monitoring techniques are required.

Except for a few creeks and streams with originally applied names such as Yellow or Red, anecdotal evidence describing the lack of sediment in streams of the early eighteenth century in the Eastern United States indicates that the sediment in these streams today is predominately the result of European settlement (Trimble, 1974). Further analysis by Trimble (1974) determined that since European settlement, an average of eight inches of topsoil was introduced to the streams of the southeastern United States. More recently, researchers have estimated that modern annual sediment inputs into U.S. streams total 400 million tons (Connelly and Lin, 1996). The damage to agriculture from this loss has been estimated to cost the United States $44 billion per year and nearly $400 billion per year world wide (Glanz, 1995). This does not include the cost of mitigating sediments once they have entered fluvial systems as these costs are only recently being realized when the full uses of fluvial systems by humans and biota are factored into the equation.

2. LITERATURE REVIEW

2.1. Effects of Stream Sediments

Alterations within a watershed can both introduce and exclude sediment from streams. The occurrence of these changes have a wide range of effects on aquatic systems, all of which are not clearly understood, readily quantifiable or necessarily deleterious to all stream biota. That a majority of the sediment which enters a stream does so during a few heavy precipitation events in a given season or year is generally agreed upon (Campbell and Doeg, 1989; Waters, 1995).

The sands and finer sized particles of this sediment, primarily resulting from the runoff from land disturbed by such activities as road building, silviculture, widespread burning, or urbanization within a watershed, settles over and within the larger substrate of stream beds (Beschta, 1978). Sediments deposited after relatively short periods of suspension may have long-term effects on aquatic communities and may continue to cause adverse effects long after land disturbance has ceased (Waters, 1995). A large portion of the macroinvertebrate community in a stream requires the interstitial spaces of the stream bed (the hyporheos) for locomotion, shelter from high velocity flow, and habitat during low flows. Sediment deposition, therefore, appears to cause declines in biomass and species diversity as well as shifts in the species composition of the benthos through replacement, drift, and/or localized extinction (Campbell and Doeg, 1989; Waters, 1995). However, some aquatic species are well adapted to an abundant sediment supply and require geomorphic fluctuations as well as a lack of substrate.

Fish communities are also disturbed by sediment that is deposited on the streambed. In addition to the obvious reduction in available food sources due to a collapsing or shifting macroinvertebrate community, the ability of hyporheic spawning fish to spawn in substrates which have been filled by fine sediment can be greatly compromised (Campbell and Doeg, 1989; Wood and Armitage, 1997). The fish communities of the Southern Appalachians of the U.S. are almost entirely comprised of benthic spawning fishes (Burkhead and others, 1995).

Suspended sediments also degrade the respiration and feeding ability of stream biota (Campbell and Doeg, 1989). High levels of suspended sediments heavily impact filter-feeding invertebrates (Haefner and Wallace, 1981) and organisms that rely on photosynthesis (Faye and others, 1980). Fish communities are disturbed in the short term by suspended sediments as evidenced by an alteration in behavioral patterns through simply avoiding an impacted stream reach (Waters, 1995). Scour of the streambed transports relatively high concentrations of sediment, redepositing that sediment further downstream. The occurrence of scour becomes more regular when a watershed has been disturbed and the peak flows in response to given storms become greater, resulting in geomorphic work (Dunne and Leopold, 1978). Consequently, recolonization by aquatic fauna will only occur when the reach recovers as a food source and habitat (Tebo 1955).

Stream sediments have also carry contaminants from industrial and agricultural sources (Faye and others, 1980; Leigh, 1997; Balogh and others, 1997). Various nutrients, pesticides, and heavy metals sorb to sediments in streams and are transported through the system, controlled by the hydrologic forces of the stream, the characteristics of the sediments, and the partitioning of the contaminants. These contaminants tend to build up over time and slowly diffuse into the overlying water long after sources may have been controlled (Faye and others, 1980; Baylock and others, 1997; Gagnon and Fisher, 1997; Kronvang, et al, 1997; Lick and others, 1997). Health hazards to both humans and fauna in a particular water body result.

Sediment in water bodies is responsible for costly repairs and maintenance of many water resource related businesses (Faye and others, 1980; Lewis and Rasmussen, 1996). Sediment transported through river systems is deposited upon entering the placid waters of a reservoir or aqueduct, eventually filling it. Worldwide, water-related public works projects, such as reservoirs and aqueducts, will require a lessening of the present load of sediment inputs. This control is essential to prevent large expenditures of public money for the maintenance of storage and power generating capacities. Likewise, sediment must be removed during the treatment of water for human consumption adding to the cost of municipal water supplies. Damage from flooding is exacerbated by the increased elevation of streambeds through sedimentation (Connelly and Lin, 1996). Wastewater treatment processes that rely on biological methods can also be perturbed by urban storm water runoff. These perturbations can cause the release of waste solids into surface waters resulting in costly violations of clean water laws. Only effective in-plant monitoring within settling basins can detect these solids prior to outflows to surface waters.

2.2. Existing Suspended Sediment Monitoring Techniques

Accurate monitoring of the sediment in streams is a difficult process. A universally accepted method has not been devised that can continuously monitor *in situ* concentrations of suspended sediment. New monitoring methodologies that have a relatively low cost, the ability to operate continuously at remote locations, and the ability to differentiate transported inorganic sediments from organic sediments are urgently needed. These methods must also take into account as much of the spatial variability of the water body as is possible. The ability to continuously measure suspended sediment correlated to total sediment load measurements should be more accurate than flow regressions (Lewis, 1996). Multiple procedures presently exist for the monitoring and estimation of sediment in water, however, all have significant shortcomings. Timing is essential in regard to the accurate characterization of a storm or transport event, and many approaches are limited by the requirement that a researcher must be present and remain at the site during the storm or transport event.

Grab, point, and depth-integrated samples are obtained by physically collecting a sample of water in the stream (Guy, 1970a). The samples can be filtered, dried and then the filtrate is weighed and a concentration is determined based on the original water sample volume. An alternate method of this type would be to evaporate the sample and have the weights of the original sample container, the weight of the sample and container, and the weight after evaporation and drying. These techniques are time-consuming and costly (Skinner and Beverage, 1982) and the original sampling must be timed to coincide with the hydrologic events during which sediment entrainment is to be expected. Increases in sediment concentration due to storm run-off events can occur prior to the peak stage or discharge at a given point. The peak suspended sediment concentration occurs prior to the peak discharge in a majority of small streams draining small watersheds with "uniform precipitation excess" (Guy, 1970b). This early flush has been attributed to material that was left on the banks from previous events being picked up by the rising stage (Eisma, 1993). Automated grab sampling must be timed to coincide with the changing patterns of sediment concentration in these situations and samples must still be returned to a laboratory for analysis, thus limiting the number and frequency of samples that can be collected and analyzed, making it highly likely that infrequent but significant events will be missed or incompletely monitored. Sediment load calculations based on such incomplete sampling strategies would clearly be imprecise and inaccurate.

The *in situ* measurement of suspended sediment involves the placement of a device in a water body that provides continuous estimates of sediment through various techniques. The ability to set the time span of the measurement is user dependent. Instruments must be placed in such a way that they are not influenced by sediment sources that are consistently out of scale with what is indicative of the water body. The major challenges of utilizing *in situ* devices are the need to properly calibrate instrument responses with sediment values present across a cross-section as well as to keep the device free of debris and of biological growth on the instrument that may influence the output (Lewis, 1996; Buchanan and Schoellhamer, 1996). Eddy effects, commonly found in rivers and streams, will disrupt the readings of *in situ* devices by causing reverse flow of sediment laden water, not representative of the stream at the time of that flow (Buchanan and Schoellhamer, 1996) making initial siting and placement of the instruments critical.

The turbidity meter (or turbidimeter) utilizes the scattering of light by sediment across a water sample to determine the optical clarity of the water that passes within the view of the sensor and can be used *in situ* or in the laboratory. The turbidity method is widely relied upon as an estimate of suspended sediment using site specific relationships with filtered water measurements taken either by hand or through the automated sampler. However, both physically obtaining water samples (unless spatially well integrated) and using turbidity measurements often mistakenly assume that a spatial homogeneity exists in the concentration and density of sediment in a given sample across the water body of interest. Observations clearly show that this assumption is not valid as highly varied concentrations of sediment and sediment associated constituents can move through a stream cross-section (Eisma, 1993; Horowitz, 1997; Riley, 1998). At-a-point grab samples and uncorrelated continuous techniques can grossly underestimate high-flow transport, even though reasonable estimates of the dissolved constituents are possible for a cross-section (Martin, Smoot and White, 1992).

Unfortunately, the observational window of the majority of turbidity meters is never larger than several centimeters. This intensifies the need for calibration that covers the spatial heterogeneity of a given cross-section. Furthermore, organic particles within the observational window can show the same or higher optical scatter as grains of sand and clay when measured by a turbidity meter (Gippel, 1995). The linear response of turbidimeters to sediment concentration has also been shown to be highly sensitive to changes in the particle sizes in suspension (Gippel, 1995; Lewis, 1996) and to changes in water color due to dissolved constituents (Gippel, 1995). As a result, a misapplied estimation of suspended sediment in the water body can occur. Turbidity meters are also limited by the fact that the range of measurement is often well below the actual sediment concentration commonly found in streams during high flow conditions. High values can be missed entirely when these sensors are used *in situ*.

When used in the lab, turbidity meters can quantify the high values through dilution of the original sample and subsequent measurement, however this process is not practical in the field. Turbidity values of surface waters are also used to correlate with satellite imagery to estimate the sediment loads in water bodies remotely (Harrington, 1992). Planning and resource management decisions are increasingly based on these findings. It is essential that sound representative data be used during this process.

Effective use of *in situ* turbidimeters has been demonstrated. The optical backscatter sensor (OBS) uses an altered beam angle and an increased observational window in comparison to other turbidity technologies (Buchanan and Schoellhamer (USGS), 1996; Lewis (USFS), 1996). The U.S. Geological Survey (USGS) and U.S. Forest Service (USFS) are the leading developers of the technology. The USGS and USFS results are highly correlated with the sediment concentrations of water samples taken for calibration purposes providing the continuous monitoring of suspended sediment concentration and sediment load estimations. The use of turbidity meters to trigger the automated pumped sampling of stormwater was also a significant achievement. However, these projects have taken place in fluvial systems with a fairly homogenous particle size. The USGS and the USFS work are models for the application of these methods based on installation procedures and data interpretation that should always be reviewed when this type of monitoring is being considered.

Yet another method using signal scatter to estimate suspended sediment utilizes Doppler radar. This technology was initially used to measure flow velocities at-a-point and over multiple profiles. However, observations show that the Doppler shifted backscatter of both cohesive and noncohesive sediment can be detected and correlated to suspended sediment measurements (Thorne and Hardcastle, 1997; Hamilton and others, 1998; Holdaway and others, 1999). Contradictory results indicate that some researchers are satisfied with the ability of this technology to estimate continuous sediment concentrations and others have concluded that for reasons of overall accuracy and reliability, use of this method is almost wholly inappropriate for this application (Reichel and Nachtnebel, 1994). Widespread continuous monitoring with Doppler technology will only be possible with a decrease in cost and the experimental validation of this method in diverse settings.

Many other techniques exist for determining sediment concentrations (White, 1998). However, none of the other methods address all of the factors that can cause spurious and unreliable estimates. Reducing some of these factors that can make *in situ* measurements difficult or inappropriate will provide resource managers invaluable data. A scientifically valid process for the measurement of SSC that accounts for limitations in existing methods would not only add to the accurate estimation of environmental pollutants in streams, but also to the effectiveness of present and future watershed management strategies.

2.3. Previous Studies Utilizing a Densimetric Method

Variations in fluid density result from changes in temperature along with changes in dissolved and suspended solids concentrations (Skinner and Beverage, 1982; Lewis and Rasmussen, 1999). Because methods are available that account for thermal variations and dissolved solids concentrations in water, the residual effects of suspended sediment concentrations (SSC) in a column of water can be detected (Lewis and Rasmussen, 1996; Lewis and Rasmussen, 1999).

2.3.1. Oscillating U-tube

Early work in the analysis of suspended sediment concentrations through changes in fluid density was conducted by the Federal Interagency Sedimentation Project (FISP) (Skinner and Beverage, 1982). SSC was measured through the use of a cantilevered vibrating U-tube where the vibrational or oscillatory period of the U-tube increased when the density of the fluid that was passed through the tube increased. The research was conducted in a laboratory setting although many field conditions were simulated. Clay concentrations in excess of 500 $mg{\cdot}L^{-1}$ were detected to an accuracy of three percent and coarser sands to twelve percent. Below 500 $mg{\cdot}L^{-1}$, standard errors of estimate were 15 $mg{\cdot}L^{-1}$ and 25 $mg{\cdot}L^{-1}$ for clay and sand. Sediment concentrations up to 97,000 $mg{\cdot}L^{-1}$ were tested.

Skinner and Beverage (1982) concluded that organic material would not result in a measurable densimetric response because of its close similarity to the density of water.

Challenges identified by the project included the need to monitor and correct for changes in fluid temperature (1 °C amounted to a change in the measured response of 160 $mg \cdot L^{-1}$). At temperatures less than 9 °C, the instrument did not function, presumed by the researchers to be the result of condensation on the outside of the tube, altering the oscillatory period. Air bubbles had to be removed by deaeration and the pumped flow rate of the fluid had to be tightly regulated to accurately estimate the volume of water involved. Significant instrument drift was encountered from sediment and biologic material adhering to the inside of tube creating an increasing apparent concentration and necessitating regular cleaning.

2.3.2. Pressure Measurements of Bedload Sediment

Early work using pressure measurements to estimate bedload sediment transport utilized the Birkbeck pit sampler in 1980 (Lewis, 1991). The first affordable method to provide a continuous record of total sediment load with this device used water filled pressure pillows placed at the bottom of a small pit excavated in a streambed. Lewis (1991) modified the design by using a differential pressure transducer connected to a sealed pressure pillow and using a stilling well as a reference column. Difficulties with the method included air entering the system under negative pressure as a result of the transducer being placed above the water surface, ruptured pillows, overpressure damaging the transducer membrane, problems maintaining instrument calibrations, temperature effects on the ambient water density, and removing the sediment that filled the pits during storms. The method of relating the voltage output of the transducer to a mass of sediment was not provided in the report. The challenges posed by the method were deemed insurmountable and the experiment was altered to use a load cell, similar to a weighing lysimeter to accomplish the goal of obtaining a continuous record of bedload transport. The challenges associated with the differential transducers were removed except for the need to remove the sediment during and between storms. An elaborate technique to accomplish this was devised and put into practice. The researchers reported that the method was a viable alternative to much more expensive techniques for the measurement of bedload transport, however work would be required to assess and improve the accuracy of the estimates obtained.

2.3.3. Pressure Measurements of suspended sediment

Lewis and Rasmussen (1996,1999) demonstrated the utility of a fluid density method to continuously monitor suspended sediment concentration. Their study focused on the temporal variations in measured fluid pressures that are attributable to factors that alter fluid density and total head. The technique involved measuring fluid pressure at multiple points a known distance apart within a water column. Changes in fluid pressure were related to changes in density.

As also shown by Lewis and Rasmussen (1999), the relationship between fluid density and the total suspended sediment concentration, SSC (kg·m^{-3}), can be derived from Bernoulli's equation. The total head of a fluid (H) is the sum of the elevation head (h_z), the pressure head (h_p), and the velocity head (h_v) (all in units of length).

$$H = h_z + h_p + h_v \tag{1}$$

The elevation head is equal to the elevation (z) above an arbitrary datum (z_o).

$$h_z = z - z_o \tag{2}$$

The pressure head is a function of the fluid pressure, p (in, hectopascals (hPa)), relative to a standard pressure (p_o) usually taken as atmospheric pressure, and the product of the fluid density, (ρ) (kg·m^{-3}) and the acceleration of gravity (g) (m·s^{-2}).

$$h_p = \frac{p - p_o}{\rho g} \tag{3}$$

The velocity head (h_v) is a function of the fluid velocity, (v) (m·s^{-1}), and the gravitational acceleration constant.

$$h_v = \frac{v^2}{2g} \tag{4}$$

Combining Equations (1 to 4) yields

$$H = (z - z_o) + \frac{p - p_o}{\rho g} + \frac{v^2}{2g} \tag{5}$$

The derivative of Equation (5) with respect to elevation (z) is

$$\frac{dH}{dz} = 1 + \frac{1}{\rho g} * \frac{dp}{dz} - \frac{p - p_o}{\rho^2 g} * \frac{d\rho}{dz} + \frac{v}{g} * \frac{dv}{dz} \tag{6}$$

By assuming uniform total head, velocity, and density with depth (i.e., dH/dz = dv/dz = d ρ /dz = 0), Equation (6) reduces to

$$\rho = -\frac{dp}{g\,dz} \tag{7a}$$

If uniform velocity is not assumed across the measured column, the velocity component of Bernoulli's Equation is retained in Equation (7a) as

$$\rho_e = \frac{dp}{g\,dz + \frac{d(v^2)}{2}} \tag{7b}$$

Where ρ_e is the effective density. Errors of estimation for the effective density in relation to a changing velocity over a given elevation would depend mainly on the change in the elevation term (dz) or the distance apart of the pressure measurement ports (Figure 3.1). The velocity differential would have to exceed 1 $m \cdot s^{-1}$ over the elevation span of 1 meter, 0.75 $m \cdot s^{-1}$ over 0.5 meters, and 0.25 $m \cdot s^{-1}$ over 0.10 meters to exceed an error of 5 % (Figure 2.1). This relation presents a predictable source of error for the field experiments that follow, however the velocity component will not be considered in the continued derivation.

