THE STORAGE AND TRANSPORT OF PHOSPHORUS AND FECAL COLIFORM BACTERIA IN THE CHANNEL SEDIMENTS OF ENGLESBY BROOK

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Abstract

The transport and storage of total phosphorus (TP) and fecal coliform bacteria (FC) in the channel sediments of Englesby Brook were examined to gain a better understanding of the role which channel sediments play in the movement of pollutants through a fluvial system. Fifty six pool reaches were identified as possible storage and source areas for pollutants. Riffle sections of the stream were assumed to act primarily as conveyors of sediment and pollutants, having negligible storage capacity.

Eight randomly selected pools were monitored for each of eight, small to moderate sized storm events occurring from June to September 1994. Net sediment and associated pollutant removal rates were determined for each storm by measuring pollutant levels in the channel sediments just prior to storm events and measuring sediment scour and deposition during the storm event. The concentration of TP in the channel sediments during the study period averaged 0.48 mg g^{-1} (se=0.03, n=276), with no statistical differences in concentrations between storms, between pools, or at depth. The concentration of FC in the sediments averaged 456 g^{-1} (se=37, n=69), and there was no statistical difference in concentrations between storms. The constant TP and FC concentrations throughout the study period indicate that the pollutants were stored in the stream channel sediments during the period of study.

For storm events which ranged from 0.06 inches of precipitation and 9.6×10^4 ft^3 of total discharge, to 1.3 inches of precipitation and 5.3×10^5 ft^3 of total discharge, there was a range of cumulative stream power of 5.12×10^5 joules to 2.84×10^6 joules. Average scour depths ranged from 0.79 cm (se=0.15, n=62) to 5.18 cm (se=0.49, n=69), and average deposition depths ranged from 0.55 cm (se=0.17, n=62) to 4.76 cm (se=0.62, n=69). Positive mean sediment scour depths were measured for all storm events, confirming that stream channel sediments were being transported during periods of increased streamflow. Mean sediment scour depths were found to be significantly greater than mean deposition depths during the study period, indicating a net export of sediments and associated pollutants from the stream. By correlating the net sediment removal rate with cumulative stream power occurring during the storm events, a relationship was identified in which total stream power (r^2=0.90) or total storm precipitation (r^2=0.89) can be used to predict mean sediment scour depths during small, frequently occurring storm events.

Three conceptual sediment transport models have been introduced to aid in the interpretation of the sediment entrainment data. The Complete Transport Model describes the transport of fine-grained sediments (< 0.0625 mm) which are rapidly carried out of the stream. The Intermediate Transport Model describes the movement of sand sized particles (0.0625 mm < x < 2.0 mm) which are transported with the bedload, through one or two pools per storm before being re-deposited. The Incremental Transport Model describes the movement of coarse-grained particles (>2.0 mm) which move with the bedload but are transported only several cm downstream per storm before coming to rest.

Using the three sediment transport models and long-term precipitation records, minimum sediment and pollutant export rates were roughly approximated from the stream channel of Englesby Brook. Mean small storm export rates are estimated to be 2,509 kg sediment, 1.2 kg TP, and 1.4×10^9 FC. Minimum, yearly, small storm pollutant exports were estimated to be 36 kg TP yr^{-1} and 3.4×10^{10} FC yr^{-1}. These export values indicate that approximately 8 to 25% of the total estimated pollutant export can be attributed to the mobilization of stream channel sediments during small storm events.

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Table of Contents

Page

Acknowledgments........ ii

List of Tables........ vi

List of Figures........ viii

Chapter

1. Introduction........ 1
    - Statement of Hypothesis........ 2
    - Study Objectives........ 3
2. Literature Review........ 4
    - Introduction........ 4
    - Sediment Transport In Fluvial Systems........ 4
    - Phosphorus in Natural Waters........ 13
    - Fecal Coliform Bacteria In Natural Waters and Aquatic Sediments........ 18
3. Site Description........ 24
    - Introduction........ 24
    - Hydrology of Englesby Brook........ 26
    - Description of Morphological Sections........ 28
    - Summary........ 30
4. Methods........ 31
    - Introduction........ 31

Field Methods..31

Laboratory Methods..40

Data Analysis...44

5. Experimental Results...45

Introduction...45

Summary Data..47

6. Discussion...70

Introduction...70

Pollutant Storage in Englesby Brook Channel Sediments.....................................70

Sediment Transport in Englesby Brook....................75

Interpretations of Sediment Transport and Pollutant Data...80

7. Conclusions...93

References...96

Appendix A - Stream Pool Characteristics.......................... 102

Appendix B - Sediment and Pollutant Laboratory Data...104

Appendix C - Description of Individual Storm Event Data.. 114

Appendix D - Mathematical Calculations............................ 161

List of Tables

Table **Page**

2.1 Examples of Bacteriological Standards and Associated Beneficial Uses. 20

5.1 Hydrological Summary of Eight Storm Events on Englesby Brook. 46

5.2 Mean Values of Sediment Scour and Deposition Depths for 8 Storm Events on Englesby Brook. 48

5.3 Mean Sediment Density for 8 Storm Event Samplings. 57

5.4 Mean Density of Channel Sediment. 59

5.5 Sediment TP Concentrations for 0-1 cm and 1-5 cm Depths. 62

5.6 Sediment FC Concentrations for All Storm Events. 65

5.7 Individual Storm Event Statistical Comparison Summary. 68

6.1 Sediment Export Estimates for 8 Storm Events. 86

6.2 TP Export Estimates for 8 Storm Events. 89

6.3 FC Export Estimates for 8 Storm Events. 90

C.1 Depth of Scour and Deposition Data for Storm #1. 116

C.2 Depth of Scour and Deposition Data for Storm #2. 122

C.3 Depth of Scour and Deposition Data for Storm #3. 128

C.4 Depth of Scour and Deposition Data for Storm #4. 134

C.5 Depth of Scour and Deposition Data for Storm #5. 140

C.6 Depth of Scour and Deposition Data for Storm #6. 145

C.7 Depth of Scour and Deposition Data for Storm #7. 151

C.8 Depth of Scour and Deposition Data for Storm #8. 157

List of Figures

Figure		Page
2.1	Temporal Variation of Bedload Transport Rates From A Stream With Constant Water Discharge.	6
2.2	Distribution of Phosphate Species With pH.	15
3.1	Map of Englesby Brook Watershed	25
3.2	Elevation Profile of Englesby Brook	27
4.1	In Situ Measurement of Scour and Deposition with Scour Chains.	34
4.2	Scour Chain Setup and Sampling Regime for Typical Study Pool.	36
4.3	Standard Curve for November 30, 1994.	42
5.1	Mean Sediment Scour and Deposition Values for 8 Storm Events on Englesby Brook.	50
5.2	Results of Regression Analysis of Scour & Deposition Depths Versus Precipitation.	51
5.3	Results of Regression Analysis of Scour & Deposition Depths Versus Cumulative Stream Power.	53
5.4	Scour and Deposition Versus Cumulative Stream Power for Control Pool #25.	54
5.5	Average Scour and Deposition for All Storms, Considered for Each Stream Section.	55
5.6	Mean Channel Sediment Density for 8 Storm Event Samplings on Englesby Brook.	58

5.7 Mean Grain Size Distribution for Channel Sediments in Englesby Brook. 61

5.8 Mean TP Concentrations in Channel Sediments of Englesby Brook. 63

5.9 Mean Fecal Coliform Levels in Channel Sediments of Englesby Brook. 66

6.1 Illustration of Sediment Transport Models. 82

6.2 Comparison Between Englesby Brook Estimated Sediment Export and Sediment Discharge Values Measured and Computed by Yang and Stall 1976. 87

C.1 Storm #1 Hydrology. 115

C.2 Mean Scour and Deposition Values for Storm #1. 117

C.3 Scour and Deposition for Storm #1, Divided into Morphological Stream Sections. 119

C.4 Storm #2 Hydrology. 121

C.5 Mean Scour and Deposition Values for Storm #2. 123

C.6 Scour and Deposition for Storm #2, Divided into Morphological Stream Sections. 125

C.7 Storm #3 Hydrology. 127

C.8 Mean Scour and Deposition Values for Storm #3. 129

C.9 Scour and Deposition for Storm #3, Divided into Morphological Stream Sections. 131

C.10 Storm #4 Hydrology. 133

C.11 Mean Scour and Deposition Values for Storm #4. 135

C.12 Scour and Deposition for Storm #4, Divided into Morphological Stream Sections. 137

C.13	Storm #5 Hydrology.	139
C.14	Mean Scour and Deposition Values for Storm #5.	141
C.15	Scour and Deposition for Storm #5, Divided into Morphological Stream Sections.	142
C.16	Storm #6 Hydrology.	144
C.17	Mean Scour and Deposition Values for Storm #6.	146
C.18	Scour and Deposition for Storm #6, Divided into Morphological Stream Sections.	148
C.19	Storm #7 Hydrology.	150
C.20	Mean Scour and Deposition Values for Storm #7.	152
C.21	Scour and Deposition for Storm #7, Divided into Morphological Stream Sections.	153
C.22	Storm #8 Hydrology.	156
C.23	Mean Scour and Deposition Values for Storm #8.	158
C.24	Scour and Deposition for Storm #8, Divided into Morphological Stream Sections.	159

Chapter 1

Introduction

The movement of pollutants from the surface of a watershed to receiving waters is a complex process which is not well understood. Pollutants are transported from the watershed surface to streams primarily with storm water runoff, snow melt waters, and ground water. Once pollutants reach the stream waters, they can be transported either directly through the stream, to the receiving waters, or they can interact with the sediments and biota along the way.

Fine-grained, clay and silt size particles (< 0.063 mm) rarely settle out of suspension in fluvial environments (Graf 1984, Simons & Senturk 1977). Pollutants which are fine-grained particulate in form or adsorbed onto fine-grained sediments are thus unlikely to settle within a stream channel. It is therefore likely that a large portion of pollutants stored for long-periods of time (several years) within the sediments of a stream channel will be associated with coarse grained, sand size particles (≥ 0.063 mm) and the movement of these particles with the bedload must be examined as a long-term episodic transport mechanism for stored pollutants. This study investigates the movement of stream channel sediments through a small urban stream while quantifying the masses of two pollutants, total phosphorus (TP) and fecal coliform bacteria (FC), which are closely associated with sediments.

Lake Champlain, located between northwestern Vermont and northeastern New York, has developed increasing problems with eutrophication which can be attributed to loading of phosphates from point sources such as waste water treatment plants as well as non-point sources such as urban and agricultural storm runoff. The City of Burlington, Vermont has documented high levels of FC at its bathing beaches which have been attributed to urban runoff (Roy 1990). There has thus been great interest in the local communities to develop a greater understanding of how TP and FC make their way from a watershed surface to Lake Champlain.

In this thesis, concentrations of TP and FC in the sediments of Englesby Brook have been quantified in order to determine the total mass of these pollutants stored in the stream channel sediments. Scour and deposition of the stream channel sediments have been measured for eight small to moderate storm events (less than a one year occurrence interval), in order to determine if channel sediment transport is a significant mechanism in moving pollutants through a fluvial system and if the channel sediments are a source of pollutants to Lake Champlain. From the sediment scour and deposition data, the pollutant concentration data, and stream hydrology data, it is possible to estimate the long-term export of TP and FC from the stream channel sediments, as well as gain insight into residence times of pollutants in Englesby Brook.

Statement of Hypothesis

Total phosphorus (TP) and fecal coliform bacteria (FC) are stored in stream channel sediments which accumulate during receding flow following storm events and during periods of low flow. These stored sediments and associated pollutants are periodically and incrementally transported downstream, during periods of increased streamflow. Transport of stream channel sediment is therefore a significant mechanism in moving TP and FC through Englesby Brook, to Lake Champlain.

It is assumed for this study, that armored riffle sections of the stream act only as conveyors of material, having a negligible storage capacity between high flow events and thus, only "pool" reaches of the stream will be investigated for storage and export of sediments and pollutants. For this study, the stream channel sediments are defined as those sediment which reside on the bottom of the stream channel during low flow hydrological conditions. Although stream banks undoubtedly contribute a substantial amount of sediments and pollutants to the system during periods of increased stream flow, they are not considered as part of the stream channel sediments for this study.

Study Objectives

The following specific objectives have been established in order to test the stated hypothesis:

1. sample and test the stream channel sediments of Englesby Brook for TP and FC to determine if storage of TP and FC is occurring.

2. quantify the reservoir of pollutants by determining average sediment concentrations of TP and FC, and then determining a volume of sediment which is active during small and moderate size storm events.

3. determine if the sediments are transported during periods of increased streamflow from small and moderate size storm events.

4. estimate the amount of stream channel sediment which is transported during periods of elevated streamflow from small and moderate size storm events.

5. approximate the long-term export of sediment, TP, and FC from the stream channel of Englesby Brook.

Chapter 2

Literature Review

Introduction

This literature review addresses the theory of sediment transport, sediment phosphorus interactions, and the storage and transport of fecal coliform bacteria in and with aquatic sediments. Sediment transport and bedload equations have been reviewed in some detail to gain a better understanding of the many processes contributing to the mobilization and transport of stream channel sediments. Literature on total phosphorus (TP) and fecal colifom bacteria (FC), and their interactions with aquatic sediments are discussed in order to provide an understanding of the processes which control the accumulation and release of pollutants in and from stream sediments. The literature review is used to justify assumptions which have been made in the undertaking of this study.

Sediment Transport in Fluvial Systems

Introduction

The measurement and quantification of sediment transport has been described by many researchers yet definitions and accepted methodologies vary widely . Beginning with the works of DuBoys (1879), researchers have attempted to describe the movement of sediments, only to find discrepancies between different fluvial systems and under varying hydrological conditions. The state of knowledge concerning sediment transport has greatly increased since the works of DuBoys and beginning with the landmark works of Einstein (1937), the generation of data and theory has escalated tremendously.

Definitions and General Theory

Sediment in the process of transportation can be classified as either bed load or suspended load. Bedload can be defined as that sediment which moves at or near the stream channel bottom by saltation, rolling, or sliding (Graf 1984, Dunne & Leopold 1978, Simons & Senturk 1977). The bedload moves in a "bed layer" considered to be several grain diameters in thickness. Bedload is made up of those sediments which are larger in diameter than the critical diameter for suspension as determined by shear stress and stream velocity. The discharge of bedload is believed to be temporally variable, moving in pulses rather than steady flow rates, even when stream flow is relatively constant (Figure 2.1) (Edwards & Glysson 1988). Bedload also has high spatial variably across a cross section (Edwards & Glysson 1988).

Suspended sediment load is defined as that sediment which is transported in the water column and is entrained for a considerable amount of time. Suspended sediment is kept in suspension by turbulent motion and can occur throughout the entire water column above the bed layer (Graf 1984, Simons & Senturk 1977). Suspended sediment is comprised of fine grained particles having a diameter equal to or less than the critical diameter for suspension as determined by flow conditions. The discharge of suspended sediment is spatially variable with respect to both depth and across a cross section but tends to be more temporally homogeneous than bedload during constant stream flow conditions (Edwards & Glysson 1988).

Many other terms exist for the various components of fluvially transported sediments. Bed material load (BML) is the material which makes up the stream channel bed. BML is that sediment made up of the coarse grained material which is difficult to transport and is unlikely to be suspended in the flowing water. BML is generally greater in size than silt (0.0625 mm) and is likely to settle along the channel during transport (Simons & Senturk 1977, Vanoni 1977, Graf 1984).

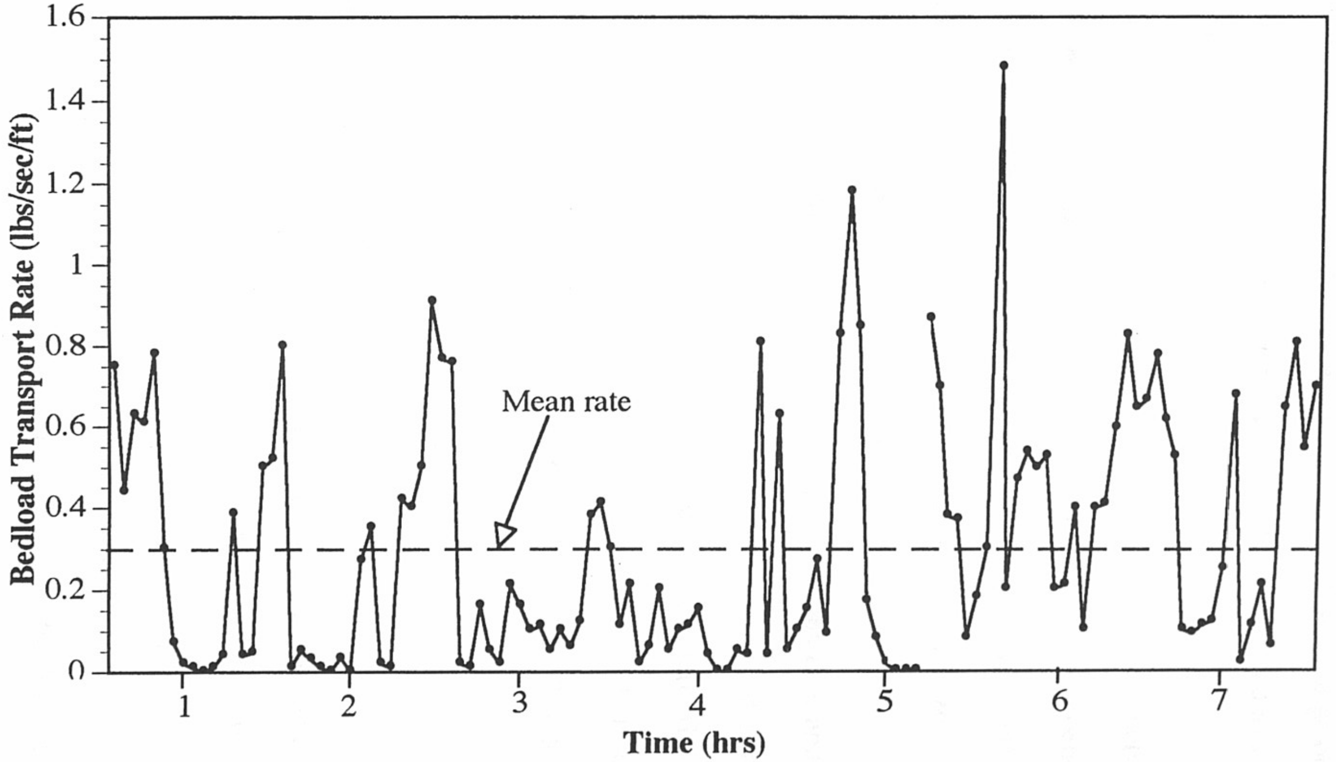


Figure 2.1 Temporal Variation of Bedload Transport Rates From A Stream With Constant Water Discharge (From Edwards & Glysson 1988 -after Carey, 1985).

Wash load (WL) is defined as the fine-grained sediments which are easily transported in suspension by stream flow. WL is generally made up of silt and clay size particles (<0.0625 mm) and is likely to travel through the entire stream system without being deposited (Shen 1971). WL makes up only a small percentage of the stream channel bed and can thus be closely associated with the suspended load (Simons & Senturk 1977, Vanoni 1977, Graf 1984).

It should be noted that the critical diameter which will ultimately determine whether a particle is transported as bedload or suspended load is dependent on the velocity and turbulence of the water in a stream. Because velocity and turbulence are highly variable throughout a stream, particles of many different sizes will move among the bed material, bedload, and suspended load fractions during transport. Einstein (1942) noted that "an intimate relationship exists between the bed material and the bedload". The mathematical descriptions which will be discussed below, are all dependent on the assumption that flows are constant over time. However in nature, flows are rarely constant and it is one of the goals for this project to demonstrate that sediments are primarily transported during discrete periods of increased flow during which time velocity and discharge change dramatically.

Sediment Transport Theory

Simons & Senturk (1977) give a complete history of the development of bedload transport theory from the first investigations by DuBoys (1879), through the works of Schoklitsch (1914), Gilbert (1914), Straub (1935), Sheilds (1936), Einstein (1937, 1942, 1950, & 1972), Meyer-Peter and Muller (1948), Brown (1950), Bagnold (1966), Toffaleti (1969), Graf (1984), and many others. Prior to the development of Einstein's bedload equations, the transport equations were based on the idea that a constant force was exerted on the sediment particles by the flowing water (Simons & Senturk 1977) which can be demonstrated by the DuBoys equation:

$$q_{bv} = K\tau_o(\tau_o - \tau_c)$$

where:

q_{bv} = volumetric transport rate of bedload (kg $m^{-2}sec^{-1}$)
K = rate constant dependent on sediment characteristics (unitless)
t_o = unit tractive force exerted on the channel bed by the flow of water (kg m^{-2})
t_c = critical tractive force at which sediment will begin to move (kg m^{-2})

Although many investigators modified or added to the DuBoys equation, the basic theory remained the same until Einstein's (1950) work.

Einstein (1950) based his bed load equation on the assumption that particles are suspended by turbulent forces which can be probablistically modeled. There is a probability that a fluctuation in the turbulent flow will be great enough to suspend particles of a given dimension and this probability can be calculated for the particle size ranges of concern. Einstein modified his equations to take into consideration the size gradation of bed material as well as the hiding effects of larger grains shielding smaller grains from turbulent forces.

Einstein's work initiated the exploration of the numerous parameters and relationships which play a role in the transport of fluvial sediments. The Einstein transport functions are perhaps the most complex and in-depth mathematical descriptions of sediment movement to date which continue to be reliable with only a few modifications over the years.

Dawdy and Vanoni (1986) give a strong comparison of the reliability of the historical sediment discharge equations, showing that each of the equations has been developed for a unique set of stream characteristics which when applied to a wide variety of streams, prove to be unreliable. When the models are properly calibrated as with the Modified Einstein Model (Colby and Hembree 1955) or are applied using actual stream parameters as with the Revised Modified Einstein Model (Burkham and Dawdy 1980), the reliability of the models becomes quite reasonable.

Perhaps the most encouraging mathematical description of sediment transport is that of Yang and Stall (1976), who explored the use of a unit stream power equation to predict fluvial sediment transport. Yang and Stall used 156 sediment transport data sets measured in five natural rivers by eight different investigators to derive coefficients for, and compare results predicted by, their unit stream power equation:

$$\log C_t = 5.435 - 0.286 \log \frac{wd}{u} - 0.457 \log \frac{U_*}{w}$$

$$+ \left(1.799 - 0.409 \log \frac{wd}{u} - 0.314 \log \frac{U_*}{w}\right) \log \left(\frac{VS}{w} - \frac{V_{cr}S}{w}\right)$$

in which:

C_t = total sediment concentration in bedload (ppm by weight)
ω = terminal fall velocity of particles (m sec^{-1})
d = median sieve diameter of bed material (mm)
υ = kinematic viscosity ($\mathrm{m}^2 \mathrm{sec}^{-1}$)
U_* = shear velocity (m sec^{-1})
VS = unit stream power (J $\mathrm{sec}^{-1} \mathrm{m}^{-1}$)
$V_{cr}S$ = critical unit stream power (J sec^{-1} m^{-1})

For values of $\frac{U_*d}{\upsilon}$ between 1.2 and 70:

$$\frac{V_{cr}}{w} = \frac{2.5}{\log\left(\frac{U_*d}{u}\right) - 0.06} + 0.66$$

and for values of $\frac{U_*d}{\upsilon}$ greater than or equal to 70:

$$\frac{V_{cr}}{\omega} = 2.05$$

Yang and Stall's unit stream power equation (Yang & Stall 1976) shows excellent agreement with the real data collected by Gilbert (1914), Einstein (1950), Hubbel and Matejka (1959), and Nordin (1964). When compared to other sediment discharge equations, the unit stream power equation appears to be a much more dependable predictor than any of the historical equations discussed above. Of 13 different sediment transport equations evaluated by Yang and Stall (1976), only those by Colby (1955), Laursen (1958), Tofaletti (1969), and Einstein (1950) were able to estimate transport reasonably under similar conditions as they were derived under. The Yang and Stall (1976) unit stream power equation was able to give reasonable sediment transport predictions under a wide variety of conditions.

Scour and Deposition of Stream Channel Sediments

The transport theories presented above all describe a total mass of sediment capable of being transported in a given reach of stream, under specific hydrological conditions and assuming steady flow rates. There is no distinction between those sediments which originate in the stream itself and those which enter the stream from surface runoff or watershed erosion. It is the goal of this study to estimate the amount of stream channel sediment which is being mobilized from the stream channel bottom, exclusive of any other sediment sources.