Equation (7a) shows that the average fluid density can be obtained by measuring the pressure change with elevation. The relationship between fluid density ρ_f and the total suspended sediment concentration, C ($kg \cdot m^{-3}$) is

$$\rho_f = \frac{m}{V} = \frac{(m_s + m_w)}{V} = \frac{(\rho_s V_s + \rho_w V_w)}{V} \tag{8}$$

where: $m = m_s + m_w$ mass of sediments and clear water (kg)

$m_s = \rho_s V_s$ mass of suspended sediment (kg)

$m_w = \rho_w V_w$ mass of clear water (kg)

$V = V_s + V_w$ volume of sediments V_s and clear water V_w (m^3)

ρ_s and ρ_w sediment and clear water densities ($kg{\cdot}m^{-3}$).

Clear water refers to the fluid solution absent sediment, containing dissolved solids and gasses. Simplification of Equation (8) yields

$$\rho_f = \rho_w \frac{V_w}{V} + \rho_s \frac{V_s}{V} \tag{9}$$

$$\rho_f = \rho_w + C_v\left(\rho_s - \rho_w\right) \tag{10}$$

where $C_v = V_s / V$ is the volumetric concentration of suspended sediments ($m^3{\cdot}m^{-3}$). This is equivalent to

$$C_v = \frac{\rho_f - \rho_w}{\rho_s - \rho_w} \tag{11}$$

The mass concentration, $C_s = \rho_s C_v$ ($kg{\cdot}m^{-3}$), and the change in pressure with elevation given in Equation (7a) can be used to obtain

$$C_s = \frac{\dfrac{-dp}{g\,dz} - \rho_w}{1 - \dfrac{\rho_w}{\rho_s}} \tag{12}$$

In the laboratory (Lewis and Rasmussen, 1996 and Lewis and Rasmussen, 1999), sediment concentrations were determined to ninety-nine percent accuracy over the range of size classes studied. The size classes were estimated using equations derived from Stokes' Law. Particle sizes were determined with ninety-five percent accuracy for the lower size class analyzed. The larger size class determination was less accurate, this was attributed to possible limitations in the application of Stokes' Law. The authors identified the challenges likely to be faced under field conditions including temperature, velocity and particle density variability.

For a differential pressure transducer, Equation (12) can be tailored to fit the specific design. In the numerator, the density of water is eliminated based on the placement of the transducer and the use of a reference column of water. The sign of the remaining numerator becomes positive when the arbitrary datum z_o is placed lower than the reference point z. The remaining equation becomes

$$C_s = \frac{\frac{dp}{g\,dz}}{1 - \frac{\rho_w}{\rho_s}} \qquad (13)$$

The final modifications of Equation (13) involves a units conversion and an attribution of the individual properties of the instrument used and of the experimental conditions. The denominator of Equation (13) is dimensionless and is solved to a constant of 0.6226 when the density of clear water is taken as 1000 kg·m^{-3} and 2650 kg·m^{-3} is used for the density of sediment. In System International (SI), the gravitational constant is 9.8706 m·s^{-2}. To convert millivolts to the SI unit of pressure, hectopascals (hPa) is used to dimensionalize the differential pressure in Equation (13) *dp* to create the following relationship

$$dp = \beta_1\, dV + \beta_o \qquad (14)$$

where:

$$1psi = 5{,}000mV = 69hPa$$
$$\beta_1 = 0.014\ hPa / mV$$
$$\beta_o = offset$$
$$dV = sensor\ output(mV)$$

A 69 hPa (1 psi) range differential pressure transducer will be considered with a 0 to 5 volt sensitivity as well as an observational window (*dz*) of 1 meter. The output of the meter is in millivolts but the reported pressure range is 0 to 69 hPa (0 to 1 psi) over 5 volts. Inserting Equation (14) into (13) and applying the constants, as well as converting SI concentration to milligrams per liter, yields

$$C_s = 162.71(\beta_1\, dV + \beta_o) \tag{15}$$

The offset is a point at which a quiescent period is reached and where the suspended sediment concentration can be assumed to be at a minimum. The offset coefficient is also instrument dependent and, as was found in the field experiments that follow, temporally dependent as the baseline of the differential pressure output shifted considerably during the study period. Some of this drift may be temperature dependent, however this drift did not always seem to correspond to the drift in temperature. Regardless of the cause of the drift, this necessitates the resetting of the offset when analysis is performed on individual storm events or on the laboratory response of the densimeter.

3. LABORATORY TESTS

3.1. Design

The experimental design for this study focused on the control of factors that alter the fluid density of water. Laboratory trials were first conducted in which these factors were not present to evaluate the theoretical foundations of this study and of the particular instrument utilized. Figure 3.1 presents a schematic of the experimental design that defines some of the variables used in the previous section. Druck high accuracy differential pressure transducers of various pressure measurement ranges were tested. Swagelok stainless steel tubing and pipe fittings were attached to the transducers to create measuring points in the water column at set distances apart (See Appendices A and B for tools and parts used in construction). For the purposes of this investigation, the distances of fifty and one-hundred centimeters were chosen. The tubing is inserted into holes set fifty and one hundred centimeters apart along a four-inch diameter PVC pipe (Figure 3.2) and the apparatus is placed in a plexiglass box with an open top that is filled with deionized water. Glass spheres, of various diameters and concentrations, are dropped into the PVC pipe. The analysis presented in this report deals with the results of the 360-µm (average diameter, ± 60-µm) beads. The beads settling between the ports that are spaced 100-cm and 50-cm apart create an increased pressure that is measured by the differential pressure transducer and translated into an analog signal that is passed to a Campbell Scientific CR23X datalogger for storage and transferred to a desktop computer for analysis. A sample datalogger program is shown in Table 1.

3.2. Results

Results for the LPM 9381 model transducer demonstrate that a low range of pressure measurement (0 to 1.0 hPa (0 to 0.4 inches H_2O)) is useful for the target field conditions for suspended sediment concentrations. Figure 3.3 illustrates the pressure response derived from the addition of 0.3 grams of 360-μm beads. The response is in the negative direction because of the tubing connection; this was changed for the field application to produce a positive millivolt output with increasing fluid density. The sediment concentration, calculated from the mass of beads passing through the PVC tube volume that is between the two measurement points, is 38 $mg \cdot L^{-1}$ for the one-meter distance of observation. The minimum response of the instrument to the applied beads was used for interpretation because it was determined that this value was reliable (Figure 3.6). The equation used was the instrument specific version of Equation (13). The minimum pressure response translates to an observed concentration of 37.8 $mg \cdot L^{-1}$. The error associated with this measurement is 1 percent, based on the expected value. The time periods of the response also correspond to the published fall velocities of like-sized quartzite spheres (Chang, 1988). The fall velocity of 360-μm particles is reported to be between three and five centimeters per second. For a 30-cm water filled space above the first measuring point, this would average eight seconds. The particles were dropped after a ten-second delay and the response is apparent at 18 seconds. The one-meter distance would be covered in an average of 27 seconds, completing the passage of the particles through the observational window in 45 seconds. The sensitivity of the instrument to pressure variances and the instrument's overall sensitivity are both apparent in the instability of the readings.

Multiple tests have been conducted using the 1.0 hPa (0.4 inch) range transducer (Figures 3.4 and 3.5) and indicate that the optimal results are obtained between 10 $mg \cdot L^{-1}$ and 1,000 $mg \cdot L^{-1}$, for this particular sensor. Error analysis is presented for the two methods of signal interpretation (Figure 3.6). The minimum pressure reached was utilized as was the average value of the most stable minimum period within the response to determine which of the two obtained a more useful offset. The minimum response method appeared to return the more accurate estimate. The sampling error exceeds 15 percent when the concentration nears 1,000 $mg \cdot L^{-1}$ and when it drops to 10 $mg \cdot L^{-1}$. Parallel tests were also conducted over a 50-cm sampling distance and the results were similar, although by decreasing the length of the column, the sensitivity of the sensor to the applied beads is reduced by half.

Initial tests of differential transducers with a relatively large pressure measurement range indicate that at greater than 69 hPa (1 psi) the transducer is no longer able to differentiate the change in pressure attributable to added particles. Results for a 69 hPa (1 psi) differential transducer indicate that for bead concentrations greater than 1,000 mg·L^{-1}, a higher range transducer than the 1.0 hPa (0.4 inches H_2O) would be more useful. Figure 3.7 illustrates the pressure response to 50 grams of the 360-µm beads. The expected concentration was 6,400 mg·L^{-1} and the error based on the observed concentration was 2 percent.

3.3. Conclusions

These results indicate that the findings of the Lewis and Rasmussen (1999) study can be replicated with field ready devices. The error that has been observed would presumably be reduced through a refinement of the laboratory procedures. This would involve the application of deaeration methods to ensure that bubbles of air are excluded from within the device that would dampen the response of the transducer and magnify error. Also, methods should be implemented to ensure absolute seals in the fittings and tube connections. However, the purpose of this experiment is to develop this instrument for use in applied settings, thus reducing the ability to produce further results within the controlled setting. Particle size determinations were also beyond the scope of this study, however conducting them would not require considerable extra effort.

4. FIELD EXPERIMENTS

4.1. Site Description

The study site for the field trials is the South Fork of the Broad River watershed in Northeast Georgia, U.S.A. Three sites at different locations within the watershed have been chosen in conjunction with the EPA to test the densimeter. The present field sites are located in Brushy Creek at McCarty-Dodd Road and in the South Fork of the Broad River at State Highway 172. An additional site in Clouds Creek, a tributary to the South Fork of the Broad River within Watson's Mill State Park, has also been instrumented. Permissions for stream-side access have been obtained from landowners whose properties border the study sites as well as the Superintendent of the State Park.

4.2. Installation Description

The lab configuration of the densimeter was little modified for the field application, but as mentioned earlier, certain variables must be accounted for. The in-stream platform is constructed using an upright galvanized steel signpost bolted to an angled signpost, both driven into the bed approximately 1 to 1.5 meters (Figure 4.1). The densimeter is shielded by a 0.3 m (12 inch) diameter PVC pipe cut in half and bolted to the posts. Meters attached to the PVC shield and placed into and on the side of a slotted 0.05 m (2 inch) diameter PVC pipe monitor and record water velocity (Rocky Mountain Instruments, Inc.), stream stage (PDCR gage pressure transducers, Druck, Inc.) water temperature, and specific conductance (a surrogate for dissolved solids content) (Campbell Scientific, Inc.). Turbidity meters (Global Water, Inc.) are also installed within the pressure measuring points to provide for continuous readings. The cabling is run up the stream bank through a 0.05 m (2 inch) PVC pipe to an instrument shelter and CR23X datalogger equipped with a solar panel to charge the

12 V DC power supply (Campbell Scientific, Inc.). Table 2 presents an example datalogger program for the field investigations. The site at Brushy Creek was equipped with a manual rain gage from which rainfall was recorded at thirty minute interval during storm events.

The third site instrumented, at Watson's Mill State Park, has a variation on the original field design. The higher range Druck differential pressure transducer (PMP 4130, 69 hPa (1 psi) range) is attached to a rebar rod driven into the bed and the top of the rod is attached to a tree overhanging the stream. The measurement points are one meter apart and the lower port is installed approximately thirty centimeters below the bed. Also attached to the rebar are the previously mentioned stream stage and specific conductance meters. The intent of this experiment is to attempt to monitor the lifting of the bed material during high flow events. It was not possible within the context of this project to verify the sediment concentrations that actually occur during events for numerous logistical reasons or to instrument for flow velocity. The bed material within the measurement column should not register a signal when it is not in movement as the bed matrix is supporting the mass of the sediment, not the fluid column, therefore the fluid density should not change until the material is moved by changing flow conditions.

Manual suspended sediment sampling was conducted by using a DH-48 handheld sampler. The samples are taken by passing the sampler near the pressure ports and obtaining a depth-integrated sample utilizing a consistent transit rate and number of passes during a given sampling event. Sampling was conducted during various flow conditions and the measured parameters of temperature, conductance, flow velocity, and turbidity were periodically verified during site visits with calibrated hand-held portable meters.

A scanning rate can be set by the user to take practically as many readings as is desired. During storm events, the instruments were set to take one second readings and averaged over ten-minute intervals. Direct comparisons of the pressure-derived readings to the simultaneously collected and filtered samples as well as to the turbidity readings provide a clear answer as to the instrument's effectiveness.

Early field results indicated that the differential transducers, as well as the doppler flow-velocity meters, are affected by the supply voltage. The responses of these instruments are artificially high during periods that the solar panel charging is at its peak. The power supply was modified to create a regulated twelve-volt supply to both of these instruments.

4.3. Results

Two storms were effectively monitored and the results analyzed. For a storm on September 20, 1999 graphs are included that illustrate the densimetric response, the manually collected sediment concentrations and the other measurements taken during the event (Figures 4.2 through 4.5). Just under 0.025 m (one inch) of rain fell during the four hour event with the maximum intensity of 0.013 m hr^{-1} (0.5 inches hr^{-1}) occurring at 1500 hours EST. The absolute stream stage would be obtained by adding the distance that the gage transducer is above the bed, approximately 0.2 m, to the values in Figures 4.2 through 4.5. The *in situ* measurements were recorded by the datalogger every ten minutes and were based on the averages of one second readings. The turbidity meter readings were taken every minute and the values recorded were the of ten minute average. The millivolt response of the densimeter was corrected using Equation (13). The timing of the densimetric response corresponded with the timing of the fluctuations in the concentrations of sediment in manually collected samples. However, the variability in the magnitude of the response is considerable. This is illustrated in Figure 4.6. Several possibilities exist to explain some of the discrepancy. First, a portion of the variance in the density attributed sediment concentration is the occurrence of the water temperature drop during the event. Second, the decrease in the specific conductance of the water, thus the dissolved solids content (after correction by a standard value of 0.65) would be of little significance at this scale. Third, the manual collection using the DH-48 was performed over the entire water column (which varied over the storm from about 0.7 m to 1 m), whereas the densimetric scan is performed over the lower 0.5 m (from 0.1 m above the bed) of the water column. Fourth, the densimetric value is a ten-minute average of data collected every one second, whereas the DH-48 sample was taken over a period of about two minutes towards the beginning of each ten minute period. The only way to eliminate the third and fourth sources of error would be to sample as close to the 0.5 m window as possible and to lessen the averaging period while precisely recording the times of the manual collections. The fifth possible source or error would be from a velocity difference over the pressure measurement distance. After corrections using the correction formulas for velocity (Figure 2.1), temperature (Appendix C), and specific conductance, the total error attributable to these sources would be less than 1 percent. This would be a net decrease in the densimetric readings. The velocity difference used was 0.2 meters per second.

It can be noted that the response of the *in situ* turbidity meter is completely out of range with all of the other estimates of suspended sediment during the storm. Although calibrated well in the lab (up to one thousand FTU), these meters do not seem capable of measuring relatively normal turbidity values in the field. It can also be seen that the stream stage during this event was still increasing well after the sediment concentration had declined. This is common for small streams in this region under moderate storm conditions and is something to consider when developing sampling strategies.

A second storm was monitored on January 10, 2000. The results for this storm are included in Figures 4.7 to 4.10. The datalogger was set to record one minute averages of five second readings. The scatter in the one minute readings of the densimeter are considerably more than when the ten minute values were recorded for the September 20, 1999 storm. A ten-minute moving average was later applied to the densimetric values and is included in Figure 4.7. The manually collected samples show a decline over the storm from 250 $mg \cdot L^{-1}$ to 150 $mg \cdot L^{-1}$, whereas the ten-minute averages of the densimetric values show more fluctuation. The scale of the response is much more similar to the manual samples than was the instrument response to samples from the previous storm. An effort was made in the manual sampling with the DH-48 to pass quickly through the area of the water column that was not sampled by the *in situ* measurements. The velocity, temperature, and conductance error corrections amounted to a total correction of minus 0.3 percent. The temperature response (Figure 4.8) during this storm was the reverse of that seen in the September storm (Figure

4.3). This had the effect of canceling some of the error associated with a presumed velocity gradient of 0.3 meters per second.

A longer term record of the measured parameters from December of 1999 to April 2000 at the Brushy Creek site is included in Figures 4.11 through 4.14. The densimeter output is given in millivolts because, as evidenced by the temperature changes during storms, continuous adjustments are necessary. Also highly significant is the between storm drift of the baseline non-storm voltage. The record of specific conductance illustrates some appreciable changes in the dissolved solids concentration over the period. Some of this may be blamed on bio-fouling of the instrument as cleaning should have been done more regularly. For a reliance on the adjustment for dissolved solids, the instrument and response record would have to be better maintained, however the before seen increases in SSC far shadow any fluctuations seen in the dissolved component of the fluid density in this setting. In consideration of the long term record of flow velocity, it can be noted that considerable scatter exists, although the storm responses appear stable. This would have to be corrected were this particular device used for long term calculations of flow and extensions to sediment loads.