It can be observed by watching a stream during and following a storm event, that as flow increases, channel sediments begin to move downstream and scour is initiated. These sediments will continue to be scoured and transported until the flow velocity slows and the turbulent forces decrease at which time the sediments will discontinue their motion and will settle on the stream channel bottom.

Lane (1955) expressed the relationship:

$$Q_{sD_{50}} \propto QS$$

where:

$Q_{sD_{50}}$ = transport rate of the median diameter sediment fraction (D_{50}) per unit width of channel (kg sec^{-1})

Q = water discharge per unit width of channel ($\mathrm{m}^3\ \mathrm{sec}^{-1}$)

S = slope of the stream bed (unitless)

This relationship suggests that if either stream flow or stream bed slope increases, then the sediment transport rate or the median sediment diameter must increase (Simons & Associates 1982). In a channel where gravel and cobbles are the dominant bed material, increased flow will tend to selectively remove the finer grained material thus increasing the median diameter of the residual sediment, causing an "armoring" effect (Graf 1984, Simons & Senturk 1977). In a sand bed channel armoring is not likely to occur. Therefore, the results of increasing stream flow must be increased sediment discharge, and scouring of the stream channel sediments will occur. As stream flow decreases, sediment transport must decrease and deposition will occur (Simons & Associates 1982).

Field Measurements of Sediment Transport

The measurement of sediment transport in natural fluvial systems is critical to determining rates of sediment transport and associated pollutant transport (Edwards & Glysson 1988). Measurement of suspended sediment loads are difficult, yet depth integrated sampling techniques have yielded relatively accurate estimates (Hubbell 1964, Simons & Senturk 1977, Edwards & Glysson 1988). Bedload measurements have proven to be much less reliable and no method of measurement has been universally accepted (Hubbell 1964, Edwards & Glysson 1988).

Suspended sediment loads are generally measured by collecting depth integrated samples in a vertical column of a stream to determine an average suspended sediment concentration for that vertical. A series of verticals are then measured to get an average suspended sediment discharge across a stream cross section. For streams greater than 5 feet in width a minimum of 10 verticals is desirable. For streams less than 5 feet in width as many verticals as is possible that are spaced 3 inches apart should be used (Edwards & Glysson 1988). Suspended sediment samples can be retrieved using a variety of sampling techniques including grab sampling, automatic pumping samplers, hand-held single stage suspended sediment samplers, and depth or point integrated samplers (Hubbell 1964, Simons & Senturk 1977, Edwards & Glysson 1988).

Bedload is generally measured by sampling across a stream cross section in equal increments. Twenty increments are generally desirable, and 8 to 10 repetitions of the measurements is recommended (Edwards & Glysson 1988). The most popular sampling device for bedload measurements is the Helley-Smith sampler (Edwards & Glysson 1988). Equations must be used to correct for the capture of excess suspended material (Edwards & Glysson 1988).

Scour of sediments in a stream channel has for the most part been measured along piers and bridge abutments where scour is evident from previous sediment depths

(Simons & Associates 1982). However, these techniques usually underestimate scour due to infilling or deposition of new sediments between measurements. Scour chains (Lisle and Eads 1991) allow for the in situ measurement of total scour and net deposition. By inserting a dowel with an attached chain into the stream bottom sediments and draping the chain over the top of the sediments, the depth of scour can be determined by the final burial depth of the chain. Net deposition or erosion of sediments in stream channels is generally accomplished by surveying changes in channel bottom elevations (Lisle & Eads 1991).

Phosphorus in Natural Waters

Introduction

Increases in nutrient levels in natural waters can accelerate the growth of aquatic plants and algae, leading to eutrophication. The buildup and subsequent decay of organic matter lowers dissolved oxygen levels which can lead to large fish kills and the elimination of many aquatic species of plant and animals. Eutrophication poses a general nuisance to recreational users and commonly presents taste and odor problems in drinking water (Thomann & Mueller 1987).

Phosphorus is generally considered to be the limiting nutrient in fresh water systems and controls the rate of growth of aquatic plants and algae. Phosphorus is added to receiving waters (lakes and ponds) through both point sources and non-point sources and is transported in stream waters. Point sources, such as waste-water treatment plants, discharge their effluent directly to receiving waters at a specific outfall location. Non-point sources of TP include urban and agricultural runoff which contains TP from lawn and crop fertilizers, domestic animal and live stock feces, and detritus material. Because point sources of TP have been drastically reduced over the past two decades, it is the non point sources of TP which often pose long-term eutrophication problems.

Forms of Phosphorus in Fluvial Systems

Phosphorus (P) is transported and stored in fluvial systems in a number of different forms. Phosphorus can be transported in the dissolved state within the stream waters as either soluble inorganic phosphorus or as soluble organic phosphorus. Phosphorus in nature is most often found as soluble inorganic phosphorus such as oxidized phosphates or orthophosphates (HPO_4^{2-}, $H_2PO^{4\ -}$, or PO_4^{3-}) which are derived from the weathering of phosphorus bearing minerals (Holtan et al. 1988). The form which orthophosphate will take in water is pH dependent (Figure 2.2, Holtan et al. 1988). Soluble inorganic phosphorus is the primary form which is readily available for biological uptake, although some plant species are able to make use of other forms of phosphorus. Soluble organic phosphorus is derived from the decay of detrital material and from direct leakage from aquatic plants (McCarty 1968). Soluble organic phosphorus may in some instances be utilized by aquatic plants but in most cases must be degraded back to soluble inorganic phosphorus before it is readily available for uptake (Bostrom et al. 1988).

Phosphorus can also be transported and stored along with the sediments as particulate inorganic phosphorus or as particulate organic phosphorus. Particulate inorganic phosphorus is composed of adsorbed (exchangeable) phosphorus, chemisorbed phosphorus, and amorphous phosphorus (Holtan et al. 1988). Particulate inorganic phosphorus generally forms from the precipitation or adsorption of orthophosphate (McCarty 1968). Particulate forms of phosphorus can be easily dissolved or desorbed when pH or redox conditions change. Particulate organic phosphorus is derived from detritus and is formed when either soluble inorganic phosphorus or soluble organic

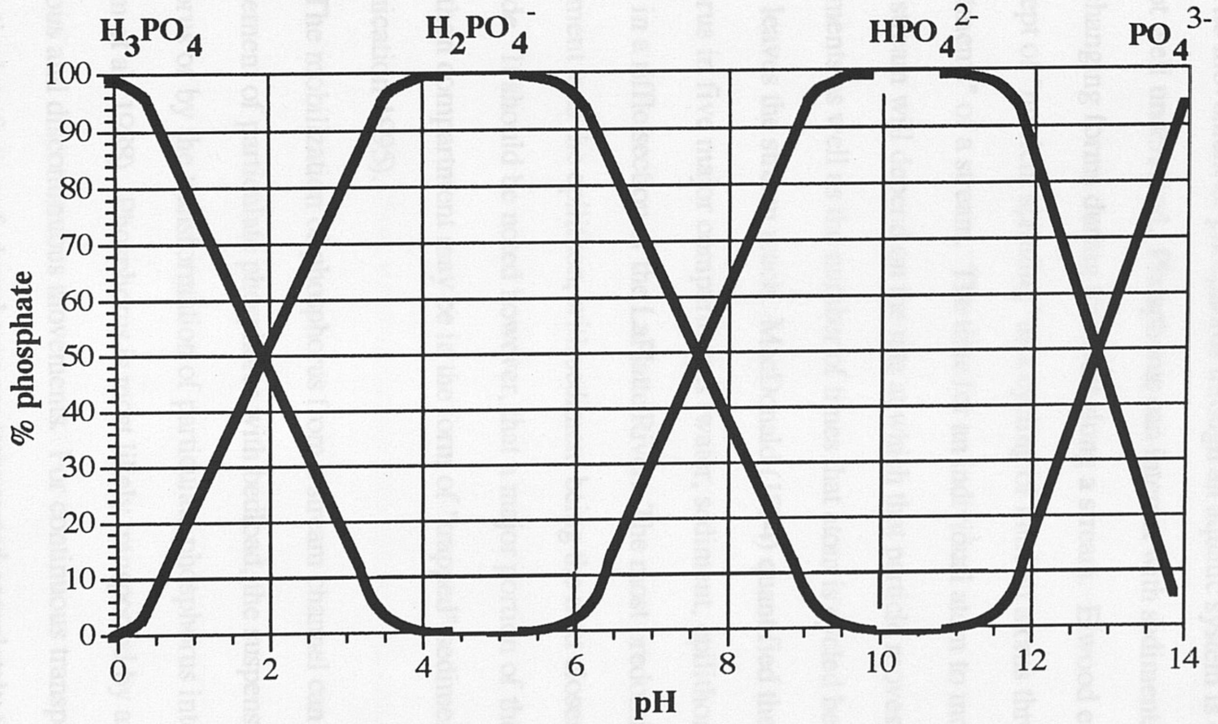


Figure 2.2 Distribution of Phosphate Species With pH. (Holtan et al. 1988)

phosphorus is taken up by aquatic plants (MacDonald 1994, Lee et al. 1985, McCarty 1968).

Phosphorus Transport and Storage in Fluvial Systems

The movement of phosphorus through an aquatic system is extremely complex and is not well understood. Phosphorus can interact with sediments and aquatic biota as well as changing forms during transport along a stream. Elwood et al. (1985) discusses the concept of "nutrient spiraling" as a cycling of nutrient atoms through individual "compartments" of a stream. The time for an individual atom to move through a given reach of stream will depend on the rate at which that particle moves between compartments as well as the number of times that atom is cycled between compartments before it leaves the stream reach. MacDonald (1994) quantified the standing stock of phosphorus in five major compartments (water, sediment, epilithon, macrophytes, and detritus) in a riffle section of the LaPlatte River. The most predominant storage compartment was the epilithon, with sediment being the next closest in storage magnitude. It should be noted however, that a major portion of the phosphorus stored in the epilithon compartment may be in the form of "trapped" sediments (Hoffman, personal communication 1995).

The mobilization of phosphorus from a stream channel can be accomplished by the movement of particulate phosphorus with bedload, the suspension of particulate phosphorus or by the transformation of particulate phosphorus into dissolved phosphorus (Bostrom et al. 1988). Phosphorus is most likely transported by a combination of continuous and discontinuous movements. For continuous transport, dissolved and small particulate forms of phosphorus are transported completely through the entire fluvial system. For discontinuous transport, coarse particulate phosphorus is deposited and remobilized during a series of discrete high flow events in between which there may be long periods of phosphorus storage (Verhoff et al. 1982). Dissolved phosphorus is taken up by plants and algae and is later re-introduced into the waters through decay or leakage.

The mobilization of particulate phosphorus may be an important mechanism in the transport of phosphorus through fluvial systems. By introducing particulate phosphorus into the water column as well as releasing pore-waters containing soluble phosphorus into the overlying waters, re-suspension of bottom sediments has been identified as an important source of phosphorus (Rosensteel & Strom 1991, Pilleboue & Dorioz 1986). Pilleboue & Dorioz (1986) observed increases in phosphorus concentrations during high flow events which they attributed to the re-suspension of phosphorus enriched bottom sediments that had accumulated since the last high flow event . Pilleboue and Dorioz (1986) argued that much of the phosphorus being transported through a fluvial system settles out of suspension onto the stream bottom during low flow periods where it could be stored for long periods of time. This stored particulate phosphorus is then slowly released back into the overlying waters during later re-suspension or erosional events.

The transformation of phosphorus from the particulate phase to the dissolved phase and back is controlled by temperature, pH, redox potential, sediment size and composition, soluble phosphorus concentrations, stream velocities, and diffusion rates (Bostrom et al. 1988, Drake & Heaney 1987, Fowler et al. 1984, Messer et al. 1983, and Golterman 1976). Increased temperature increases biological activity or primary production which increases nutrient uptake (Bostrom et al. 1988). Increased pH decreases the phosphorus adsorption capacity of iron and aluminum fractions of the sediment by increasing competition between hydroxide ions and orthophosphates (Lijklema 1977). At low redox potentials (below 200 mv), Iron(III) is reduced to Iron(II) releasing phosphorus into the overlying waters (Lijklema 1977, Bostrom et al. 1988). Sediment comprised primarily of small particles has more surface area and thus more adsorption potential than sediments made up of larger particles. Sediments which are rich in clay, iron, and alluminum will also have high adsorption capabilities (Stone & Mudroch 1989).