The largest storm event that occurred during the 1999 through 2000 monitoring record was March 20 to March 22, 2000. Approximately two inches of rain fell during the storm. The monitoring records for this event are displayed in Figures 4.15 through 4.18. The data was stored as thirty minute averages of five second readings. Manually collected samples were not performed to enable a comparison to the densimetric output. During the three days a 60 cm increase in stream stage occurred and this was coupled with a densimetric response that was unique to the other storms that were monitored during this project. A large-scale multiple peaked response can be seen throughout the hydrograph. After correction for velocity (0.4 $m \cdot s^{-1}$ gradient), temperature, and conductance, the maximum response would be converted to approximately 14,000 $mg \cdot L^{-1}$. The total error associated with the measured parameters reached a maximum during the densimetric peaks and varied during the event from 1 to 10 percent. Most of the error seen involved the assumed velocity differential. The absolute value of the derived concentrations is not as significant as the fact that the large variation in the densimetric response occurred for such sustained periods. This illustrates the importance that continuous monitoring may play in the reliable determination of sediment load estimations as the effort extended for manual or automated sampling to capture these fluctuations would be considerable. One explanation for these multiple peaks is that the watershed may have responded to the storm sequentially with different portions of the sediment supply occurring at different times based on variations in the rainfall and rainfall intensity over the watershed and on the travel times of the respective subwatersheds.

A short term record of the Clouds Creek site is included in Figures 4.19 through 4.21. The higher range pressure transducer was used here and the lower port was placed beneath the surface of the mobile stream bed. It is difficult to determine at this point if the 69 hPa range transducer is capable of accurately determining the sediment that moves at the interface of the bed. Once mobile, this total sediment concentration (TSC) would be much higher than the SSC measured at the Brushy Creek site.

The March 20, 2000 event at Clouds Creek was the only significant storm measured. With an increase in the stream stage of fifty centimeters, the increase in TSC from Equation (14), would have been close to 20,000 mg $\cdot L^{-1}$. While this concentration is consistent with bedload concentrations, much work remains to be done to get this site ready for storm sampling. This would involve making bedload concentration and suspended sediment concentration measurements to validate the pressure transducer measurements. There is a significant daily fluctuation in the water temperature and density, that may affect the pressure readings. From cursory analysis, there are periods when the two fluctuate in phase and times when the fluctuations are out of phase. Future work will be required to address this issue.

The results of the South Fork Broad River site at State Highway 172 were not presented in this report because, after one storm that showed a promising response, the instrument no longer registered a densimetric reaction to increasing stream stage. It is assumed that either air entered the system that attempts to remove could not reach, or a leak in the fittings' connections occurred that opened the system to the surrounding fluid column.

This would have had the effect of changing the measured column to an unquantifiable separation.

4.4. Conclusions

The field experiment component of this research was not as conclusive as the laboratory component. The difficulty of quality storm sampling is self-apparent to any researcher who has had the experience. Difficulties were compounded by the fact that for this instrument to perform as needed, many facets have to act in concert, including the work that must be conducted for the manual collection of suspended sediment and bedload sediment during storms to verify the densimetric readings.

Success was achieved in the design and installation of an instrument that can continuously measure the fluid density of a water column *in situ*. Responses of the instrument corresponded to increases in stream stage for both suspended sediment increases during two storm events and for suspected lifting and transport of the mobile bed. A method was developed to correct the raw millivolt pressure output of the instrument for flow velocity, stream temperature, and specific conductance changes. It was also determined that these factors had limited effect on the readings of the instrument under most of the conditions that were monitored, however this would change under more extreme fluctuations in these potential sources of error.

5. EQUIPMENT COSTS

The costs of building and mounting a sensor described in this report is under $3,000. Associated measurements of stage, temperature, conductance, stream velocity, and turbidity would add around $4,000. To record and store the information generated by the sensors adds about $3,500. The densimeter costs decrease with an increase in pressure measurement range and increases as the range is limited. This type of testing should be conducted in partnership with a manufacturer to reduce the cost associated with purchasing multiple transducers. Exploration of alternative manufacturers of the transducers and the supporting instrumentation could decrease the prices incurred in this study. It is difficult to quantify a cost versus benefit of this method when compared to existing approaches. Determining the fluid density of stream water is a direct measure of sediment concentration in any form where other *in situ* measurements are surrogates for sediment characterization. The instrument is theoretically not influenced by changes in particle size or by some of the other factors that can influence optical methods. Essentially, the densimeter, when perfected, will not necessarily provide cheaper data, rather the data will be more representative of sediment that is being transported through water bodies. This is especially relevant when large variations in sediment concentrations can quickly occur at-a-point. If perfected for bedload measurements, the densimeter will be the only practical way to continuously measure this type of sediment transport. It is financially and physically impossible to manually sample over the time scales that a densimetric approach is capable of, for both suspended and bedload sediment.

6. CONCLUSIONS

Although not fully conclusive, the densimetric analysis of *in situ* suspended sediment concentrations does hold promise to increase the knowledge of this important area of environmental science. A reliance on traditional methods for the determination of sediment concentrations in water can be problematic. Sediment sampling and gravimetric analysis is time consuming and must be timed to coincide with the hydrologic events during which transport is to be expected. Optic sampling is spatially limited to point measurements that do not represent the entire water column and can be confounded by multiple factors. Other methods exist that are not universally applicable or affordable. The development of sensors that can accurately determine sediment concentrations is therefore essential for the characterization of sediment and sediment bound contaminant amounts present in fluvial systems and to assess the success of mitigation efforts.

This study established that fluid density can be measured in the laboratory with field ready devices and in typical alluvial streams using precision *in situ* pressure transducers. Initial hand sampling at Brushy Creek showed that differential pressure measurements can be related to suspended sediments but additional development is necessary to develop continuous corrections for variations in flow velocity, stream temperature, dissolved solids, and the baseline output of the densimeter during quiescent periods. Instrument optimization is necessary to broaden the range of applicability. Measurements at Clouds Creek establish that bed load and total load characterization is also feasible.

This work has also revealed that many challenges remain. The need for design improvements is evident involving the deaeration of the system, a more user friendly in-stream mounting process, a reliable regulated power supply and a sealing of the internal system from the sampled water. Competent engineering expertise must be focused on refining the densimetric approach through these improvements. Were these steps taken, accurate, remote, and *in situ* estimations of the concentration of suspended sediments in a body of water would be an eventuality. From this, load calculations can be made that reflect the spatial and temporal character of sediment fluxes known to exist and known to result in the degradation of surface waters worldwide.

7. RECOMMENDATIONS

Future work utilizing this instrument will be required to improve the practicality of the design and field placement, the methods of calibration, and the analysis of the results. A deaeration procedure possibly using CO_2 gas may be necessary to prevent air entrapment or to remove that which enters the system. It is important to consider the overpressure ranges of these transducers when transporting or testing them, which would make a sealed system precarious depending on the length of the tubing, necessitating the addition of a cutoff valve to isolate the sensor. The power supply problems were solved, however maintaining two 32 amp hour batteries to provide a 24-volt supply is cumbersome and needs improvement. Ideally, a sealed system with a flexible membrane that would keep debris and/or biological material out should also be devised.

It is also essential to consider the site and the intended range of measurement of SSC before selecting a transducer. The lab tests indicated that the 1.0 hPa (0.4 inch) range is effective for 10 to 1,000 $mg \cdot L^{-1}$ concentration. Smaller range transducers are available that could be tested to improve the accurate detection near or below 10 $mg \cdot L^{-1}$. The high end detection, especially for bedload could be improved by a transducer with a range between the 1.0 hPa and 69 hPa sensors that were tested in this study.

REFERENCES

Balogh, S.J., M.L. Meyer, D.K. Johnson. 1997. Mercury and suspended sediment loadings in the lower Minnesota River. Environmental Science and Technology 31(1):198-202.

Beschta, R.L. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14(6):1011-1016.

Buchanan, P.A. and D.H. Schoellhamer. 1996. Summary of suspended-solids concentration data, San Francisco Bay, California, water year 1995: U.S. Geological Survey Open-File Report 96-591, 40 p.

Buchanan, P.A. and D.H. Schoellhamer. 1999. Summary of suspended-solids concentration data, San Francisco Bay, California, water year 1997: U.S. Geological Survey Open-File Report 99-189, 52 p.

Burkhead, N.M., S.J. Walsh, B.J. Freeman, J.D. Williams. 1995. Status and restoration of the Etowah River, an imperiled southern Appalachian ecosystem. in press. Symposium Proceedings: Tennessee Aquarium Symposium on Aquatic Fauna in Peril, The Southern Perspective.

Campbell, I.C. and T.L. Doeg. 1989. Impact of timber harvesting and production on streams: a review. Australian Journal of Marine and Freshwater Research 40 519-539.

Chang, H.H., 1988. Fluvial Processes in River Engineering. J. Wiley and Sons, Inc. N.Y., N.Y.

Connelly, R.R. II and S.S. Lin. 1996. Dam alteration: Issues & concepts regarding sediment control. Land and Water 40(2):10-13.

Dunne, T. and L.B. Leopold, 1978. Water in Environmental Planning. WH Freeman and Co. San Francisco.

Einstein, H.A. 1971. Sedimentation in River Ecology and Man. From International Symposium on River Ecology and the Impact of Man. ed. R.T. Oglesby. University of Massachusetts. 309-318.

Eisma, D. 1993. Suspended Matter in the Aquatic Environment. Springer-Verlag, Berlin, Germany.

Faye, R.E., W.P. Carey, J.K. Stamer, and R.L. Kleckner, 1980. Erosion, Sediment Discharge, and Channel Morphology in the Upper Chattahoochee River Basin, Georgia. U.S. Geological Survey Professional Paper 1107, U.S. Government Printing Office, 85 pp.

Gagnon, C. and N.S. Fischer. 1997. Bioavailability of sediment-bound methyl and inorganic mercury to a marine bivalve. Environmental Science and Technology 31(4):993-998.

Gippel, C.J. 1995. Potential of turbidity monitoring for measuring the transport of suspended-solids in streams. Hydrological Processes 9(1):83-97.

Glanz, J. 1995. Erosion study finds high price for forgotten menace. Science 267(5201):1088.

Guy, H.P. 1970a. Field methods for measurement of fluvial sediment. United States Geological Survey Techniques of Water-Resource Investigations. Book 3. Chapter C2.

Guy, H.P. 1970b. Fluvial Sediment Concepts. United States Geological Survey Techniques of Water-Resource Investigations. Book 3. Chapter C1. U.S. Govt. Printing Office, Washington, D.C.

Haefner, J.D. and J.B. Wallace. 1981. Production and potential seston utilization by Parapsyche cardis and Diplectrona modesta (Trichoptera: Hydropsychidae) in two streams draining contrasting southern Appalachian watersheds. Environmental Entomology 10, 433-41.

Hamilton, L.J., Z. Shi, and S.Y. Zhang. 1998. Acoustic backscatter measurements of estuarine suspended cohesive sediment concentration profiles. Journal of Coastal Research 14(4):1213-1224.

Harrington, J., F.R. Schiebe and J.F. Nix. 1992. Remote-sensing of Lake Chicot, Arkansas - monitoring suspended sediments, turbidity, and secchi depth with Landsat MSS data. Remote Sensing Of Environment 39(1):15-27.

Holdaway, G.P., P.D. Thorne, F.D. Flatt, S.E. Jones, and D. Prandle. 1999. Comparison between ADCP and transmissometer measurements of suspended sediment concentration. Continental Shelf Research 19(3):421-441.

Julien, P.Y. 1998. Erosion and Sedimentation. Cambridge University Press UK. 280p.

Kronvang, B., A. Laubel, and R. Grant. 1997. Suspended sediment and particulate phosphorus transport and delivery pathways in an arable catchment, Gelbaek Stream, Denmark Hydrological Processes 11(6):627-642.

Leigh, D.S. 1997. Mercury-tainted overbank sediment from past gold mining in north Georgia, USA. Environmental Geology 30(3/4):244-251.

Lewis, A.J. and T.C. Rasmussen. 1996. A New, Passive Technique for the *In Situ* Measurement of Total Suspended Solids Concentrations in Surface Waters. Environmental Resource Center, Georgia Inst. of Technology ERC 08-96.

Lewis, A.J., and T.C. Rasmussen. 1999. Determination of Suspended Sediment Concentrations and Particle Size Distributions Using Pressure Measurements. Journal of Environmental Quality 28:1490-1496.

Lewis, J. 1991. An improved bedload sampler. *In:* Fan, S. and Y.H. Kuo, eds., Fifth Federal Interagency Sedimentation Conference Proc.:18-21, Las Vegas, NV.

Lewis, J. 1996. Turbidity-controlled suspended sediment sampling for runoff-event load estimation. Water Resources Research 32(7):2299-2310.

Lick, W., Z. Chroneer, and V. Rapaka. 1994. Modeling the dynamics of the sorption of hydrophobic organic chemicals to suspended sediments. Water, Air, & Soil Pollution 99(1-4), 225-235.

Martin, G.R., J.L. Smoot and K.D. White. 1992. A comparison of surface-grab and cross sectionally integrated stream-water-quality sampling methods. Water Environment Research 64(7):866-876.

Miller, C.R., 1951. Analysis of flow-duration, sediment-rating curve method of computing sediment yield, U.S. Bureau of Reclamation, Hydrology Branch, 55p.

Paterson, R.G., M.I. Luger, R.J. Burby, E.J. Kaiser, H.R. Malcolm. 1993. Costs and Benefits of Urban Erosion and Sediment Control: The North Carolina Experience. Environmental Management 17(2):167-178.

Phillips, J.M., B.W. Web, D.E. Walling and G.J.L. Leeks. 1999. Estimating the suspended sediment loads of rivers in the LOIS study area using infrequent samples. Hydrological Processes 13(7):1035-1050.

Reichel, G. and H.P. Nachtnebel. 1994 Suspended sediment monitoring in a fluvial environment: Advantages and limitations applying an Acoustic Doppler Current Profiler. Water Research 28(4):751-761.

Riley, S.J. 1998. The sediment concentration turbidity relation: its value in monitoring at Ranger Uranium Mine, Northern Territory, Australia. Catena 32(1):1-14.

Rouse, H. and S. Ince. 1957. History of Hydraulics, Iowa Institute of Hydraulic Research, Iowa City, Iowa.

Skinner, J.V. and J.P. Beverage. 1982. A fluid-density gage for measuring suspended sediment concentration. Federal Inter-Agency Sedimentation Report X *of* A study of methods used in measurement and analysis of sediment loads in streams. USACE.

Stevens, H.H. and C.T. Yang, 1989. Summary and use of selected fluvial sediment-discharge formulas. U.S. Geological Survey Water Resources Investigation Report 89-4026.

Tebo, L.R. 1955. Effects of siltation, resulting from improper logging, on the bottom fauna of a small trout steam in the Southern Appalachians. Progressive Fish Culturalist 17: 64-70.

Thorne, P.D. and P.J. Hardcastle. 1997. Acoustic measurements of suspended sediments in turbulent currents and comparison with in-situ samples. Journal of the Acoustical Society of America 101(5):2603-2614.

Trimble, S.W. 1974. Man-induced erosion on the Southern Piedmont 1700-1970. Soil Conservation Society of America Report. Anteny, Iowa. 179 pp.

Walling, D.E. 1977. Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resources Research 13(3):531-538.

Waters, T.F. 1995. Sediment in streams: sources, biological effects, and control. American Fisheries Society Monograph 7.

Wolman, M.G. 1977. Changing needs and opportunities in the sediment field. Water Resources Research 13(1):50-54.

White, T.E. 1998. Status of measurement techniques for coastal sediment transport. Coastal Engineering 35:17-45.

Wood, P.J. and P.D. Armitage. 1997. Biological effects of fine sediment in the lotic environment. Environmental Management 21(2):203-217.

Yang, C.T. 1973. Incipient motion and sediment transport. Journal of the Hydraulics Division ASCE, 99 (HY10):1679-1704.

Yang, C.T. 1977. Comment on ‘Changing needs and opportunities in the sediment field’ by M. Gordon Wolman. Water Resources Research 13(5):860-862.

Yang, C.T., 1979. Unit stream power equations for total load. Journal of Hydrology 40:123-138.

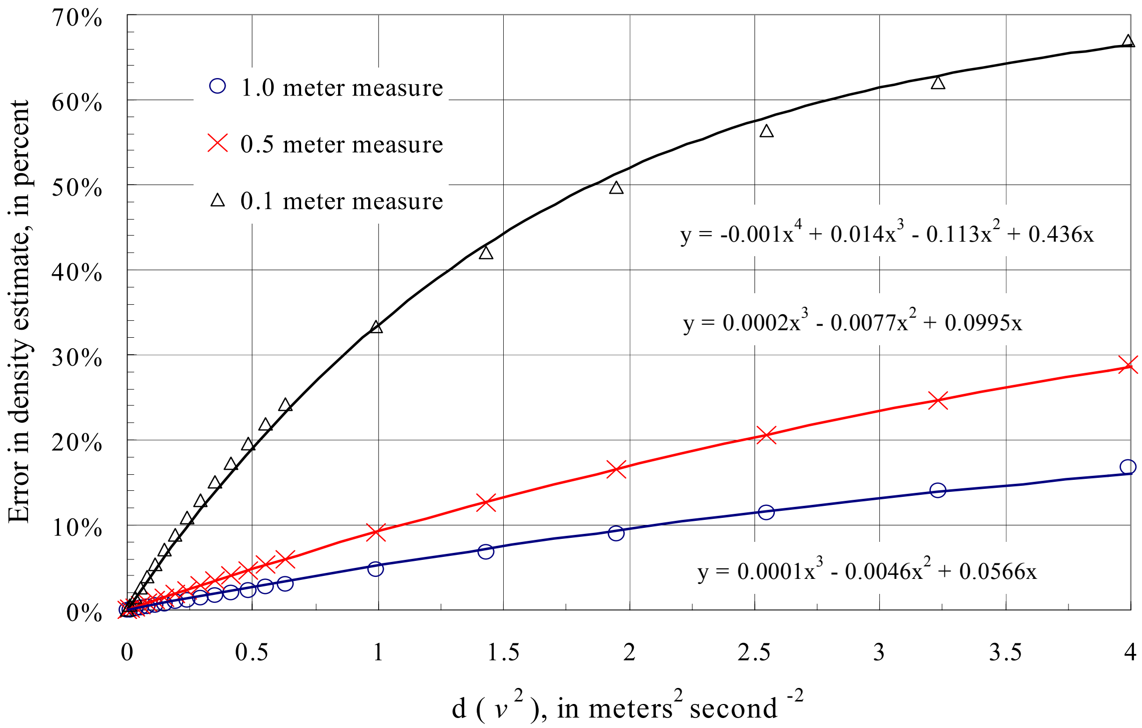


Figure 2.1. Sources of error in the velocity component of fluid density.

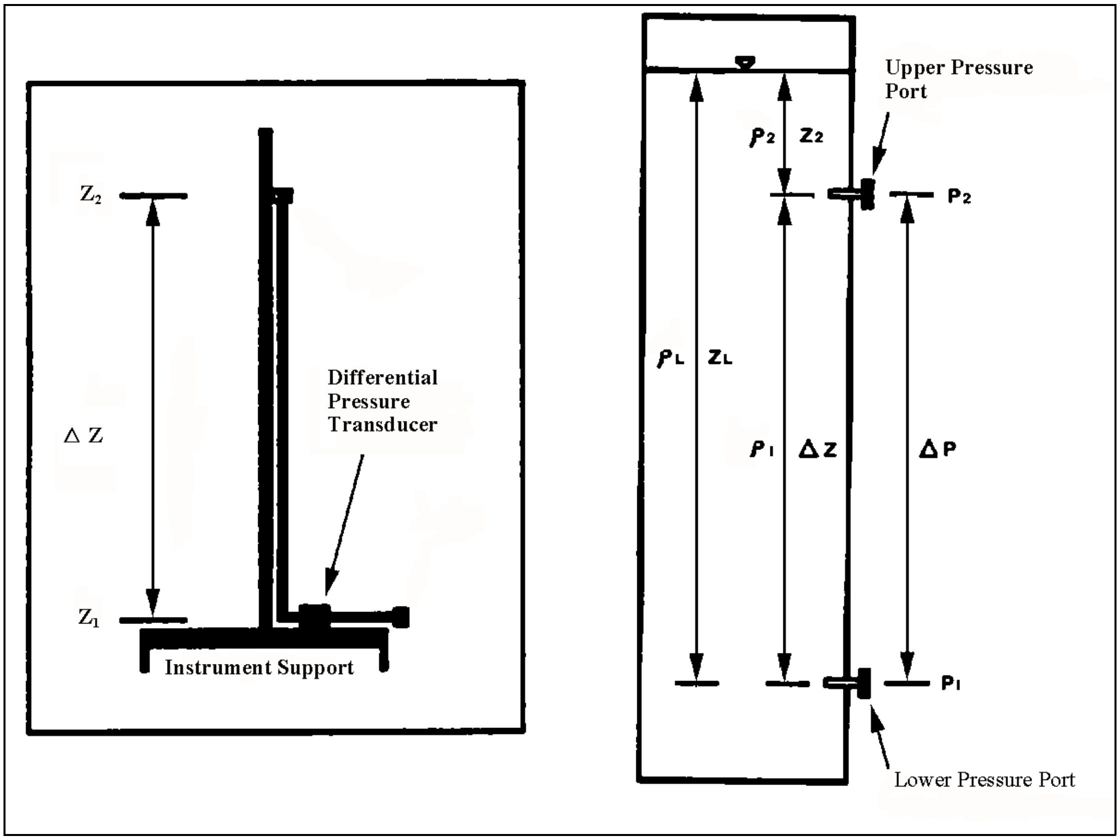


Figure 3.1. Schematic of the proposed densimeter applications in the field and laboratory. The image to the left is the field placement scheme and the image to the right displays the laboratory application to test the field transducer. Note that the points depicted as upper and lower pressure measurement ports are connected to different sides of a differential pressure transducer. Symbols $\rho_{1, 2, L}$ refer to density, P to pressure, and Z to distance or length.

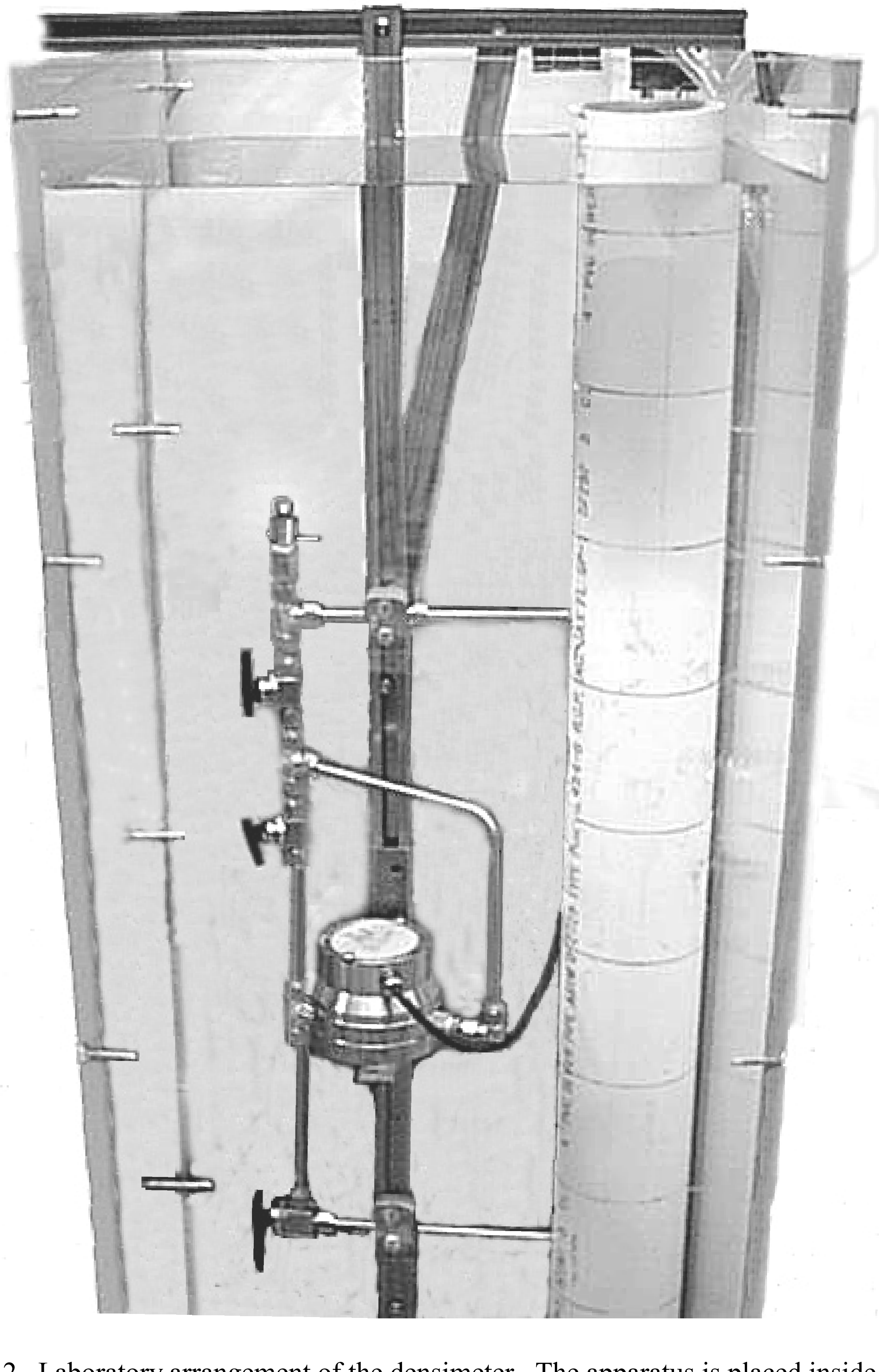


Figure 3.2. Laboratory arrangement of the densimeter. The apparatus is placed inside of a Plexiglas box that is filled with deionized water.

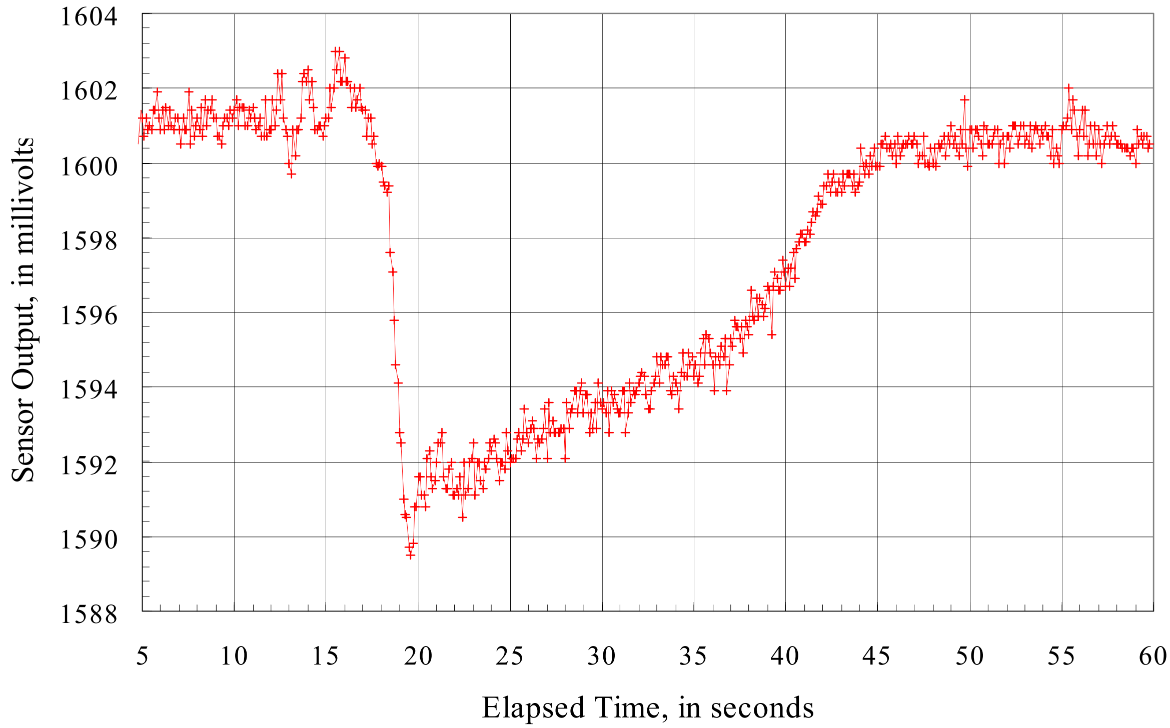


Figure 3.3. Densimetric response to 0.3 grams of 360 µm beads. The instrument used was the LPM 9381 1 hPa (0.4 inch) range transducer. The expected concentration was 38.2 $mg{\cdot}L^{-1}$, the minimum value was utilized for analysis, the derived concentration was 37.8 $mg{\cdot}L^{-1}$, and the calculated error was 1 percent.

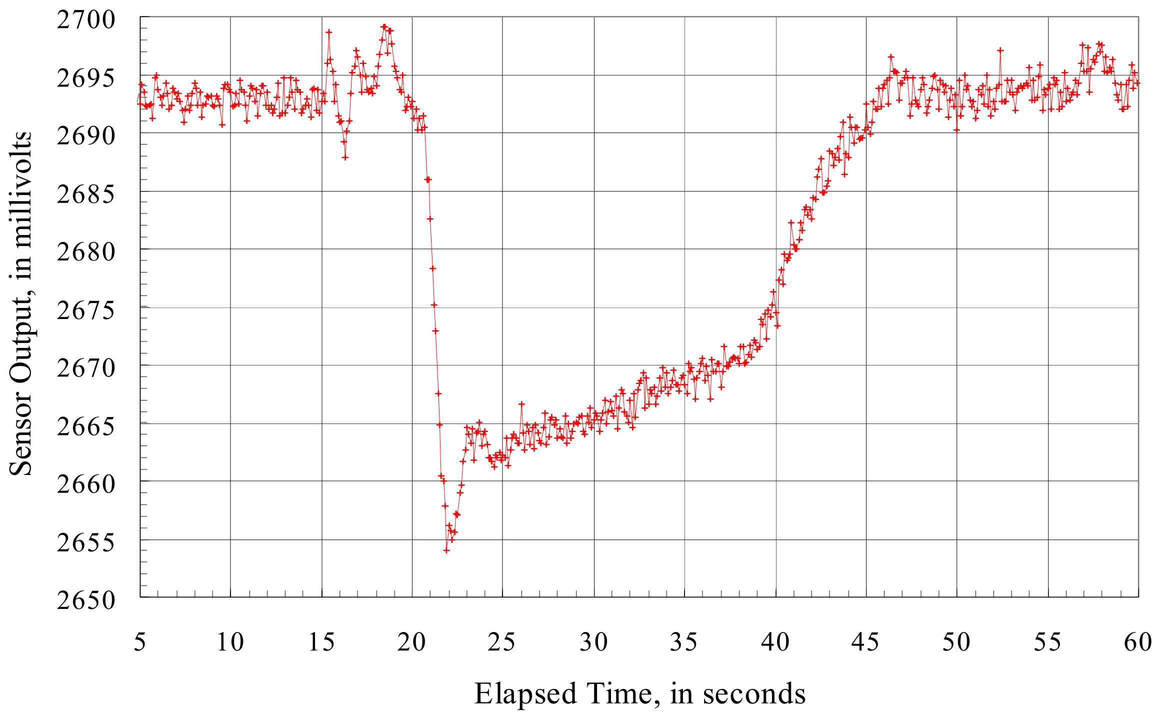


Figure 3.4. Densimetric response to 1.0 grams of 360 µm beads. The expected concentration for the 1 hPa range transducer was 127.3 mg·L^{-1}, the minimum value was utilized for analysis, the derived concentration was 127.28 mg·L^{-1}, and the calculated error was less than 1 percent.

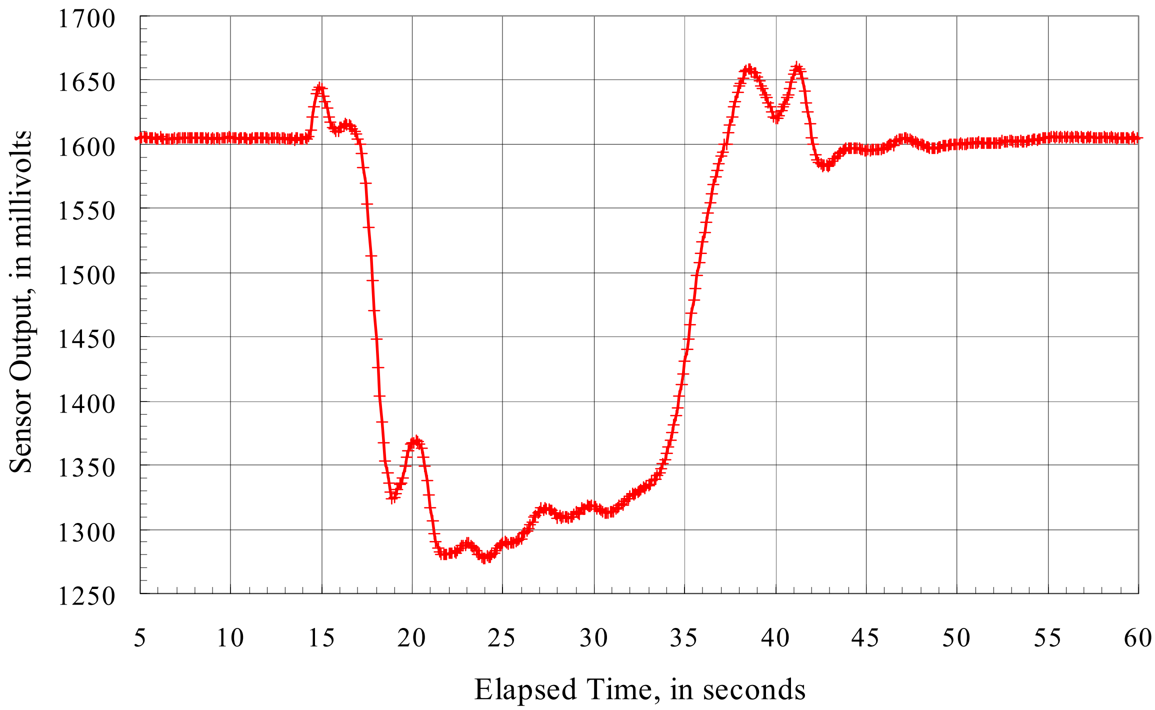


Figure 3.5. Densimetric response to 10.0 grams of 360 µm beads. The expected concentration for the 1 hPa range transducer was 1,200 $mg \cdot L^{-1}$, the minimum value was used for analysis, the derived concentration was 1,070 $mg \cdot L^{-1}$, and the calculated error was 12 percent.