The concentrations of soluble phosphorus in the overlying waters will control the amount of phosphorus which can be adsorbed onto the sediments as described by adsorption isotherms (Langmuir 1918, Freundlich 1926, Drake & Heaney 1987). High concentrations of soluble phosphorus in the water will cause slower diffusion due to smaller concentration gradients or may even cause soluble phosphorus to move back into the sediments if a reverse gradient is present. Low concentrations of soluble phosphorus in overlying waters will increase concentration gradients, increasing phosphorus diffusion into overlying waters (Bostrom et al. 1988).

The investigation of stream bed sediment transport and sediment phosphorus concentrations is a critical link to understanding the transport and storage of phosphorus in natural streams (Meals 1990; Holtan et al. 1988). Brown et al. (1995) have shown that a significant portion of the phosphorus stored within a stream reach is associated with the channel sediments. MacDonald (1994) observed low overall sediment storage of phosphorus in a riffle section of stream, yet closer examination of the data reveals that when random sampling landed in a small pool section of that riffle reach, finer sediment particles where present and the storage of phosphorus was dramatically higher.

Fecal Coliform Bacteria In Natural Waters and Aquatic Sediments

Definitions and General Theory

Fecal coliform bacteria (FC) found in natural waters are used as an indicator of water quality (Thomann & Mueller 1987). FC are easily measured and are generally not present in uncontaminated waters. FC are generally found in association with pathogens (such as Salmonella and Shigella), viruses (such as Hepatitis A and Polioviruses), and pathogenic protazoa (such as Giardia) which are much more difficult and expensive to measure. Therefore, FC is often measured to determine the probability of harmful microbes existing in water.

Ingestion of water with any countable FC can lead to gastro-intestinal disease. Exposure to waters having elevated levels of pathogens can cause eye, ear and nose infections, and skin rash, (Thomann & Mueller 1987). The primary modes of pathogenic infection are through ingestion of contaminated waters or fish and through contact or submersion in contaminated waters. To insure public health safety, it is therefore important for managers of drinking waters, recreational waters, and fishing waters, to monitor the levels of FC. Table 2.1 shows public safety standards for a variety of water uses. Most municipalities have set maximum drinking water levels of FC at 0.0 per 100 ml of water and exposure levels for swimming at 200 per 100 ml water.

FC contamination is a common problem in waters adjacent to urbanized areas or agricultural lands. FC bacteria, which originate in the intestinal tract of humans and animals, are introduced to natural waters by: (1) direct discharge of human wastes (Thomann & Mueller 1987), (2) urban runoff containing fecal matter from domestic and wild animals (Pitt 1985), and (3) agricultural runoff containing fecal matter from live stock (Stephenson & Rychert 1982, Meals 1990, Vermont RCWP 1991). Meals (1990) and Vermont RCWP (1991) found that FC levels in the streams of two Vermont agricultural watersheds were reduced 50-70% by implementing best management practices (BMPs). It is thus critical to the development of remediation plans and implementation of BMPs, to understand the mechanisms by which FC is transported to receiving waters and possible long-term storage of FC in natural systems.

Table 2.1 Examples of Bacteriological Standards and Associated Beneficial Uses (Thomann & Mueller 1987)

* *TC=total coliforms*

** *FC= fecal coliforms*

Beneficial Use	Bacteria Group	Concentration (num/100ml)	Agency
Public Water Supply	TC*	0	WHO
	FC**	0	WHO
Primary Water (contact recreation, bathing)	TC	2400	New York
	FC	200	New York
Secondary Water (contact recreation)	FC	1000	Washington, D.C.
Fishing	TC	1000	New Hampshire
	FC	100	North Carolina
Shellfishing	TC	70	United States
	FC	14	Mexico, Venezuela

Transport of Fecal Coliform Bacteria

FC bacteria are transported through a fluvial system as small suspended particles ($\leq$ one micron) or adsorbed to sediment particles. As living organisms, out of their natural habitat, FC bacteria will generally die off over time as a function of the decay constant (K_b) described by the relationship (Thomman & Mueller 1987):

$$K_b = K_{b1} + K_{bl} + K_{bs} - K_a$$

where:

K_{b1} = death rate due to temperature, salinity, and predation (# per day)
K_{bl} = death rate due to sunlight (# per day)
K_{bs} = net loss (gain) due to settling (resuspension) (# per day)
K_a = growth rate of organisms over time (# per day)

Decay rates for FC in fresh waters are typically 1 day^{-1} and can reach rates as high as 84 day^{-1} in sea water (Thomman & Mueller 1987). The temporal distribution of FC bacteria in river and stream waters can be determined by using the decay constant (K_b) in the relationship (Thomann and Mueller 1987):

$$\frac{dN}{dt} = -K_b N_o$$

where:

N = FC concentration at time (t) $\left(\#organisms/100ml\right)$
N_0 = initial concentration of FC $\left(\#organisms/100ml\right)$
K_b = FC decay rate constant (1/ time)

Fecal Coliform Bacteria in Aquatic Sediments

As post storm event stream flow velocities decrease, many of the FC bacteria which are adsorbed onto coarse grained particles settle out of suspension onto the stream bottom (Thomann & Mueller 1987). FC can be adsorbed to sediment or may be suspended in sediment pore waters where they may exhibit significantly reduced decay rates as compared to the decay rates in open waters (Hejkal et al. 1981, LaBelle & Gerba 1980, Roper & Marshall 1979, Savage 1905). Resuspension of the FC-laden sediments during subsequent high flow events can act as a source of FC to the overlying waters (Doyle et al. 1992, Stephenson & Rychert 1982, Varness et al. 1978, Brickler et al. 1976, Grimes 1980, Savage 1905).

Beginning with the work of Savage (1905), researchers have demonstrated that concentrations of FC are often many times higher in bottom sediments than in overlying waters. In a study of a variety of lakes and streams, Van Donsel and Geldreich (1971) found FC levels to be between 100 and 1000 times greater in sediments than in overlying waters. Matson et al. (1978) found sediment levels of FC to be up to 2,500 times greater than overlying waters of the Shetucket River, Connecticut. Grimes (1980) found similar results in studies on the Mississippi River and determined that the resuspension of bottom sediments during river dredging caused increases in FC concentrations downstream.

Higher concentrations of bacteria within the channel sediments have been attributed to a combination of sedimentation, adsorption, extended survival rates of FC in sediments, and the actual growth or multiplying of FC in sediments (Doyle et al. 1992, LaLiberte & Grimes 1981, Grimes 1980, Van Donsel & Geldreich 1971). The nutrient rich environment of the sediment along with abundant surface area for microbial attachment provides stability and protection to FC colonies. Sediment composition also plays a role in the survival and growth rates of FC bacteria because fine-grained material with higher organic content is better able to support bacteria populations than are sandy sediments with low organic content.

LaLiberte & Grimes (1981) found FC populations in lake sediments were able to survive several days longer than those in the overlying waters and that populations lasted longer in fine grained sediments than in coarse sands. The FC populations displayed a growth period during the first few days before slowly declining. Roper and Marshall (1979) found FC decay rates in river sediments to be an order of magnitude lower than in the overlying waters of the Tamor River of Australia. The high sediment levels of FC bacteria reported above indicate that the role of sediments and sediment mobilization must be examined to better understand FC contamination, storage, and transport.

Thomann and Mueller (1987) described the input of organisms to overlying waters through the process of resuspension by the equation:

$$U\frac{dN}{dx} = -K_b N + \frac{v_u}{H} M_s r_N$$

where:

U = velocity
v_u = resuspension velocity
H = depth of the water column
M_s = bulk density of sediment solids
r_n = concentration of bacteria on solids
x = distance downstream

Stephenson and Rychert (1982) examined the effects of resuspension in FC contaminated, rangeland stream sediments. By manually disturbing bottom sediments and simultaneously monitoring FC levels in the overlying waters they found dramatic increases in FC concentrations. Varness et al. (1978) found river concentrations of FC greatly increased following periods of heavy recreational activity and attributed the increase to resuspension of bottom sediments by human induced turbulence. It is evident from these studies that FC bacteria are able to accumulate in aquatic sediments and can later be mobilized by increased water velocity, turbulence, or human activity. Mobilization and entrainment of contaminated aquatic sediments are therefore important mechanisms in the degradation of water quality.

Chapter 3

Site Description

Introduction

The Englesby Brook watershed is a drainage area comprised of approximately 2.2 km^2 of urbanized land. Located in the southern end of the City of Burlington, in northwestern Vermont, Englesby Brook winds a total distance of 3.1 km through a wide variety of land use areas before discharging into Lake Champlain (Figure 3.1). The climate of northwestern Vermont can be described as cool-humid (MacDonald 1994), with and average annual temperature of 6.6 ^{o}C (44 ^{o}F), a mean monthly summer high of 21 ^{o}C (70 ^{o}F), and a long-term mean annual precipitation of 86 cm (34 in).

Englesby Brook has recently been classified by the Vermont Department of Environmental Conservation (Pease, personal communication, 1995) as one of the most heavily impacted streams in the state of Vermont and has been the under a number of investigations to determine sources of pollutants and possible remediation strategies (Roy 1990, Cassell et al. 1994). The stream is believed to transport high levels of fecal coliform bacteria (FC) during and just after high flow events. A joint committee of researchers from the University of Vermont, City of Burlington, State of Vermont DEC, and The USDA Soil Conservation Service has initiated a stream remediation program which, under funding from the U.S. EPA, will begin in the summer of 1995 with a general debris cleanup by the Vermont Youth Conservation Corp.