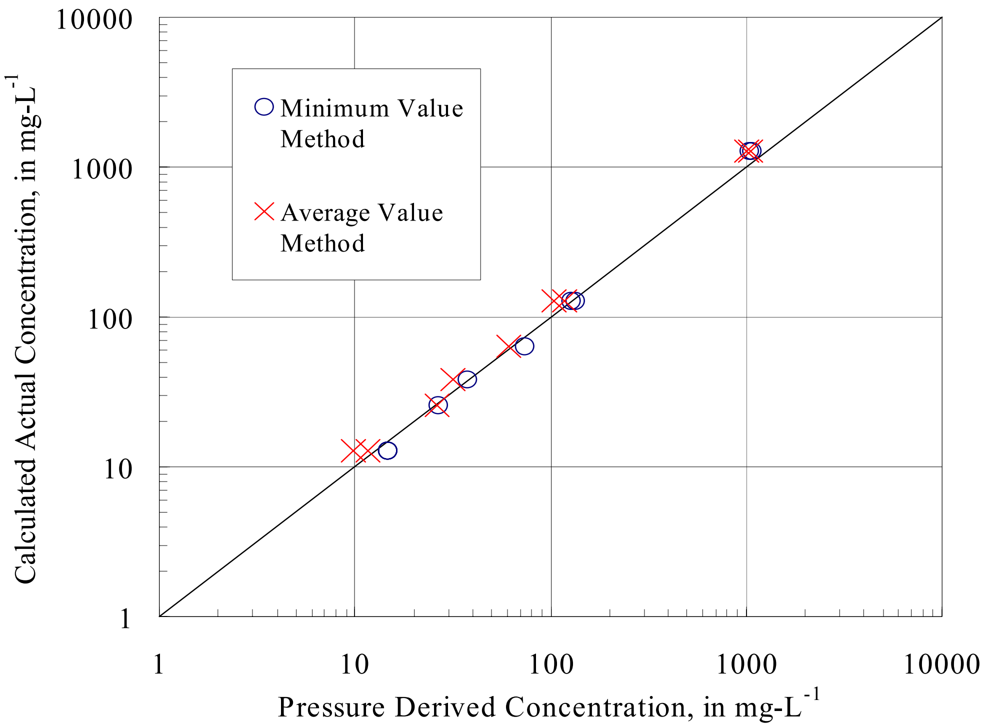


Figure 3.6. The relationship between the derived concentrations and the expected concentrations for the laboratory analysis of the 1 hPa transducer. Average error for the minimum value method was 11 percent and for the average value method was 13 percent. The maximum error was observed in the 10 $mg \cdot L^{-1}$ and 1,000 $mg \cdot L^{-1}$ tests.

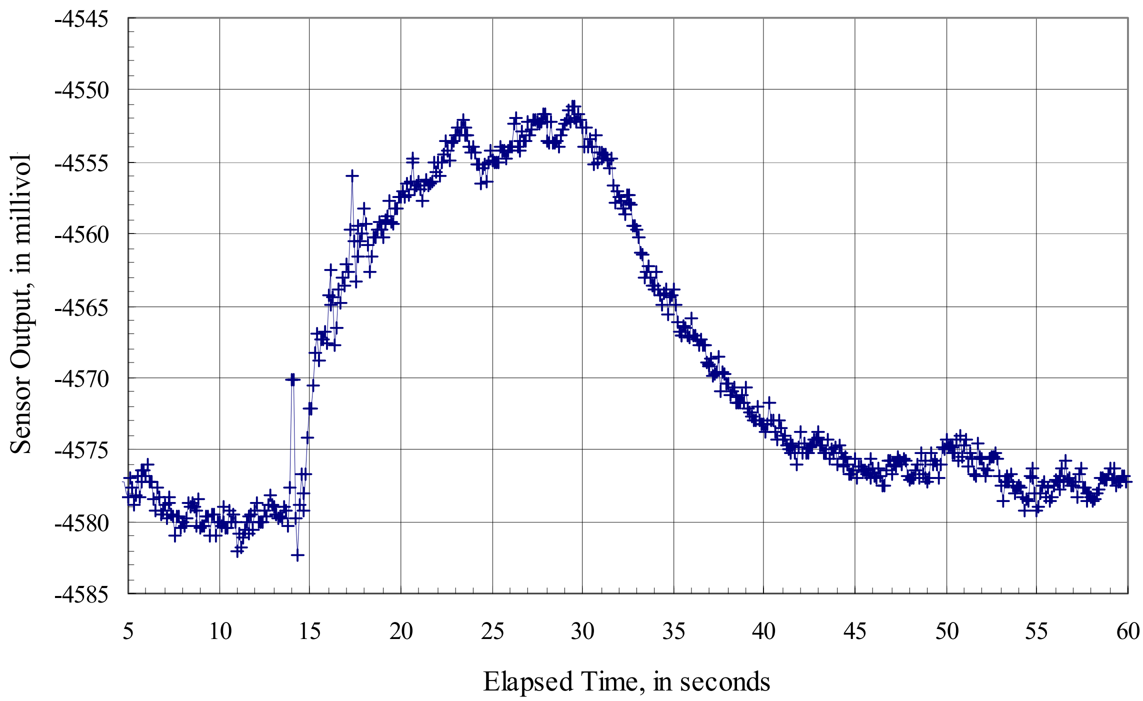


Figure 3.7. Densimetric response to 50 grams of 360 μm beads. Instrument used was the PMP 4130 69 hPa (1 psi) range transducer. The maximum value was used for analysis, the expected concentration was 6,366 mg·L^{-1}, the derived concentration was 6,237 mg·L^{-1}, and the calculated error was 2 percent.

Figure 4.1 Field placement at Brushy Creek.

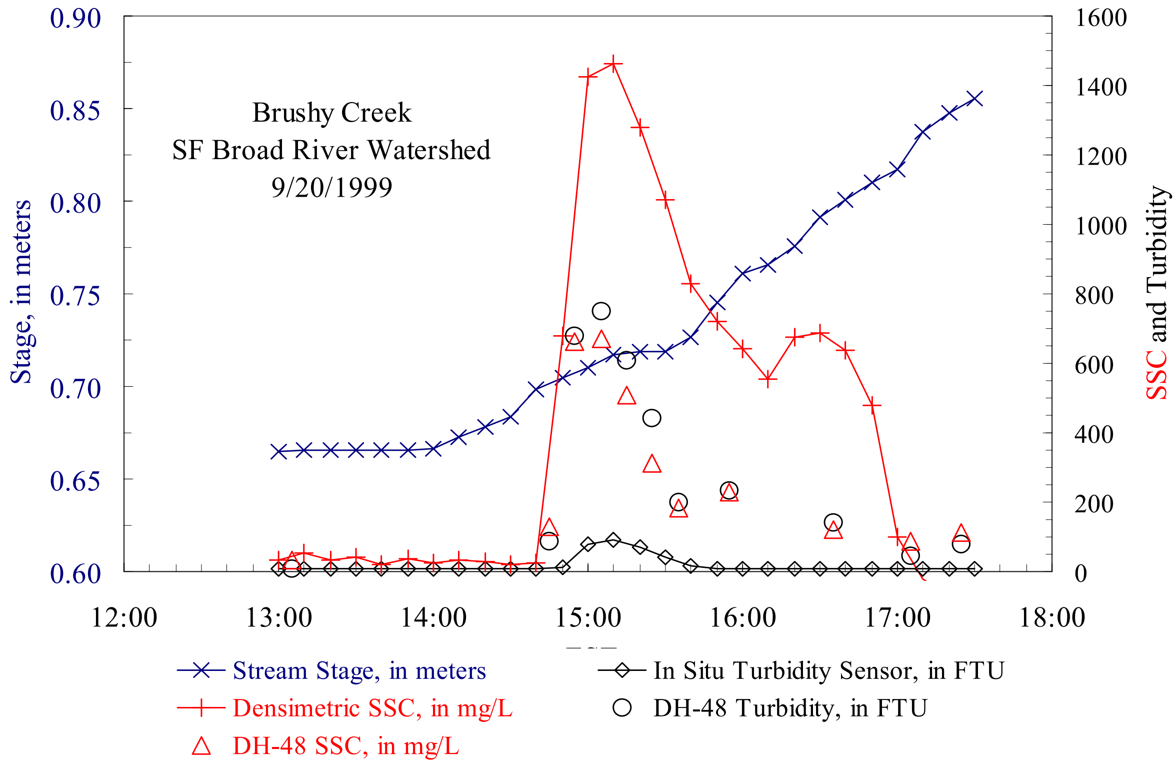


Figure 4.2 Densimetric response to the 9/20/1999 storm.

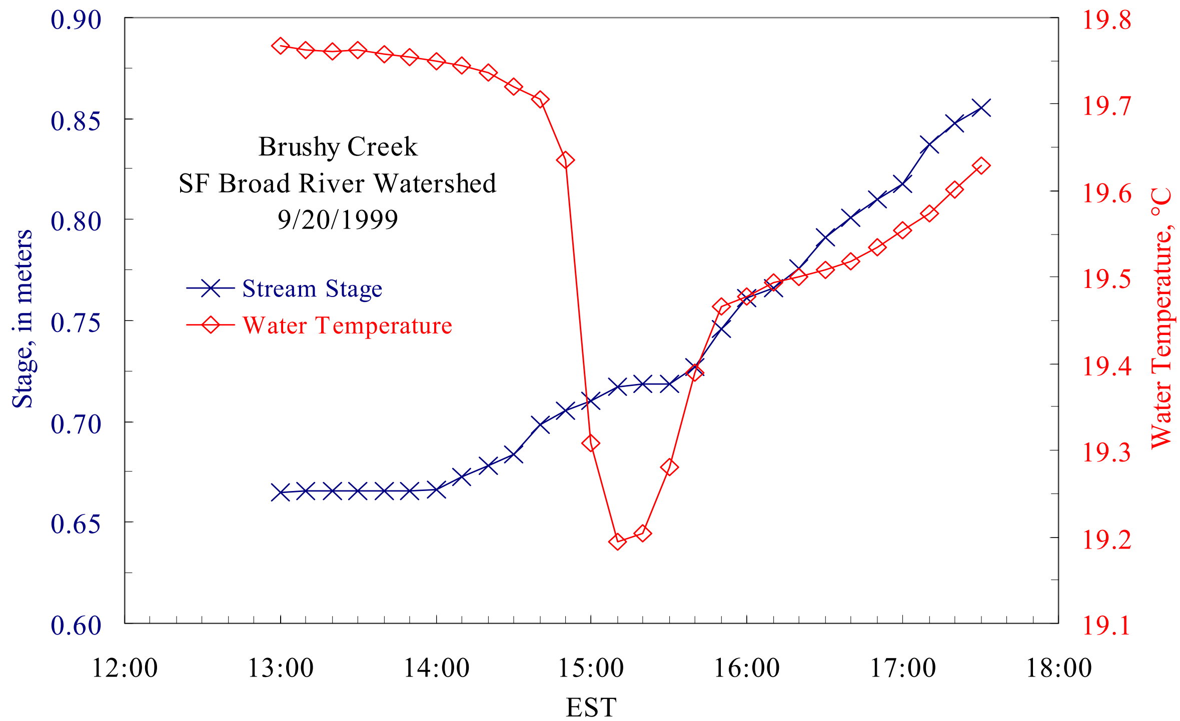


Figure 4.3. Stream temperature response to the 9/20/1999 storm.

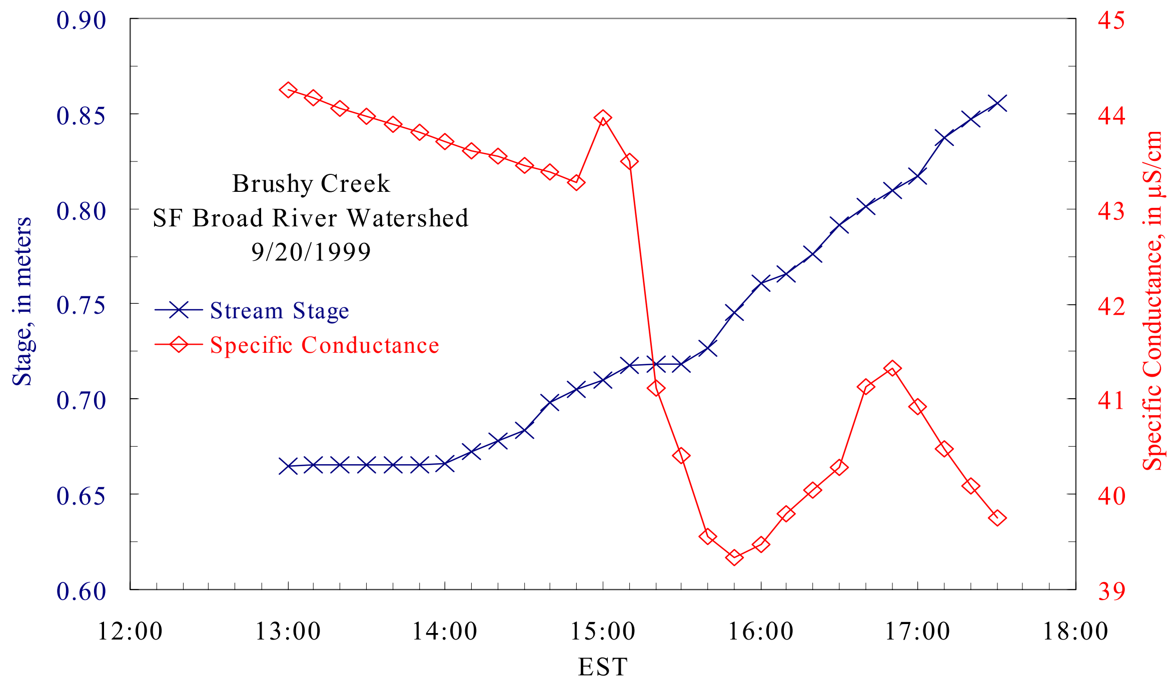


Figure 4.4. Specific conductance response to the 9/20/1999 storm.

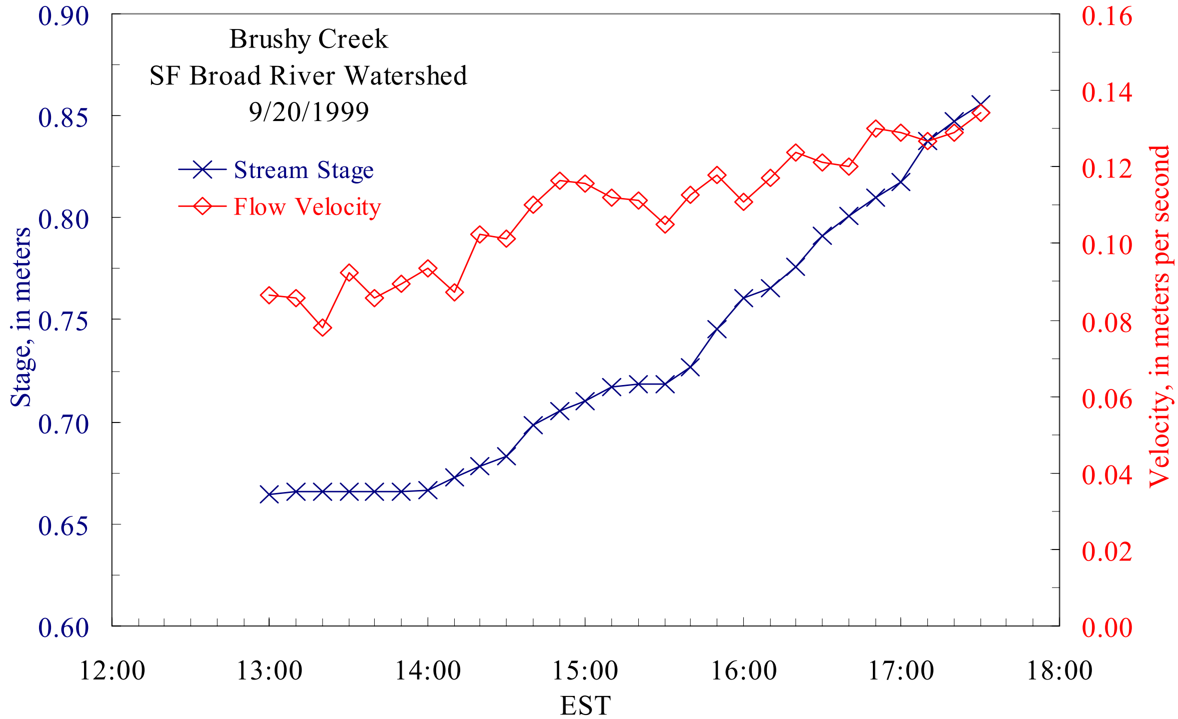


Figure 4.5. Flow velocity response to the 9/20/1999 storm.

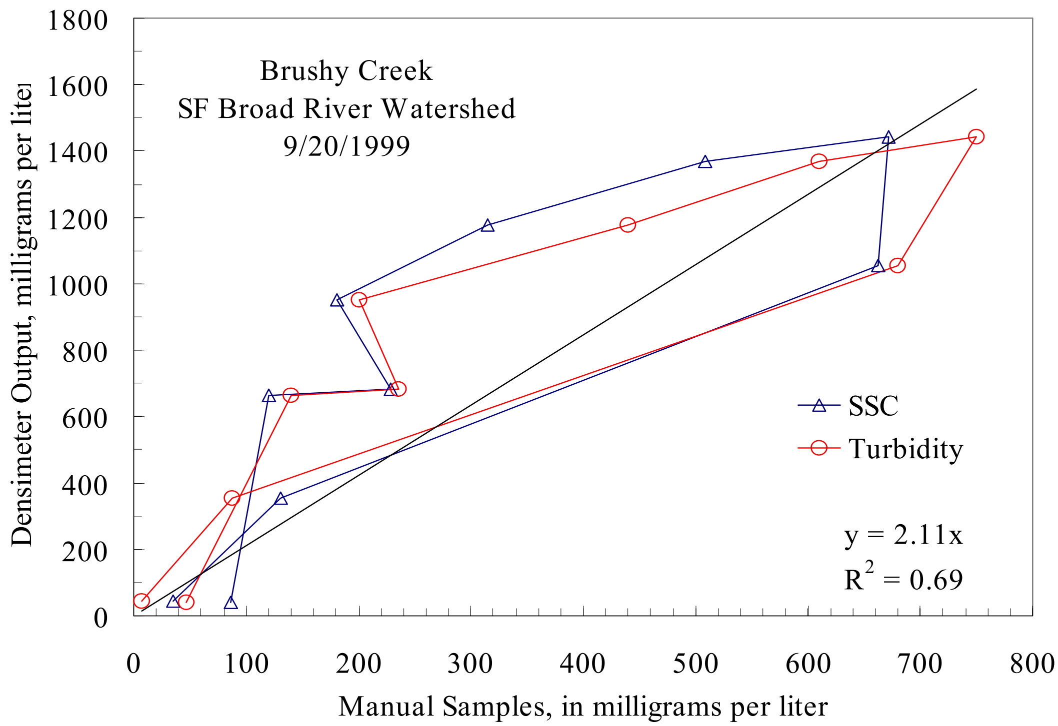


Figure 4.6. The relationship between manually collected samples and the densimetric response.

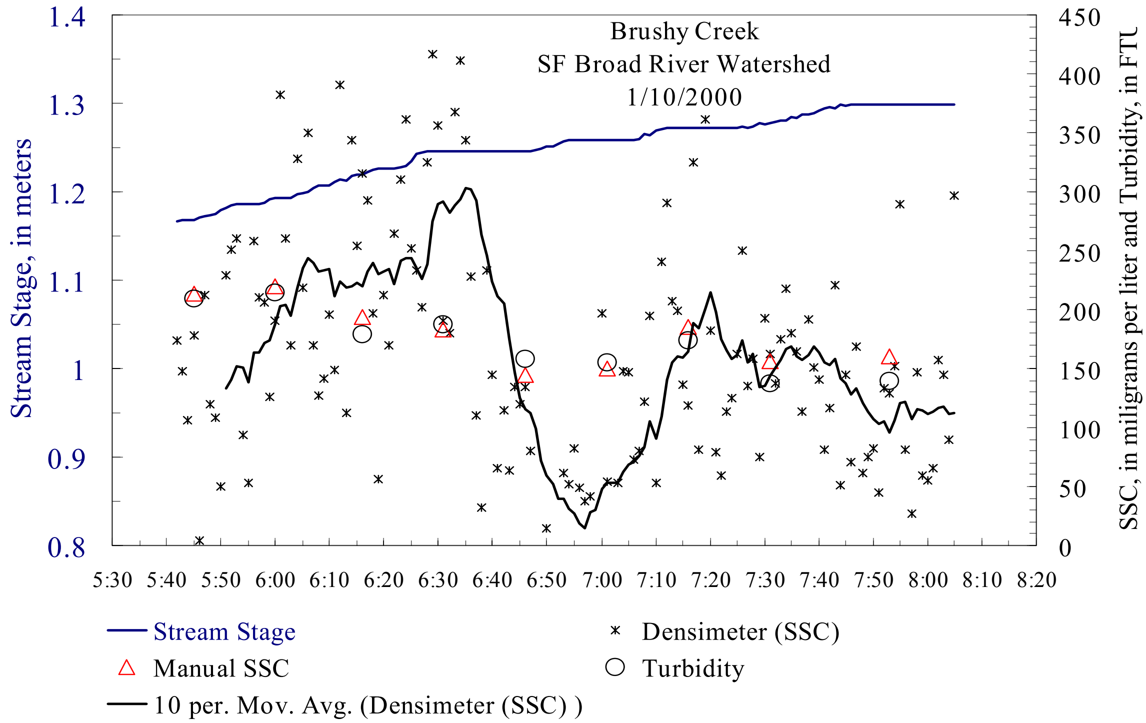


Figure 4.7. Densimetric response to the 1/10/2000 storm.

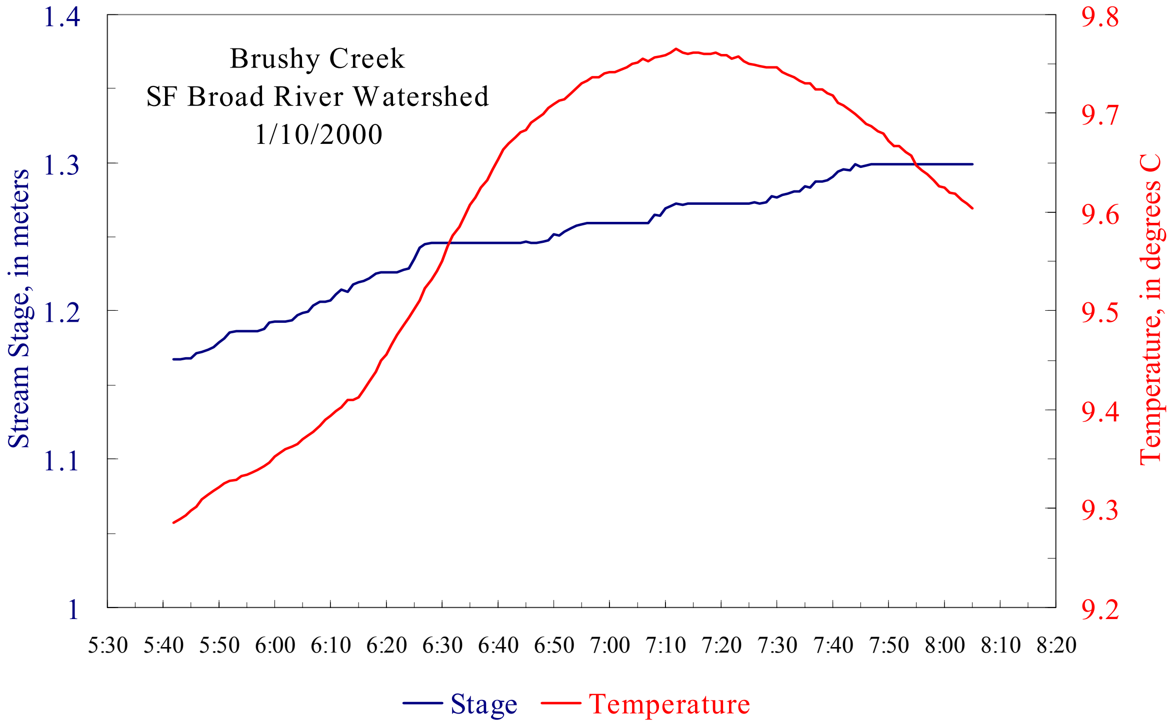


Figure 4.8. Stream temperature response to the 1/10/2000 storm.

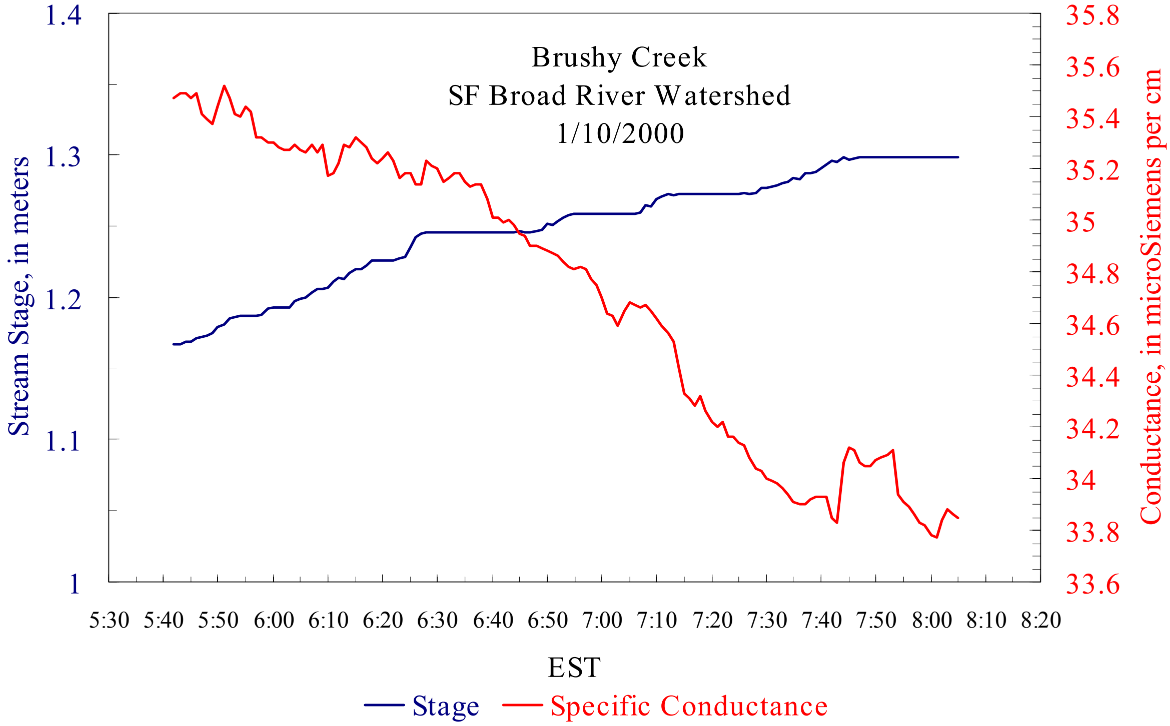


Figure 4.9 Specific conductance response to the 1/10/2000 storm.

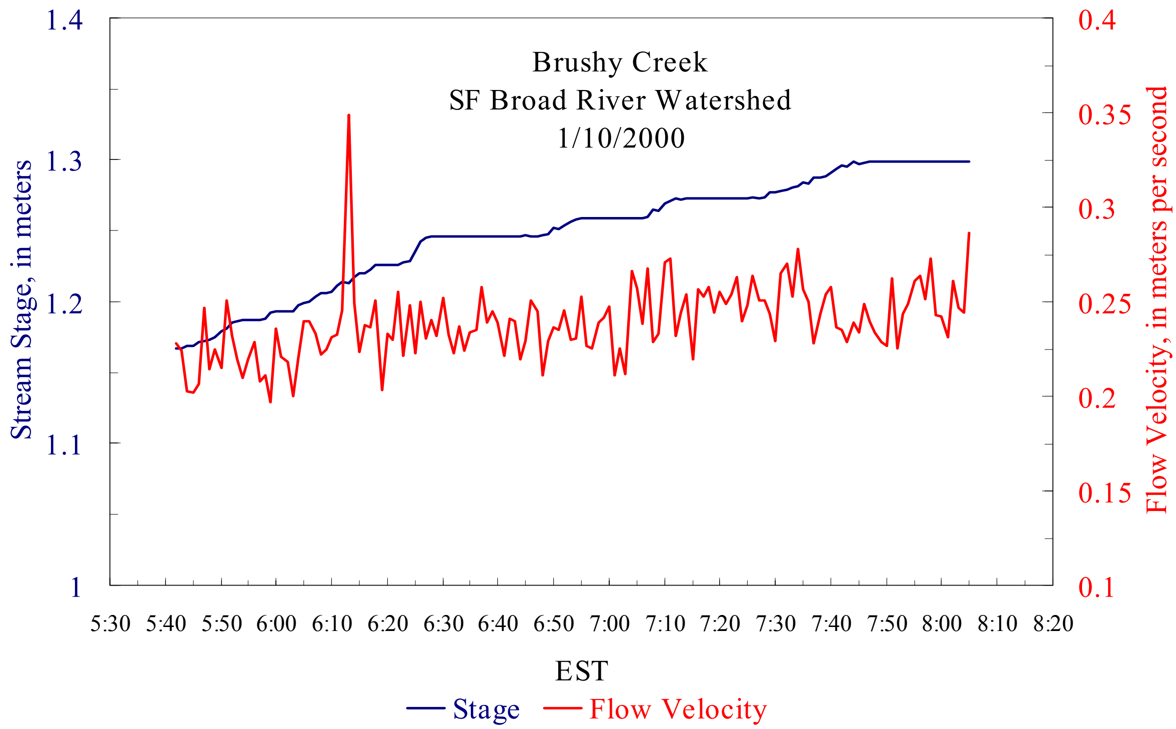


Figure 4.10. Flow velocity response to the 1/10/2000 storm.

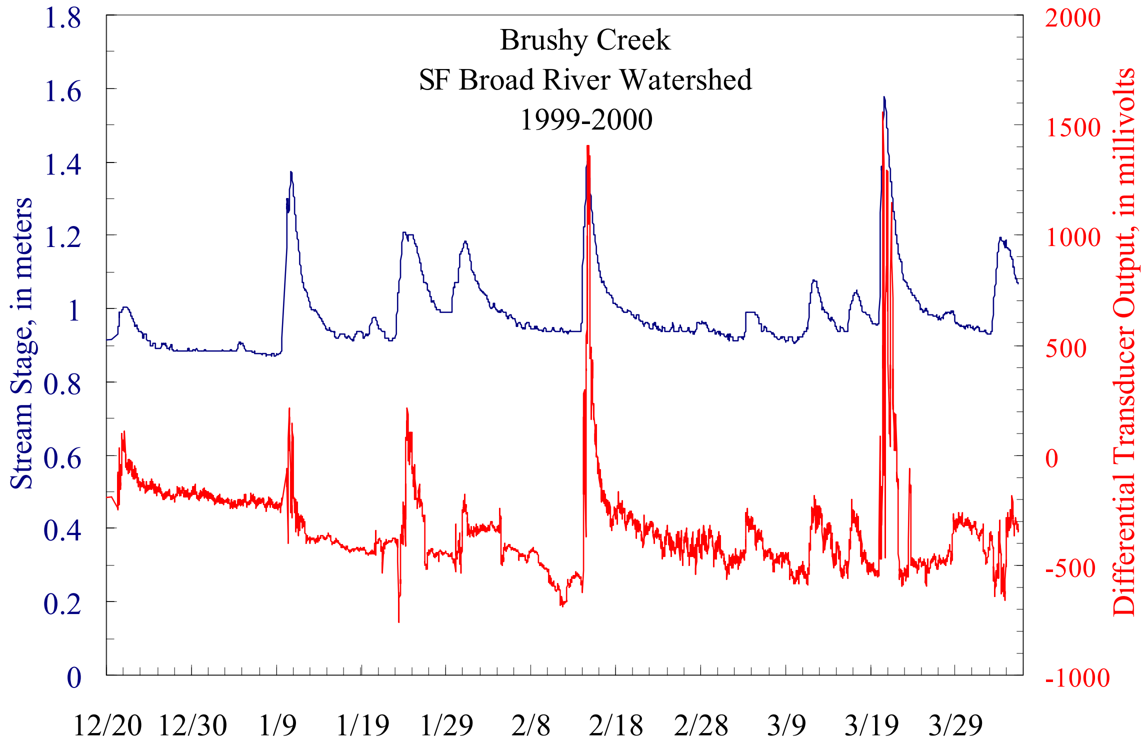


Figure 4.11. Densimetric record from December 1999 to April 2000.