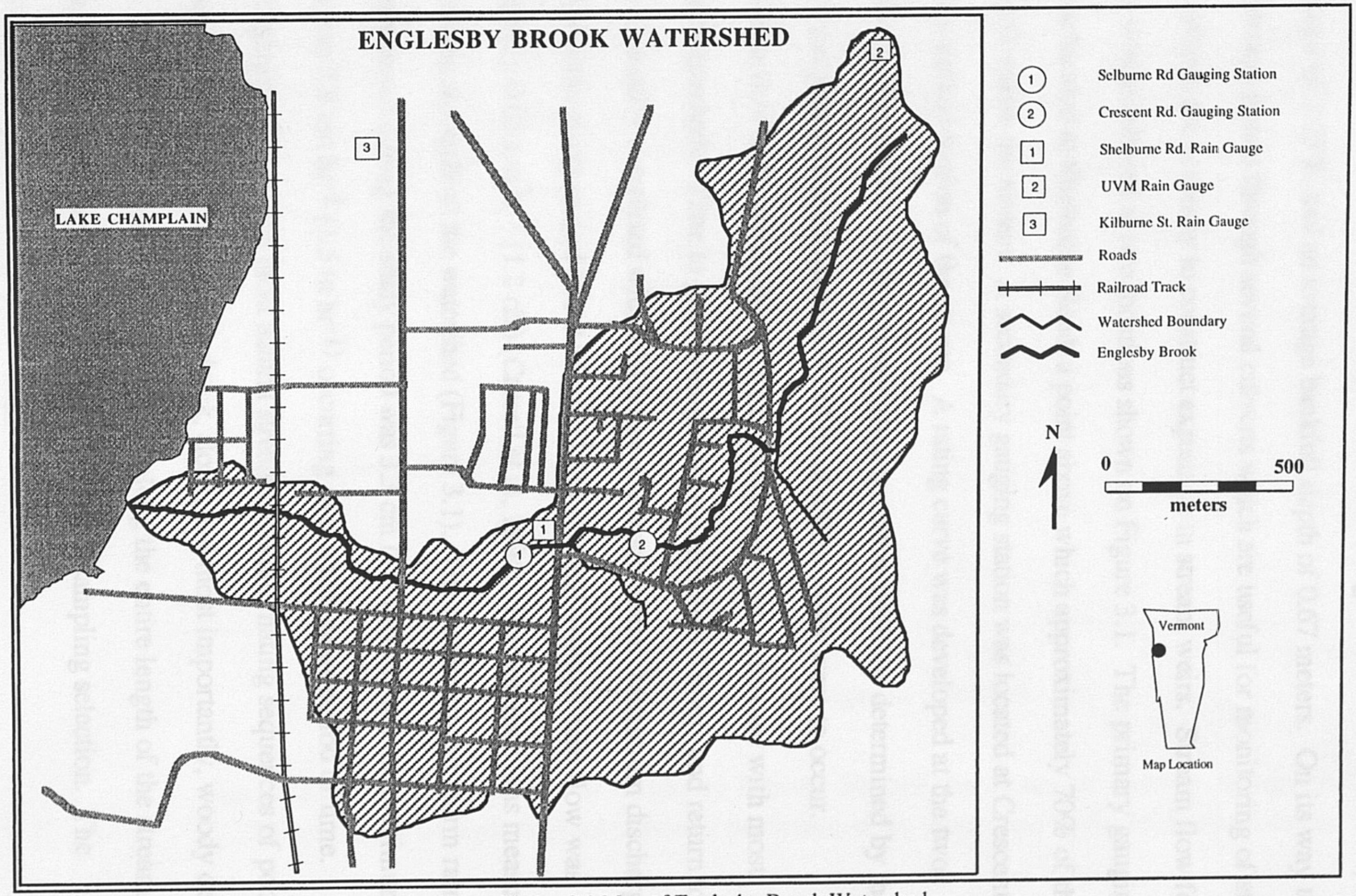


Figure 3.1 Map of Englesby Brook Watershed

Hydrology of Englesby Brook

Englesby Brook is 3.1 km in length, with an average width of 2.25 meters, an average slope of 2.23%, and an average bankfull depth of 0.67 meters. On its way to the lake, the stream passes through several culverts which are useful for monitoring of stream flow and relieve the necessity to construct expensive in stream weirs. Stream flow for this study was monitored at two locations shown on Figure 3.1. The primary gauging station was located at Shelburne Road, a point above which approximately 70% of the storm runoff enters the stream. A secondary gauging station was located at Crescent Road in the upland section of the stream. A rating curve was developed at the two stations so that stream flow at the primary gauging station could be determined by the secondary gauging station if mechanical failure of a flow meter were to occur.

Storm flow in Englesby Brook is extremely flashy as is the case with most urbanized watersheds. Time to peak averages approximately 0.5 hours and return to baseflow is usually completed within 24 hours of a storm event. Maximum discharge measured for the study period was 0.96 m^3s^{-1} (34 cfs) and average base flow was approximately 0.034 m^3s^{-1} (1.2 cfs) (Cassell et al, 1994). Precipitation was measured in three locations throughout the watershed (Figure 3.1). The maximum per storm rainfall amount measured during the study period was 3.3 cm (1.3 inches) and the maximum intensity was 3.8 cm hr^{-1} (1.5 in hr^{-1}) occurring over a half-hour period of time.

Englesby Brook, like most natural streams, has alternating sequences of pools and riffles which are controlled by bedrock, slope, and most importantly, woody debris or refuse dams. Fifty six pools were identified along the entire length of the stream, and each was assigned an identification number for random sampling selection. The distribution of the pools can be seen in Figure 3.2.

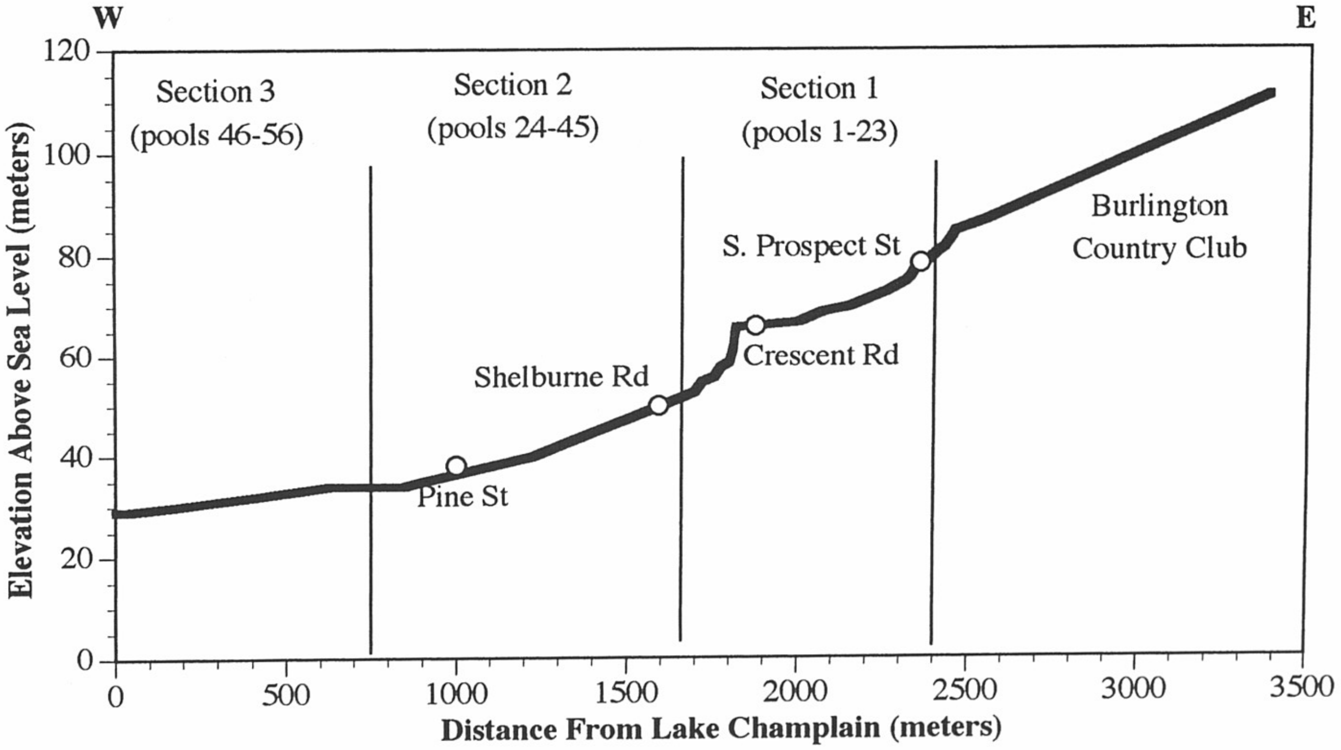


Figure 3.2 Elevation profile of Englesby Brook. Figure shows major road crossings and three major morphological sections determined by slope and hydrologic conditions.

Description of Morphological Sections

Englesby Brook can be divided into three distinct morphological sections. These three sections have distinct characteristics which control hydrology and water quality (Figure 3.2). Englesby Brook has it's headwaters at the Burlington Country Club. The country club has little development and has several detention ponds which help to attenuate storm runoff peak discharges from the well drained fairways. The ponds are also the home to aquatic fowl which add substantially to the FC problem found in the stream waters (Roy 1990). Fertilizers used on the golf course itself are a likely source of total phosphorus (TP) to the stream. Although the country club does play an important role in the hydrology and water quality of Englesby Brook, it was not examined during this study because much of the stream is artificially channeled beneath fairways making sediment transport observations arduous and poorly representative of a natural system.

Section One Section one of the stream is a steep upland reach which has it's upper limit at South Prospect Street, just after the stream exits the country club (Figure 3.2). This upper section is underlain by a resistant sandstone (Monkton Quartzite), which is responsible for the steep gradient. The land use throughout section one is primarily low density residential where storm runoff containing lawn fertilizers and domestic animal waste may add to the TP and FC levels in the stream.

The stream corridor in section one is a riparian forest with cascading waterfalls where the bedrock crops out and alternating pool and riffle sections are controlled primarily by large woody debris. Pools make up 22 % of the stream channel area and riffles make up 78%. The average gradient of this stream section is 3.85%, the average stream width is approximately 2.2 meters, the average length of the pools are about 9.8 meters with an average bankfull depth of 0.36 meters. The stream in this section is contained by steep ravine walls which are closely bordered by human development. Overbank flooding in this section is confined to a narrow area within the ravine walls.

Section Two Section two of the stream begins just upstream from Shelburne Road and ends approximately 200 meters downstream from Pine Street. The watershed adjacent to the stream in section two (Figure 3.2) is characterized by several high use commercial areas and high density residential areas. This section has a high percent of impervious area which is responsible for generating nearly half of the runoff for the entire watershed. Seventy percent of the runoff enters the stream above this section (Cassell et al. 1994). A high concentration of lawn fertilizers and domestic animal waste may add TP and FC to the stream within this section.

The stream corridor in section two is characterized by a tightly confined riparian forest with abundant unauthorized dumping sites of refuse. The stream is deeply incised in the under-lying fluvial sands and gravels, leaving little room for lateral migration or overbank flooding. The pools and riffles of this section are controlled by woody debris or refuse dams. Throughout section two, the average stream gradient (1.9%) is less than in section one, and a greater percentage of area is made up of pools (36%). The average length of a pool (15.5 meters), and the average bankfull depth (0.67 meters) are also greater than in section one. The average width (2.1 meters) of the stream is approximately the same as in section one.

Section Three The third section of the stream begins approximately 200 meters downstream from Pine Street and ends at the stream mouth. The watershed adjacent to section three is characterized primarily by industrial and high-density residential land use. The sources for pollutants are primarily the same urban runoff as described in the previous two sections. The stream is again deeply incised, and has little room to migrate. Pools and riffles are controlled by debris dams, and the ravine walls are armored with industrial refuse. The stream becomes slightly wider (2.62 meters), the pools longer

(23.4 meters), comprising a larger percentage of the total stream channel area (51%), and the bankfull depth of flow is slightly deeper (0.76 meters) than in the previous sections. The stream channel in this section has a bed of coarse sediment (≈0-50 cm thick) on top of lacustrine clays. The lower part of this section is influenced by high lake levels in early spring.

Summary

Englesby Brook is a highly impacted urban stream located in Burlington, Vermont. The stream is relatively short in length (3.1 km) making it possible to study the entire stream rather than investigating only a selected reach . The stream passes through several culverts facilitating stream flow gauging and the relatively small size of the watershed helps to limit the variability in precipitation amounts across the study area. Because the stream passes through several morphological regions with different hydrological controls and different land use patterns, and the watershed is only 2.2 km^2, Englesby Brook is an ideal location for a small scale sediment transport study. The stream is also ideal for studying pollutant transport because it is of great concern to the City of Burlington as a source of contaminants to the waters of Lake Champlain and as one of the few remaining wildlife habitat areas within the City.

Chapter 4

Methods

Introduction

The quantification of sediment movement and associated pollutant storage and transport requires the measurement of numerous parameters in the field. In order to compare the magnitude of sediment transport between various storm events, the watershed hydrology was monitored for precipitation and stream discharge at several locations. The movement of sediment was determined by randomly selecting eight stream pools per storm event and monitoring the depth of scour and deposition which occurred. Prior to each storm event, the sediment density, the sediment total phosphorus (TP), and the sediment fecal coliform bacteria (FC) concentrations were determined for each of the randomly selected pools.

With the measurements described above, the storage of TP and FC in the channel sediments could be determined and the total sediment transport and net stream export of sediment were estimated. By multiplying the concentration of pollutants in the sediment by the sediment transport values, pollutant transport and net export rates were calculated. The experimental design and methods used are described in detail in the following sections.

Field Methods

Stream Morphology

The morphology of Englesby Brook was examined from the point where it leaves the Burlington Country Club (So. Prospect St.)to where it enters Lake Champlain. A total of 56 individual "pool" sections of stream were identified, for which average length, width, and bankfull water depth were measured. The main criteria used to distinguish a pool from a riffle was the stream channel bottom composition. If the stream channel bottom was armored with cobbles and gravel it was assumed to have limited storage capacity for pollutant transporting sized sediment and was thus classified as a riffle. If a stream reach bottom was dominated by sediments of sand and gravel size or less (roughly identified in the field) it was classified as a pool.

The beginning and end of the each pool was marked with marking tape on nearby trees and an identification number was assigned. These numbers started at the headwaters and increased downstream. The downstream boundary of the pools were determined by changes in morphology or by dams created by woody debris and or refuse. Several exceptionally long pools towards the mouth of the stream were divided into two sections to ensure good coverage by the scour chains during scour and deposition depth measurements. Pools which were divided by debris dams, without any riffle section between were considered to be separate pools.