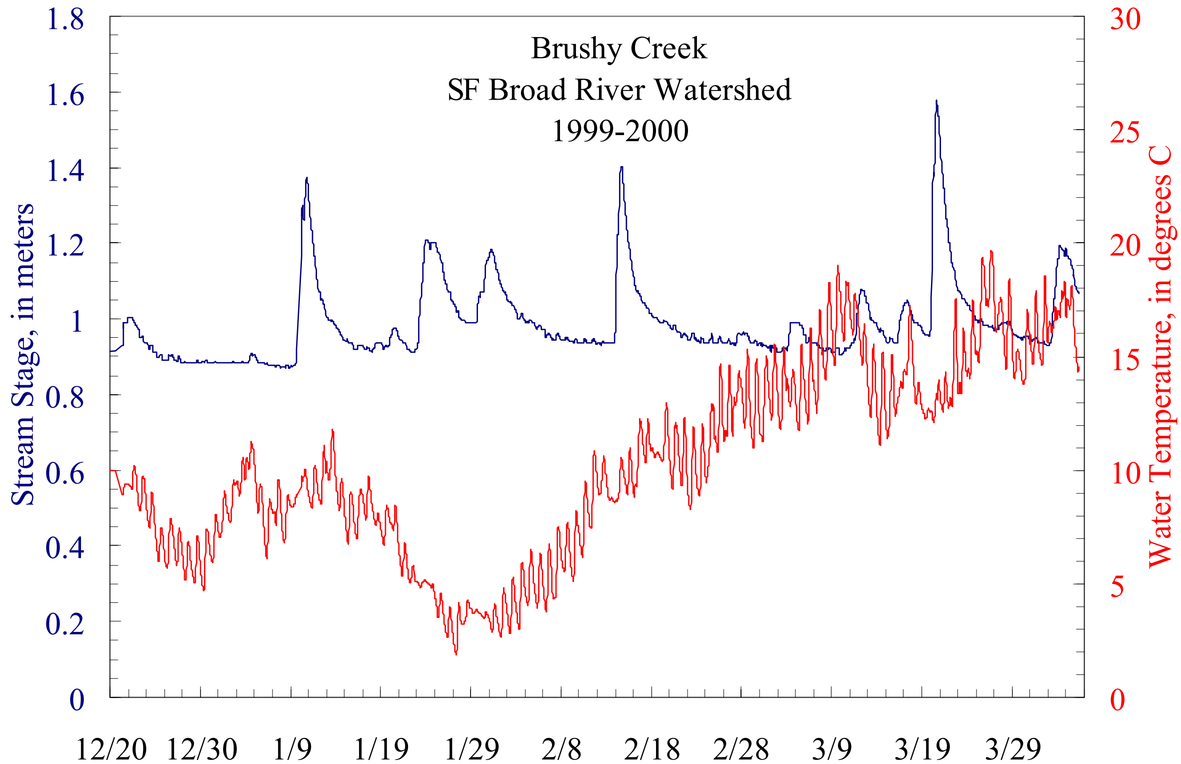


Figure 4.12. Stream temperature record from December 1999 to April 1999.

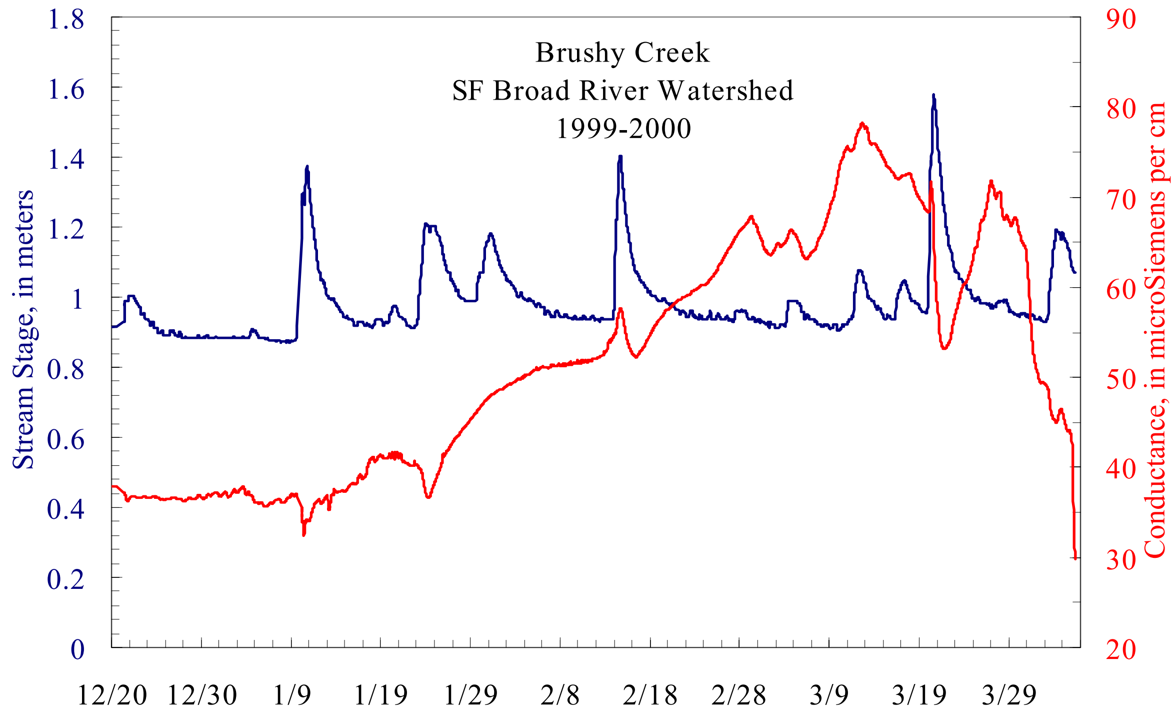


Figure 4.13. Stream specific conductance record from December 1999 to April 2000.

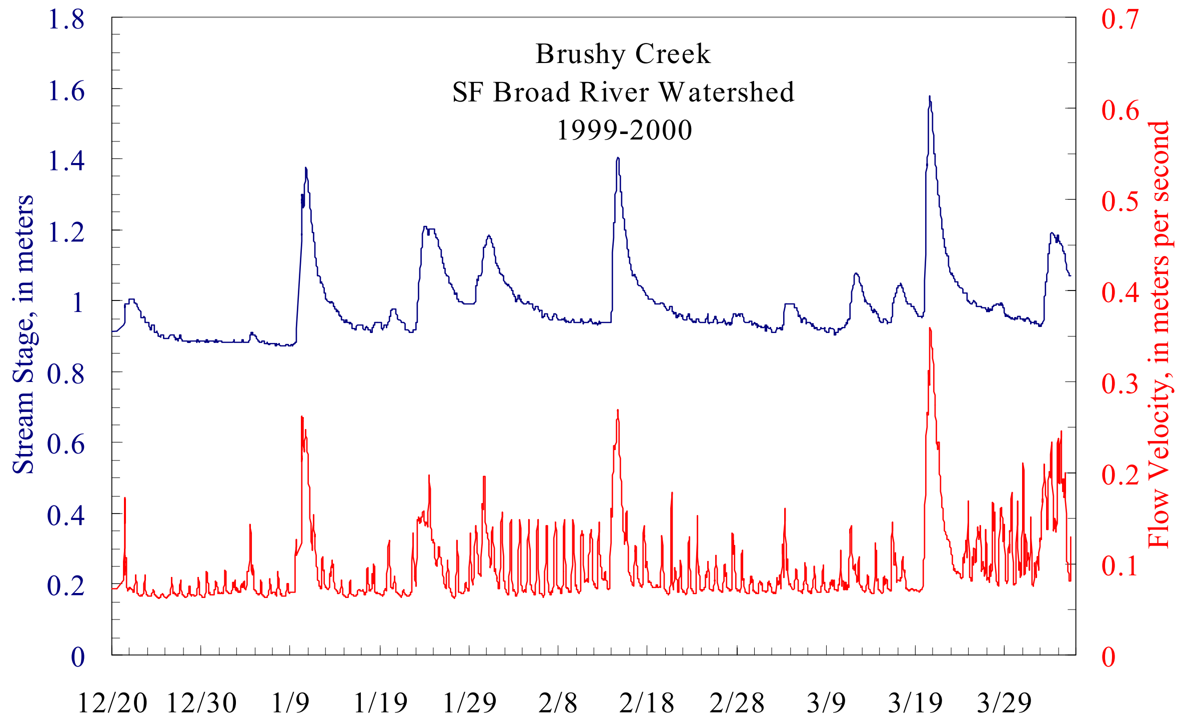


Figure 4.14. Flow velocity record from December 1999 to April 2000.

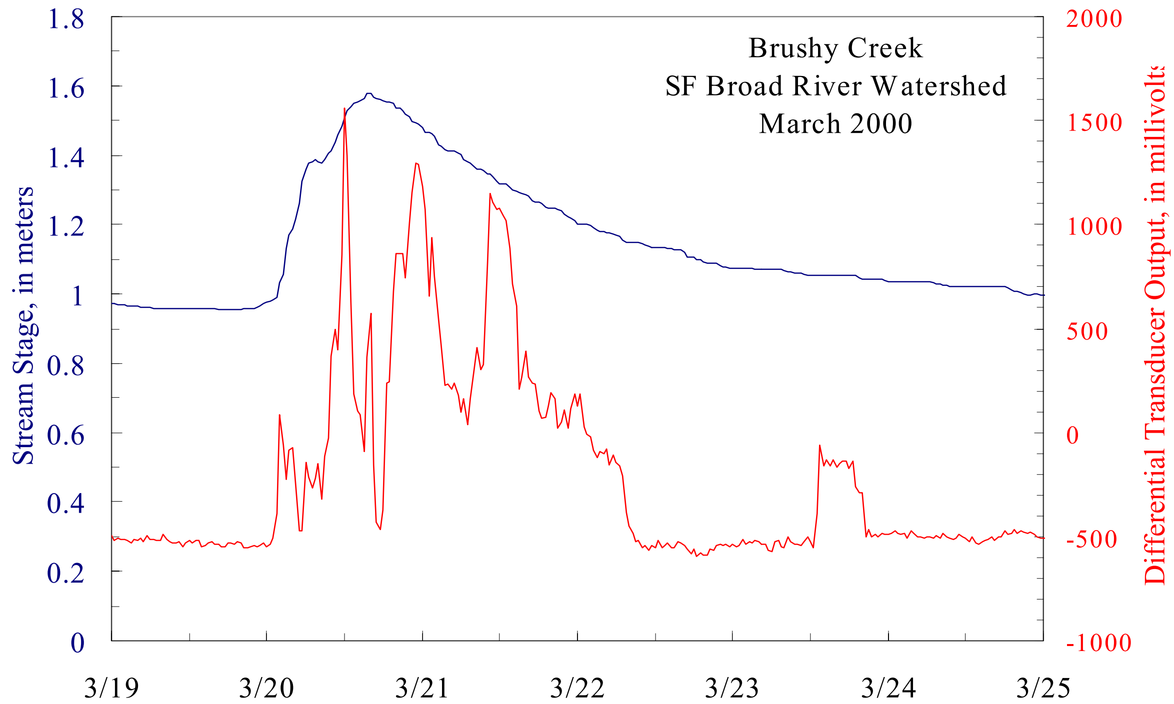


Figure 4.15. Densimetric response to the March 2000 event.

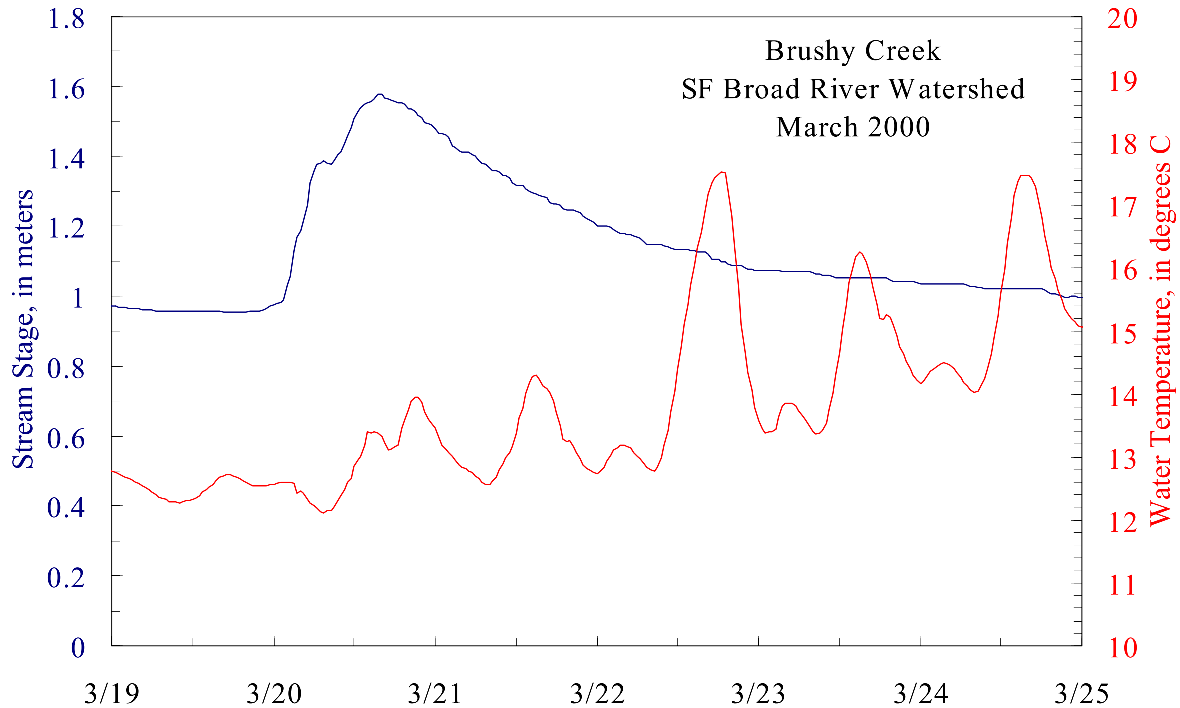


Figure 4.16. Stream temperature response to the March 2000 event.

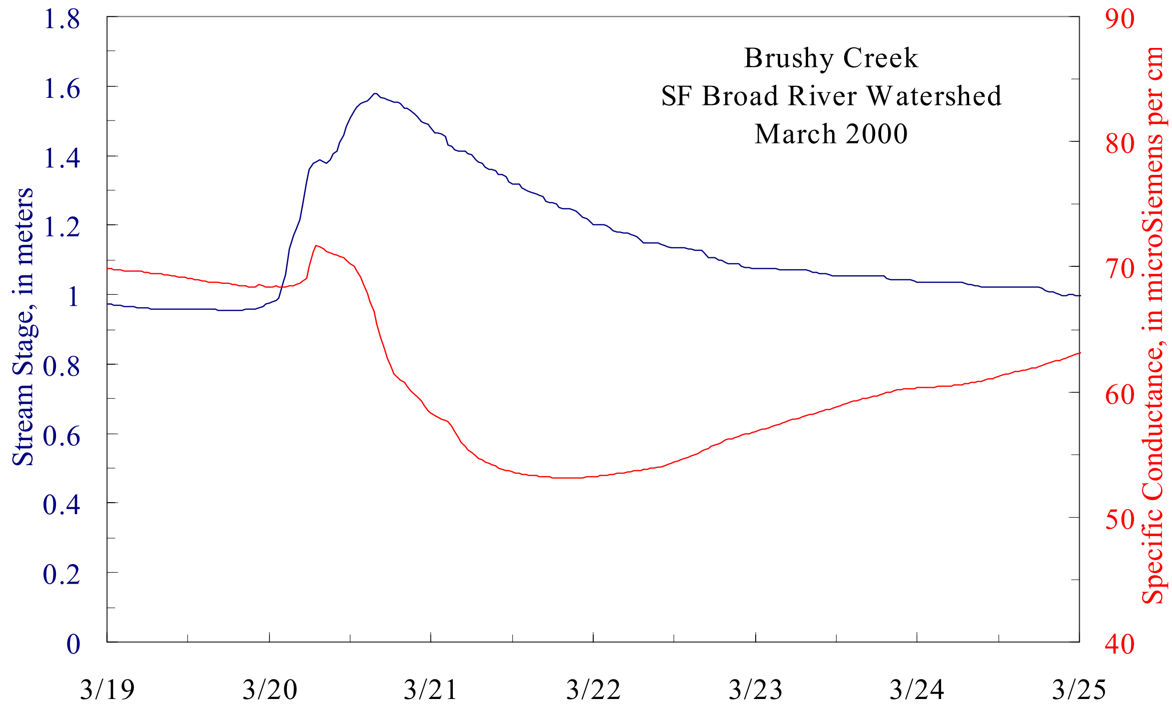


Figure 4.17. Stream conductance response to the March 2000 event.

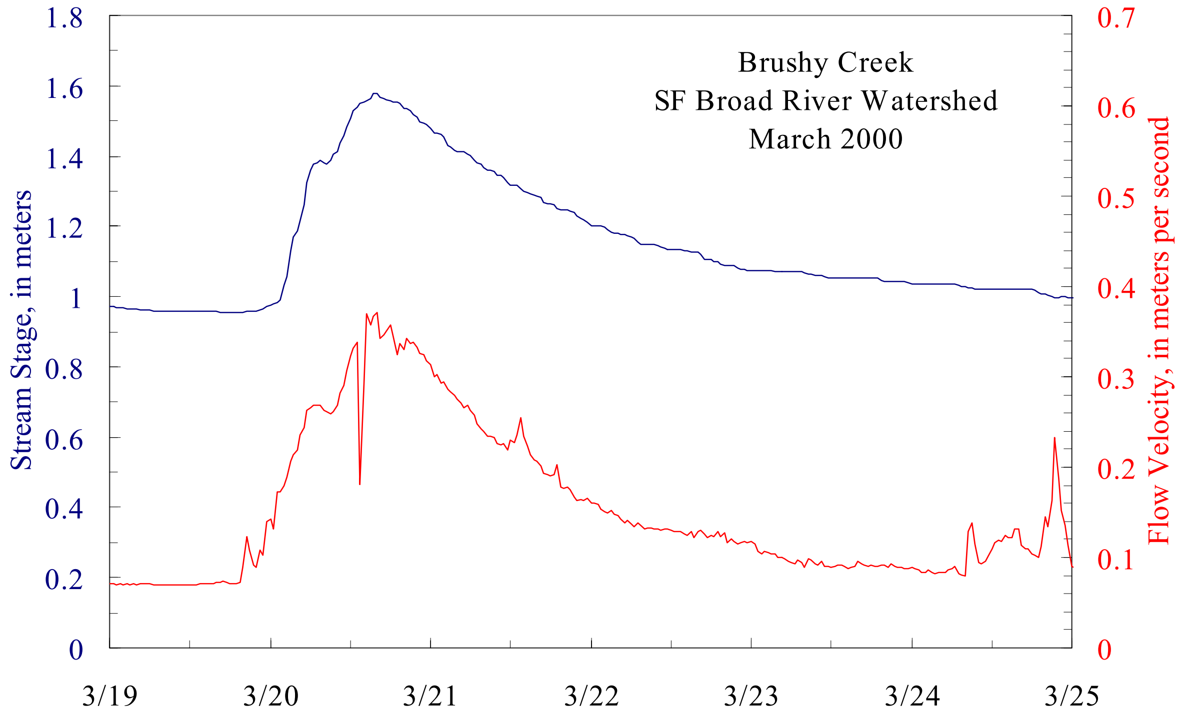


Figure 4.18. Flow velocity response to the March 2000 event.

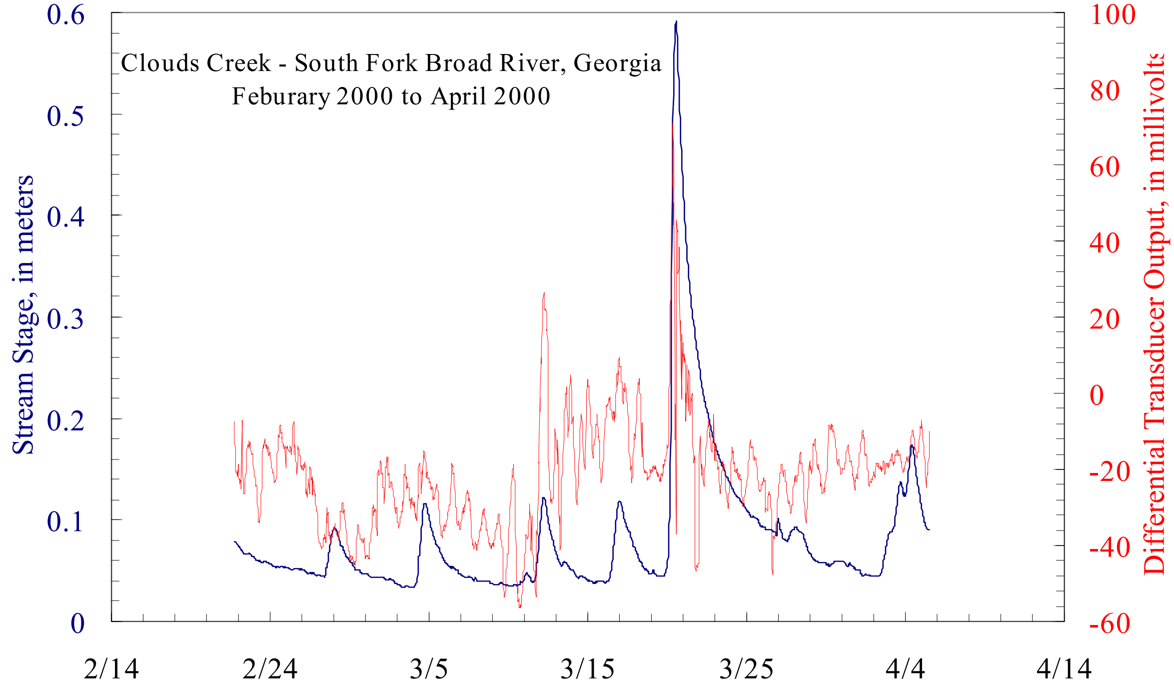


Figure 4.19. Densimetric record of total sediment concentration at Clouds Creek from February 2000 to April 2000.

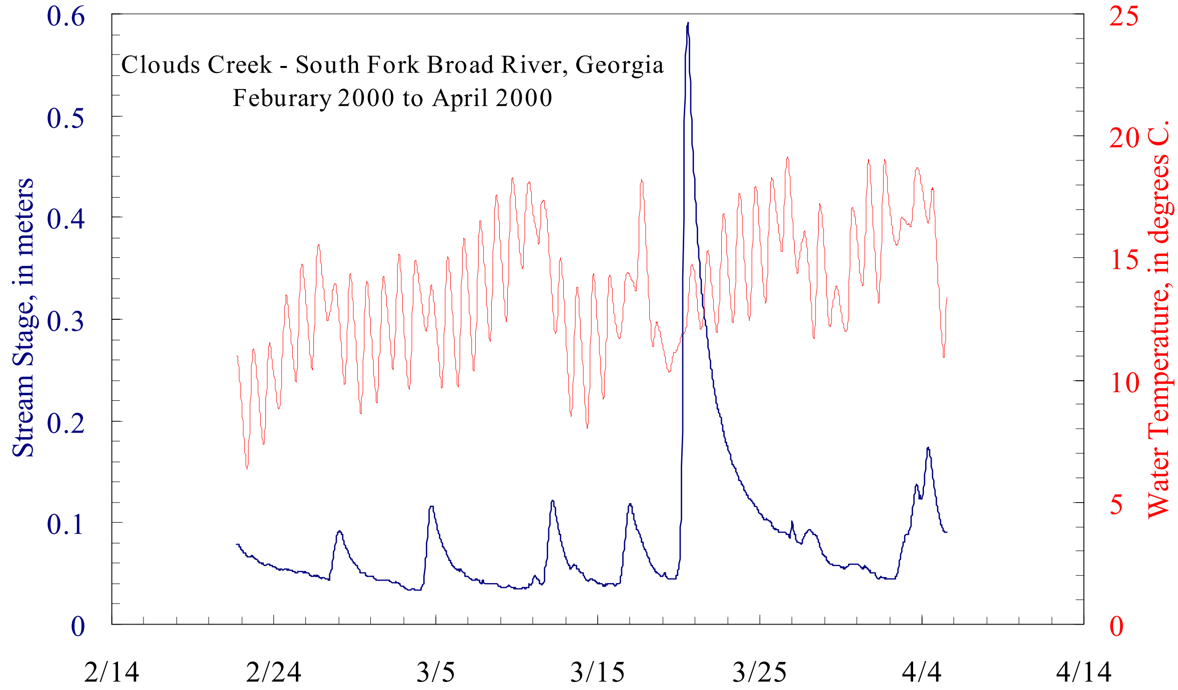


Figure 4.20. Water temperature record at Clouds Creek from February 2000 to April 2000.

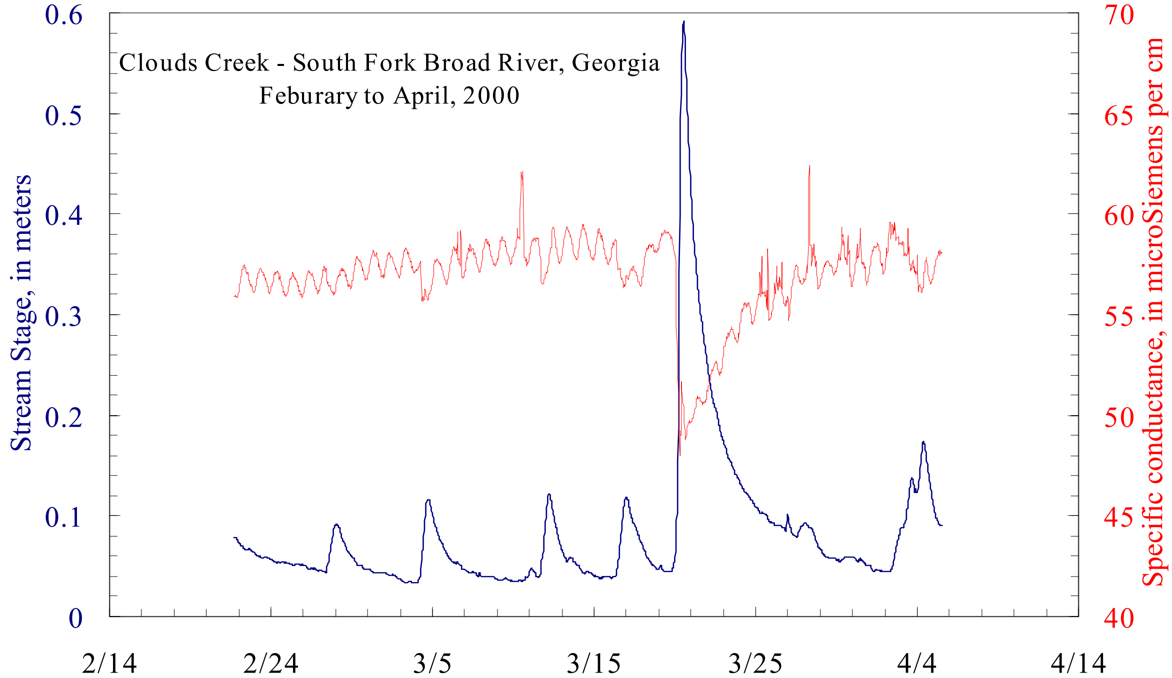


Figure 4.21. Specific conductance record at Clouds Creek from February 2000 to April 2000.

MODE 1		4:P55		8:P70	
SCAN 0.5		1:1		1:1	
1:P10		2:3		2:2	
1:1		3:3			
		4:-26.97		9:P0	
2:P1		5: 69.635			
1:1		6:-40.66		MODE 2	
2:22		7:16.573		SCAN 0	
3:6		8:-3.455			
4:2		9:.301		MODE 3	
5:1				1:P0	
6:0		5:P91			
		1:11			
3:P5		2:10			
1:1					
2:3		6:P77			
3:3		1:111			
4:2					
5:1000		7:P78			
6:3		1:1			
7:200					
8:0					

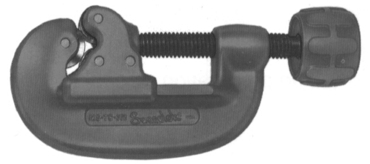
Table 1. Example datalogger program for the laboratory determination of suspended sediment in a water column. Densimeter output is stored in location 2 and temperature is stored in location 3.

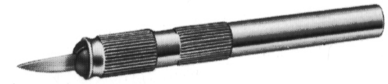
Table 2. Example datalogger program for the Densimeter and supporting sensors for the Field Monitoring of Suspended Sediments. A knowledge of Campbell datalogger programming is required for interpretation. The information below describes the storage locations of the field measurements included in the table.

Locations:	Measurement:
4	Temperature
10	Specific Conductance
11	Densimeter
12	Turbidity
13	Flow Velocity
14	Stream Stage
15	Battery Voltage

```
};CR23X

MODE 1
SCAN 1
1:P6
1:1
2:15
3:1
4:1
5:2500
6:1
7:-.001
8:1

2:P59
1:1
2:1
3:1

3:P93
1:1

4:P83
1:1.8
2:30

5:P5
1:1
2:15
3:2
4:1
5:2500
6:1
7:1
8:0

6:P95

7:P83
1:9.25
2:30

8:P6
1:1
2:15
3:1
4:1
5:2500
6:1
7:-.001
8:1

9:P95

10:P83
1:280
2:30

11:P6
1:1
2:14
3:1
4:1
5:2500
6:1
7:-.001
8:1

12:P95

13:P95

14:P59
1:1
2:1
3:1

15:P30
1:100
2:0
3:5

16:P37
1:5
2:.00032
3:5

17:P37
1:5
2:-.1
3:5

18:P34
1:5
2:-.005
3:5

19:P33
1:1
2:5
3:1

20:P42
1:1
2:2

21:P37
1:2
2:1.41
3:3

22:P11
1:1
2:3
3:2
4:4
5:1
6:0

23:P89
1:3
2:4
3:.474
4:30

24:P37
1:3
2:.95031
3:3

25:P34
1:3
2:-.00378
3:3

26:P94

27:P55
1:1
2:3
3:3
4:-.02889
5:.98614
6:.02846
7:0
8:0
9:0

28:P95

29:P34
1:4
2:-25
3:6

30:P37
1:3
2:100
3:8

31:P37
1:6
2:4.5
3:9
32:P34
1:9
2:100
3:9

33:P38
1:8
2:9
3:10

34:P1
1:1
2:25
3:5
4:11
5:1
6:0

35:P1
1:1
2:25
3:9
4:13
5:1
6:0

36:P6
1:1
2:24
3:6
4:3
5:2500
6:14
7:1
8:0

37:P10
1:15

38:P92
1:0
2:5
3:10

39:P78
1:1

40:P71
1:1
2:4

41:P71
1:2
2:10

42:P71
1:3
2:13

43:P0

MODE 2
SCAN 60
1:P92
1:00--
2:60
3:49

2:P92
1:3--
2:60
3:30

3:P1
1:1
2:25
3:7
4:12
5:1
6:0

4:P86
1:10

5:P77
1:110

6:P78
1:1

7:P70
1:1
2:12

8:P86
1:59

9:P95

10:P0
```

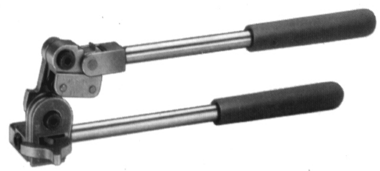
APPENDICES





Tube Cutter

Tube Deburring Tool



Tube Bender

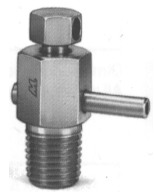
Pre-Swaging Tool

TEE Wrench

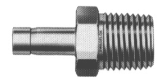
Ratchet Wrenches

Gap Inspection Gage

Appendix A. Recommended tools for densimeter construction

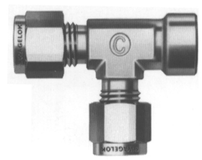


Bleed Valve

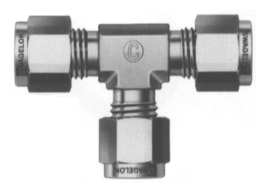


Male NPT to Swagelok

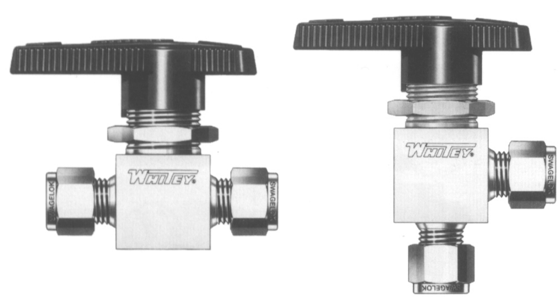
Port Connector



Female Run Tee

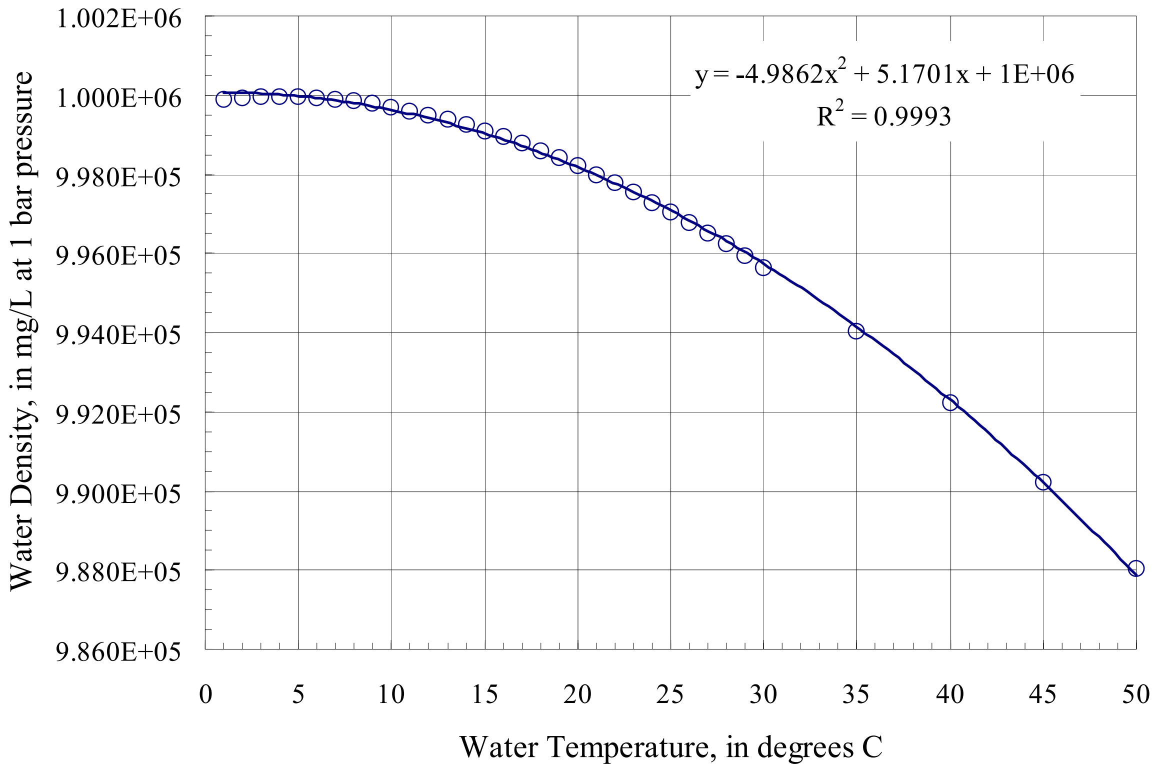


Union Tee



Two-way Straight and Angle Ball Valves

Appendix B. Fittings that were used for the densimeter construction



Appendix C. Temperature and Water Density Relationship. Note that 0.0 degrees C has been omitted to strengthen the relationship at the other temperatures.