As each pool was identified, the length along the center of the stream was recorded, as well as three measurements of width and three measurements of bankfull depth. These measurements were used to determine the surface area of each individual pool as well as the surface area for the entire stream. Individual pool characteristics are summarized in Appendix-A.

Sediment Transport

The objective of the sediment transport measurements was to determine the amount of stream channel sediments which were mobilized during storm events. In order to quantify this mobilization, standard methods of measuring bedload and suspended sediment transport could not be used because they would not distinguish those sediments which were mobilized from the stream channel from those which were added to the stream from the watershed surface or from stream bank erosion. It was thus decided that a direct measurement of the amount of sediment scoured from the stream channel would give the best indication of channel sediment mobilization.

Scour chains, as an in situ measurement of stream channel scour, have been mentioned in the literature with no reference to the original inventor (Lisle & Eads 1991). The scour chains created for this study are quite different from those described in the literature. Figure 4.1 shows the initial setup and a typical final positioning of the scour chains. The chains are set up with 2 pieces of 1/2" pvc pipe driven into the stream channel sediments, approximately 60 cm apart and 20 cm deep, leaving 10 cm sticking out of the sediments. The chains, with 3/4" steel rings on each end, are slipped over the pvc stakes and are draped over the top of the sediments. The steel rings allow the chain to move freely down the stake as sediment is scoured out beneath. Stream flow is perpendicular to chains.

At the time of deployment, the initial height of the scour chain on the stake is recorded for later reference. Following the storm event being studied, the new sediment level is recorded and then the sediment is carefully excavated to find the level of the scour chain. By excavating over the entire length of the chain, any local scour caused by increased turbulence from the stakes can be identified and corrected for. Any stakes which were found to have trapped debris causing increased scour or deposition were not considered valid measurements. The total amount of scour at the location of the stake is equal to the change in depth of the chain. The total sediment deposited at that location is equal to the depth of sediment on top of the chain. In most cases the scour chain was lower than the initial sediment and had some amount of sediment deposited on top.

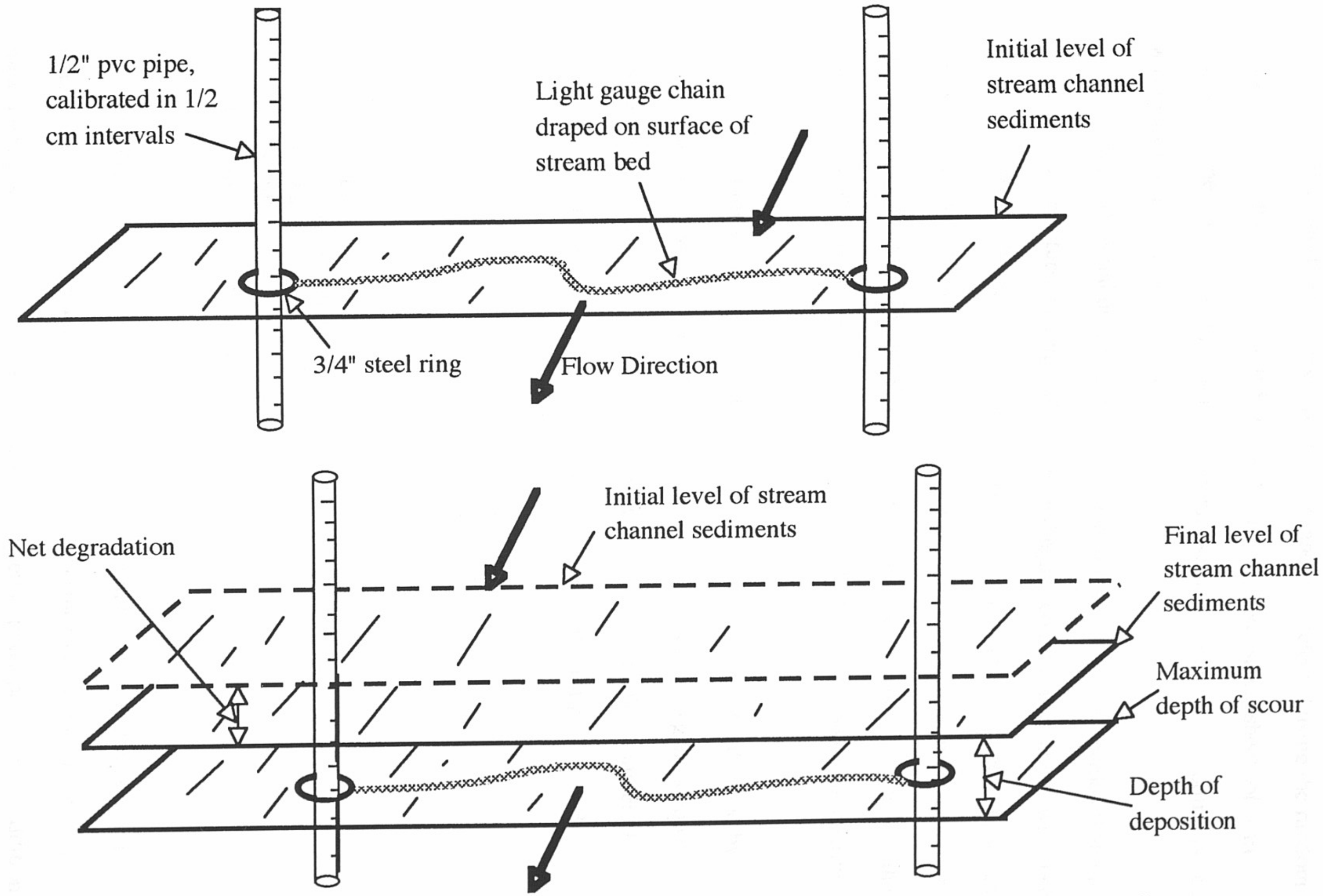


Figure 4.1 In Situ Measurement of Scour and Deposition with Scour Chains. Upper diagram shows initial chain setup and lower diagram shows typical final position of chain following a storm event.

For each storm event, eight pools were randomly selected using the random number function in the Microsoft Excel 4 (Microsoft 1992) spreadsheet software package. One pool (pool 25) was also randomly selected to serve as a control pool and was measured during every storm event.

For good spatial distribution of scour measurements, it was decided that a total of four scour chain setups totaling eight stakes and eight scour measurements were needed. Figure 4.2 shows the standard layout of scour chains used in each pool. The length of the pool was divided into four equal sections and the scour chains were centered on each section. Each chain would start at the bank and would extend into the middle of the channel. The chains were started on alternating banks to assure good areal distribution of measurements.

The number of pools monitored for each storm event was established by determining the total number of measurements needed per event to gain adequate statistical errors and dividing by eight measurements per pool. The number of measurements needed per storm was chosen using the relationship (Ott 1993):

$$n = \frac{(\sigma^2) * (z_{\alpha/2})^2}{E^2}$$

where:
n = sample size
σ = standard deviation
z = z value
E = tolerable error $= z_{\alpha/2}\sigma_{\bar{y}}$
$\sigma_{\bar{y}}$ = standard error $= \sigma/\sqrt{n}$

At the 95% confidence interval, a total of 66 measurements are needed per storm to give tolerable errors within 1.4 mm (± 6%). When the 66 measurements are divided by eight measurements per pool the result is approximately eight pools per storm in addition to the control pool (pool 25).

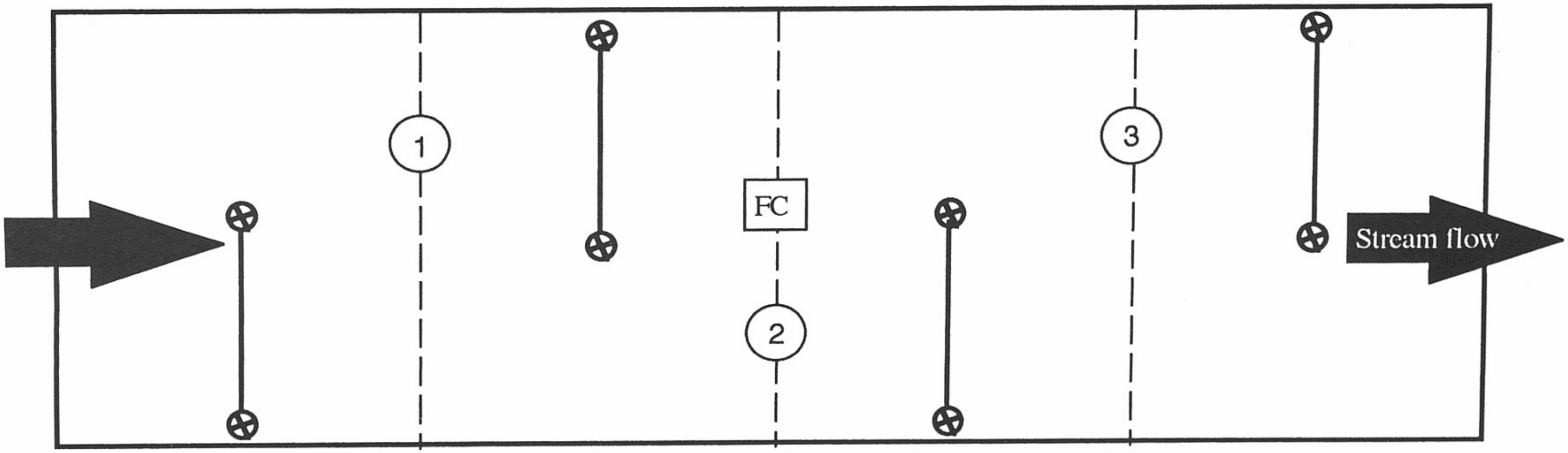


Figure 4.2 Scour Chain Setup and Sampling Regime for Typical Study Pool.

⊗ **Location of pvc calibrated stake**

① **Sampling locations for sediment P**

FC **Sampling locations for sediment FC**

The number of storm events to be measured was left open ended, with the goal being eight to ten storms. Eight out of nine storm events occurring during the study period were measured before the field season was over.

Sediment Sampling

Pool sediments were sampled for total phosphorus (TP), fecal coliform bacteria (FC), sediment density and particle size. To collect samples for TP, sediment density, and particle size, two inch diameter sediment cores were taken using a US BMH-53 type bed material sampler and 20 cm long plastic core barrels. Prior to use these core barrels were washed in a 20% hydrochloric acid solution and rinsed with distilled water. For bacterial sampling, standard household plastic spoons were autoclaved and stored in a sterile "Whirl-Pack". The spoons were then used to scoop sediment directly from the stream channel into sterile "Whirl-Packs". New spoons were used for each sample. All samples of FC and TP were stored on ice, in a cooler for several hours until they could be transported to the lab. Cores were stored frozen until they could be analyzed. FC samples were analyzed within 24 hrs of sampling.

For the first four storm events, three cores were taken from each pool in order to determine the spatial variability of the TP in the sediments. For storms five through eight, only one core per pool was taken to reduce the total number of samples to analyze in the lab. For FC samples, only one sample per pool was taken for all storm events. The number of FC samples were limited by the resources made available for the study by the City of Burlington Waste Water Treatment Laboratory. The sampling locations for a typical study pool are illustrated in Figure 4.2.

Hydrology

Hydrological conditions were measured in Englesby Brook Watershed to correlate with sediment transport values measured in the field and to develop a predictive tool for estimating long-term export rates of sediment, TP, and FC. Precipitation was measured at three locations throughout the watershed (Figure 3.1) using Belfort weighing-type rain gauges. The gauges were checked twice a week and reset once a week throughout the study period. An arithmetic average of the three stations was used for a comparison with sediment transport data and as input to a hydrologic model for predicting stream flow.

Stream flow was monitored at two locations along the stream as shown in Figure 3.1. ISCO #1870 bubbler type flow meters were placed at the Englesby Brook culverts beneath Shelburne and Crescent Roads. These meters provided a continuous record of depth of flow throughout the study period. Using the depth of flow record and the known circular geometry of the culverts, cross sectional area and wetted perimeter were calculated. The Manning Equation was then used to estimate stream discharge. The Manning relation can be described by the equation:

$$Q = \frac{1.49 R^{2/3} S^{1/2} A}{n}$$

where:

Q = stream discharge
R = hydraulic radius = A / wetted perimeter
S = energy gradient closely approximated by the slope
A = cross sectional area of channel
n = Manning roughness coeficient

Slope, pipe diameter, and roughness coefficients for the culverts were provided by the City of Burlington Department of Public Works.

For the first storm event the flow meters had not yet been deployed. It was therefore necessary to estimate stream flow from the measured precipitation data using a runoff model previously created for the watershed (Cassell et al. 1994). Stream flow was successfully monitored at both locations for four storm events. A relationship between discharge at the two locations was then established to estimate flows when flow meter malfunctions occurred. This relationship was used to predict flow at the Shelburne Road gauging station for storm three. The Shelburne Road Gauging station is considered the primary station against which all transport data are being compared. The Crescent Road station is used as a backup to the primary station and to gain some insight as to how stream flow changes downstream.

The flow data for the Shelburne Road station is representative of approximately 70% of the total discharge from the watershed (Cassell et al. 1994). An additional 30% of the watershed discharge enters the stream below this gauging station. Flow data at the Shelburne Road station were therefore increased by 30% to estimate the total stream discharge entering Lake Champlain during the measured storm events.

Stream power (Ω) was calculated from the measured stream discharge using the equation (Summerfield 1993):

$$\Omega = \rho_w g Q s$$

where:

Ω = unit stream power ($J\ s^{-1}$)
ρ_w = the density of water ($kg\ m^{-1}$)
g = the acceleration due to gravity ($m\ sec^{-2}$)
Q = stream discharge ($m^3 sec^{-1}$)
s = channel gradient ($m\ m^{-1}$)

The slope of the culverts in which stream flow was being measured was used as the channel gradient in the stream power calculations.

Laboratory Methods

Sediment Sample Processing

Stored sediment cores were thawed for 4 hours, then vertically extruded and cut into two fractions. As each core was being extruded, the top 1 cm was sliced off using a knife or scooped off using a metal spatula and was then stored in a sterile "Whirl Pack". The procedure was repeated for the 4 cm section between 1-5 cm depth. Each sediment sample fraction was then weighed to ± .01 grams to determine a wet weight of the sediment and then placed back in the freezer for storage.

When it was time for the sediment analysis, the samples were again removed from the freezer and placed in pre-weighed 50-200 ml beakers. The beaker and sediment sample were again weighed and placed in a drying oven for a minimum of 24 hours at approximately 105°C. The beakers and dry sediment were again weighed to determine the dry weight of sediment . The dry sediment samples where then disaggregated in the beaker using an acid washed, rubber pestle and were then dry sieved through a 2 mm mesh USA Standard Testing Sieve (No. 10, Tyler Equivalent 9 mesh) to remove any gravel sized material. The gravel sized material was then weighed to determine the percent fraction of coarse material, but was not further analyzed for TP. The remaining sample of sands, silts and clays were homogenized and then prepared for TP analysis. The raw data for these analyses are summarized in Appendix B.

Total Phosphorus Analysis

From the dry, homogenized sediment samples, approximately 0.20 grams of sediment were weighed onto weighing paper and placed in 200 ml Erlenmeyer flasks filled to 50 ml with distilled water. The 50 ml samples were then analyzed for TP using the US EPA method # 365.2 (US EPA 1983). This method is a persulfate digestion which converts all forms of TP to orthophosphate, and an ascorbic acid colorimetric analysis which determines the concentration of orthophosphate in the 50 ml sample. Once the digestion step is completed, the pH of the sample is adjusted using a phenolthalein indicator solution and titration with 11N sulfuric acid and 10N sodium hydroxide. The samples are then filtered through a glass fiber filter (type A/E) in order to remove any particles or precipitate which may interfere with colorimetric analysis.

By adding a combined reagent containing ammonium molybdate and antimony potassium tartrate, an antimony-phospho-molybdate complex forms which reacts with the ascorbic acid and is reduced to a blue colored complex. The intensity of this blue color is proportional to the orthophosphate concentration of the sample. To determine the actual concentration of orthophosphate in the sample, a standard curve is constructed (Figure 4.3) by analyzing samples with known concentrations of orthophosphate and determining the absorbance using a spectrophotometer. The relationship between absorbance and the known concentrations of orthophosphate is then used to determine the concentrations of orthophosphate in the 50 ml samples. All samples are diluted so that they fall within the range of the standard curve. The concentration of orthophosphate is then related back to the known sediment mass of the sample to get a sediment concentration of TP.

To assure the quality of the TP analysis, several measurements were replicated and the US EPA method 365.2 (US EPA 1983) quality assurance procedures were followed. Two blanks, at least two standards, and a filtrate blank were run with each experimental batch. With each batch, a National Bureau of Standards sediment sample (#2704) was run which has a weight % TP of 0.0998 ± 0.0028 at the 95% confidence interval (National Institute of Standards and Technology). The persulfate recovery rate averaged approximately 89% of the actual value for the standard sediment sample.

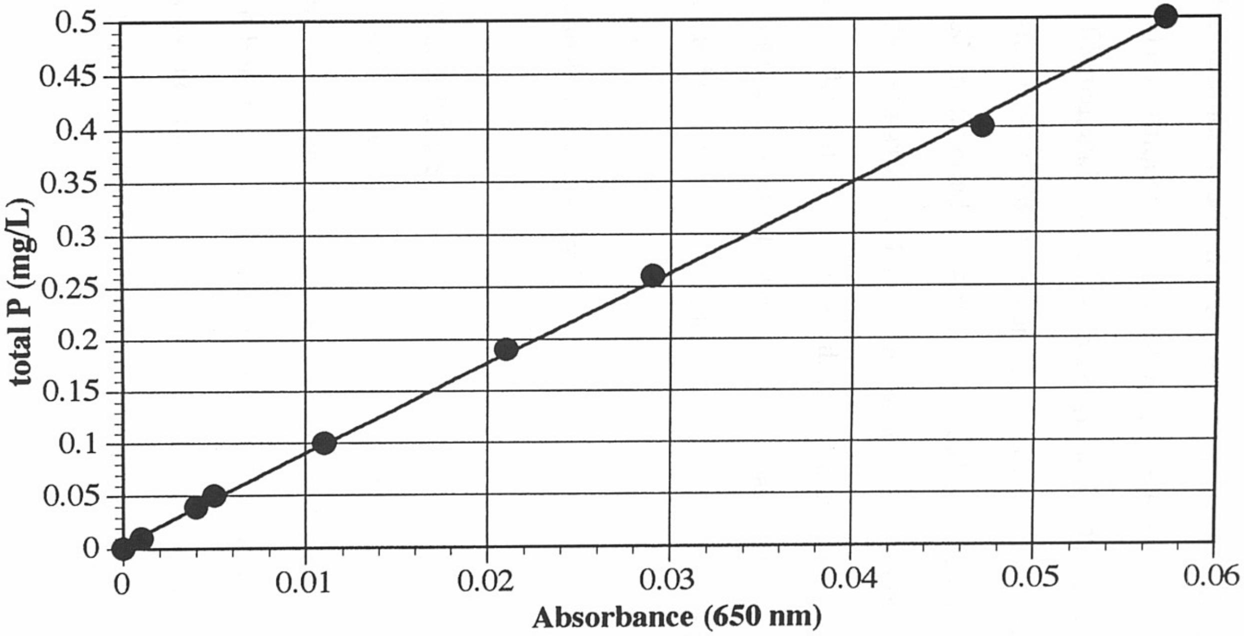


Figure 4.3 Standard Curve for November 30, 1994. Typical standard curve relating absorbance to total P concentration.

$r^2 = .9992$

Fecal Coliform Bacteria Analysis

Analysis of sediments for fecal coliform bacteria (FC) was conducted by the staff at the City of Burlington Waste Water Treatment Laboratory. One to three grams of homogenized sediment is added to an autoclaved 200 ml Erlenmeyer flask and then diluted to 100 ml. Aliquots of these dilutions are then placed on a filter with 1.8 ml of MFC broth, filtered, and rinsed with bacto-peptone. The filters are placed in sterile plastic petri dishes with covers and are then placed in sterilized "Whirl-Packs". The "Whirl-Packs" are inverted in 44.5^{o}C water and incubated for 24 hours. After incubation, the number of "colonies" that appear as blue dots on the filter are counted. This number is then multiplied by the dilution factor to get the number of FC per gram of sediment. For quality control, two dilutions of each sample are run. In addition, both a positive (seaded with water known to have FC present) and negative (seaded with distilled water) sample are run with each batch to ensure there is no outside contamination and that incubation has occurred.

Grain Size Analysis

A grain size analysis was run on one randomly chosen sediment sample for each of the eight storm events. Grain size analysis was conducted using methodology described in Folk (1974), with coarse particles ($\geq$.0625 mm) being analyzed by a dry sieve analysis and fine particles (<.0625 mm) being analyzed by pipette method. The graphical phi means method was used to determine the average grain size.

Data Analysis

The data upon which this thesis is based were collected for eight storm events. For each storm event eight pools were randomly selected and eight measurements of scour and deposition were made in each pool. One to three measurements of TP, FC, sediment volumes and sediment density were made for each pool. Therefore, scour could be statistically compared to deposition for all measurements and for each individual storm. Scour, deposition, TP, and FC could be compared from storm to storm and from pool to pool.

A number of statistical tests were conducted on the data in order to test the hypothesis proposed in this thesis. All descriptive statistics were run on the MYSTAT software package (Hale 1992) at 90 and 95% levels of confidence. It was determined that, in all cases, the data were not normally distributed and thus non-parametric tests were used throughout the analyses. In all comparisons of scour versus deposition the Wilcoxon signed rank test was used because of paired scour and depositional values. To compare scour between storm events or between pools, the Kruskal-Wallis test was used to determine if the populations were different. If the populations did prove to be different, a Tukey-W test or Tukey-Kramer test was used to tell which populations differed from which. The Tukey-Kramer test is used when populations are of different sizes (Ott 1993). The correlation analysis between sediment transport and hydrological conditions was conducted using DeltaGraph Pro 2.0.2 (DeltaPoint 1989).

Chapter 5

Experimental Results

Introduction

The concentrations of pollutants in the stream channel sediments of Englesby Brook and the transport of these channel sediments has been measured during eight periods of increased stream flow occurring from June through September, 1994 . These periods of increased flow were generated from rainfall events which ranged from 0.06 to 1.30 inches of rainfall and resulted in total runoff volumes of 137,142 cubic feet to 760,531 cubic feet, and peak discharge values of 7.24 to 30.84 cfs (Table 5.1). For each of the eight storm events, the stream channel was monitored for scour and deposition of sediments in eight randomly selected pools out of a total of 56 pools identified along the stream. The sediment in these eight pools was also sampled for sediment density, mean grain size, total phosphorus (TP) concentration, and fecal coliform bacteria (FC) concentration.

Long-term precipitation data from the Burlington International Airport indicate that the one year design storm yields a total of 2.6 inches of rain over an 11 hr period (Cassell et al. 1994). Thus, all of the storm events measured in this study are less than the one year design storm. These data therefore represent the sediment movement and stream hydrology of small, frequently occurring rainfall events during which surface runoff of water and pollutants is relatively low.

Table 5.1 **Hydrological Summary of Eight Storm Events on Englesby Brook. Discharge was measured at a point above which 70% of the watershed runoff enters the stream. Total runoff was adjusted to account for the additional 30% runoff.**

▨	**Measured Hydrological Parameters**					
Storm	*Start Date*	*Time Since Last Rainfall (hrs)*	*Precip (in)*	*Total Runoff (cubic ft)*	*Peak Discharge (cfs)*	*Cummulative Stream Power (J/s)*
1	6/29/94	169	0.96	465,428**	42.5	2,588,733
2	7/9/94	210	0.55	261,020	32.0	1,451,806
3	7/15/94	139	0.06	137,142*	na	762,790
4	7/18/94	68	0.50	224,248	29.5	1,247,278
5	7/22/94	101	0.20	284,505	26.0	1,582,430
6	7/26/94	23	0.75	248,925	11.5	1,384,533
7	8/18/94	290	0.70	165,102	7.3	918,305
8	8/21/94	73	1.30	760,531	29.0	4,230,110
mean			0.63	324,055	25.4	1,770,748

*** estimated using computer simulation*

** estimated using rating curve*

Summary Data

Sediment Transport

Sediment scour and deposition data for the eight storm events are summarized in Table 5.2. For each storm event the mean and standard error of the mean were calculated for all scour and deposition depth measurements. The mean scour depth for all scour chains along the stream ranged from 0.79 cm (se=0.15, n=62) for storm three to 5.18 cm (se=0.49, n=69) for storm eight. The average deposition depth for all scour chains along the stream ranged from 0.55 cm (se=0.15, n=62) for storm three to 4.76 cm (se=0.62, n=69) for storm eight.

Scour Versus Deposition Qualitative observations in the field indicated that mean scour depths were greater than mean deposition depths. In order to quantify this observation, a Wilcoxon signed rank test was used to compare the population of all scour measurements collected for all storms occurring during the study period to the population of all deposition measurements for the study period. A Wilcoxon signed rank test can be performed on two populations which are not normally distributed (nonparametric) and whose outcomes are not independent (Hale 1990). The p-value for the test is compared to the desired alpha level and the two populations are determined to be different if the p-value is less than the alpha-value (Hale 1990). The test concluded that when data from all storms were combined scour is significantly greater than deposition (p=0.0085) at the 95% confidence interval (alpha=0.05).

Storm to Storm Comparisons When comparing the mean scour depths or the mean deposition depths between storm events, statistical tests indicated that the means were not all identical. A Kruskal-Wallis nonparametric test can be used to determine if multiple populations are all the same or if some populations differ from one another (Ott 1993). In the Kruskal-Wallis test, an H-value is calculated and compared to a Chi^2-value

Table 5.2 Mean Values of Sediment Scour and Deposition Depths for 8 Storm Events on Englesby Brook.

	Scour Depth (cm)			Deposition Depth (cm)		
Storm	*mean*	**se*	*n*	*mean*	**se*	*n*
1	3.20	0.48	64	2.77	0.47	64
2	2.25	0.36	61	2.27	0.36	60
3	0.79	0.15	62	0.55	0.17	62
4	1.40	0.20	72	1.07	0.19	72
5	1.99	0.28	69	1.13	0.23	69
6	2.67	0.39	69	1.92	0.31	67
7	1.95	0.30	72	1.37	0.23	72
8	5.18	0.49	69	4.76	0.62	69
mean	2.43	0.33	538	1.98	0.32	535

**se= standard error of the mean.*

determined for a specific alpha level and the calculated degrees of freedom. The populations are all the same if the H-value is less than the Chi^2-value (Ott 1993).

The Kruskal-Wallis test was used to determine if there were differences between the mean scour depths of the eight storm events. The test concluded that the mean scour depths were not identical (H=22.27, Chi^2=14.07) at the 95% confidence interval (alpha=0.05, df=7). The same test was performed on the deposition values for each storm event using the same criteria as was used for scour. The Kruskal-Wallis test concluded that the deposition populations across storm events were not all the same (H=23.19, Chi^2=14.07)..

In order to determine which mean scour depths and mean deposition depths were different, either a Tukey-W or Tukey-Kramer nonparametric test was performed. These Tukey tests compare each possible pairing of storm events to determine if any difference exists. A Tukey-Kramer test was used only when the population sizes differed (Ott 1993). For both scour and deposition storm eight was significantly different than all other storms at the 95% confidence interval. No statistical difference could be determined among other storms (Figure 5.1). It should be noted that storm eight is a substantially larger storm than the other storm events (Table 5.1).

Sediment Transport Relationships with Hydrology Linear regression analyses were performed to determine the relationships between stream hydrological parameters and sediment transport measurements. Figure 5.2 shows the results of a regression between total event precipitation on the watershed and both mean sediment scour depth and mean sediment deposition depths shown in Table 5.2. The precipitation values are the mean values for each storm event summarized in Table 5.1. The regression results show that a strong positive correlation exists between precipitation and both scour (r^2=0.82) and deposition (r^2=0.81).

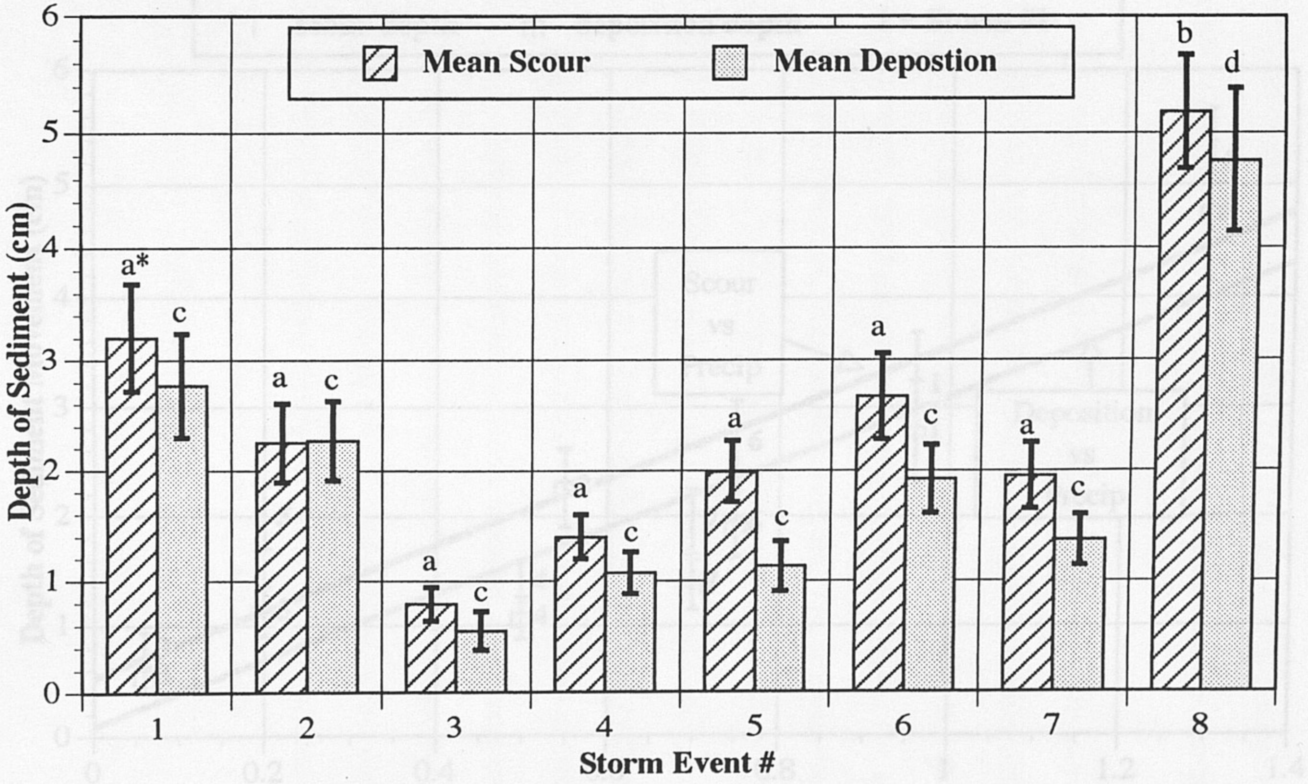


Figure 5.1 Mean Sediment Scour and Deposition Values for 8 Storm Events on Englesby Brook.

Letters above bars represent statistical equality.

Comparisons are not shown between scour and deposition

(Those events with the same letters are not statistically different by Tukey-W test.)

Error bars represent the standard error of the mean

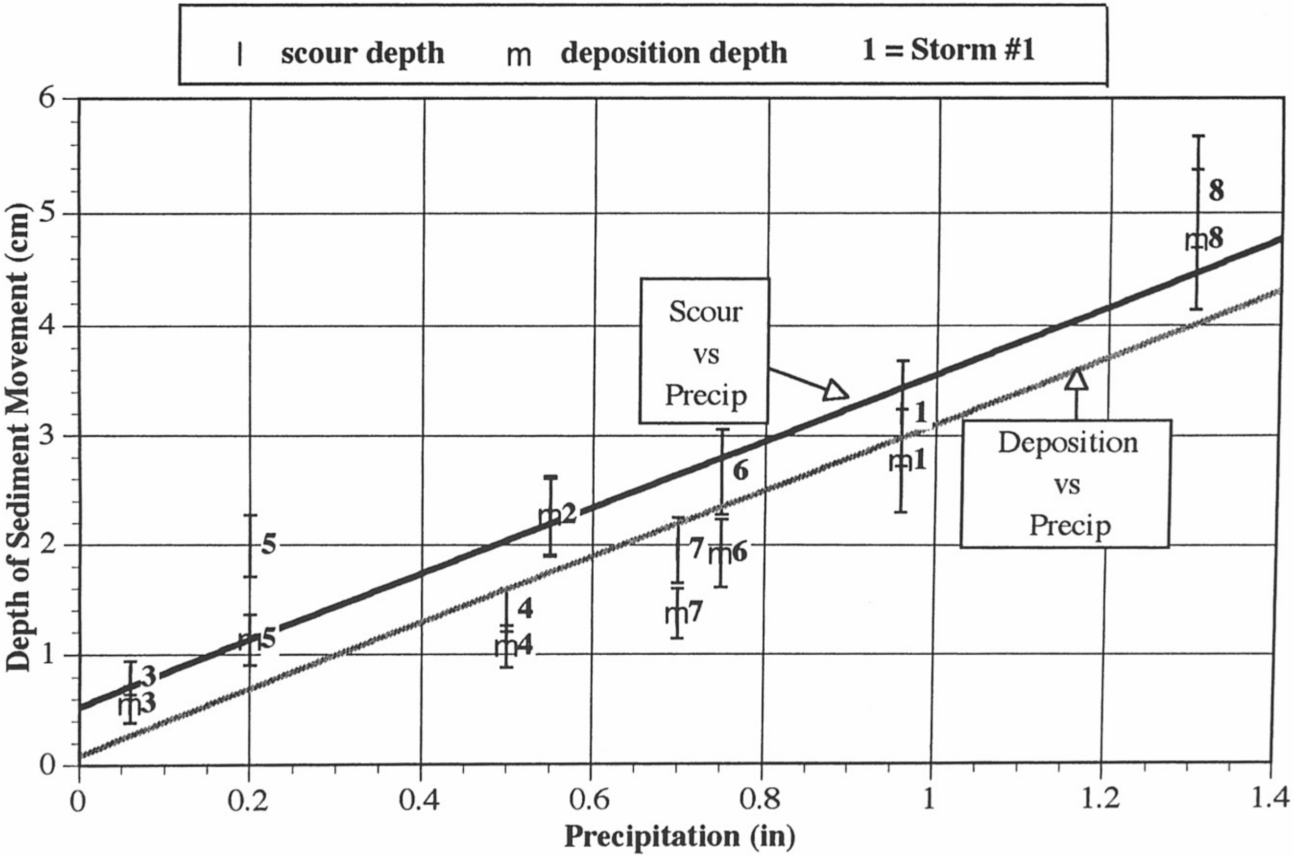


Figure 5.2 Results of Regression Analysis of Scour & Deposition Depths Versus Precipitation.

r^2 *(scour) = 0.82* $f(x) = 3.03 * x + 5.27 * 10^{-1}$

r^2 *(deposition) = 0.81* $f(x) = 3.01 * x + 8.69 * 10^{-2}$

Error bars represent standard error of the mean

Figure 5.3 shows the results of a regression between sediment transport and the cumulative stream power expended during each of the eight storm events. The values for scour depth and deposition depth are the means for each storm event shown in Table 5.2. The stream power values are those calculated from the measured total runoff volume for each storm event as shown in Table 5.1. The regression results show that a strong positive correlation exists between stream power and both scour (r^2=0.90) and deposition (r^2=0.89).

A control pool (pool #25) was monitored for all storm events. Data from this control pool can help validate the relationships which have been identified in correlations between stream hydrology and sediment transport. Figure 5.4 shows a regression analysis between cumulative stream power for each storm event, and the mean scour and mean deposition for pool 25 for all storm events. The analysis reveals that cumulative stream power has a positive correlation with mean scour (r^2=0.73) and mean deposition (r^2=0.43). Storm event one is missing from this correlation.

Sediment Transport Relationship to Pool Location Mean scour and deposition depth values for each of the three morphological sections were compared to explore the relationship between sediment transport measurements and the pool location along the stream. Figure 5.5 shows the mean scour and deposition depth values for all measurements divided up into the three populations by morphological section. The Kruskal-Wallis test performed showed that, at the 95% confidence interval, there was no significant difference between the scour or deposition means across morphological sections (H=17.41, Chi^2=5.991, alpha=0.05, df=2).

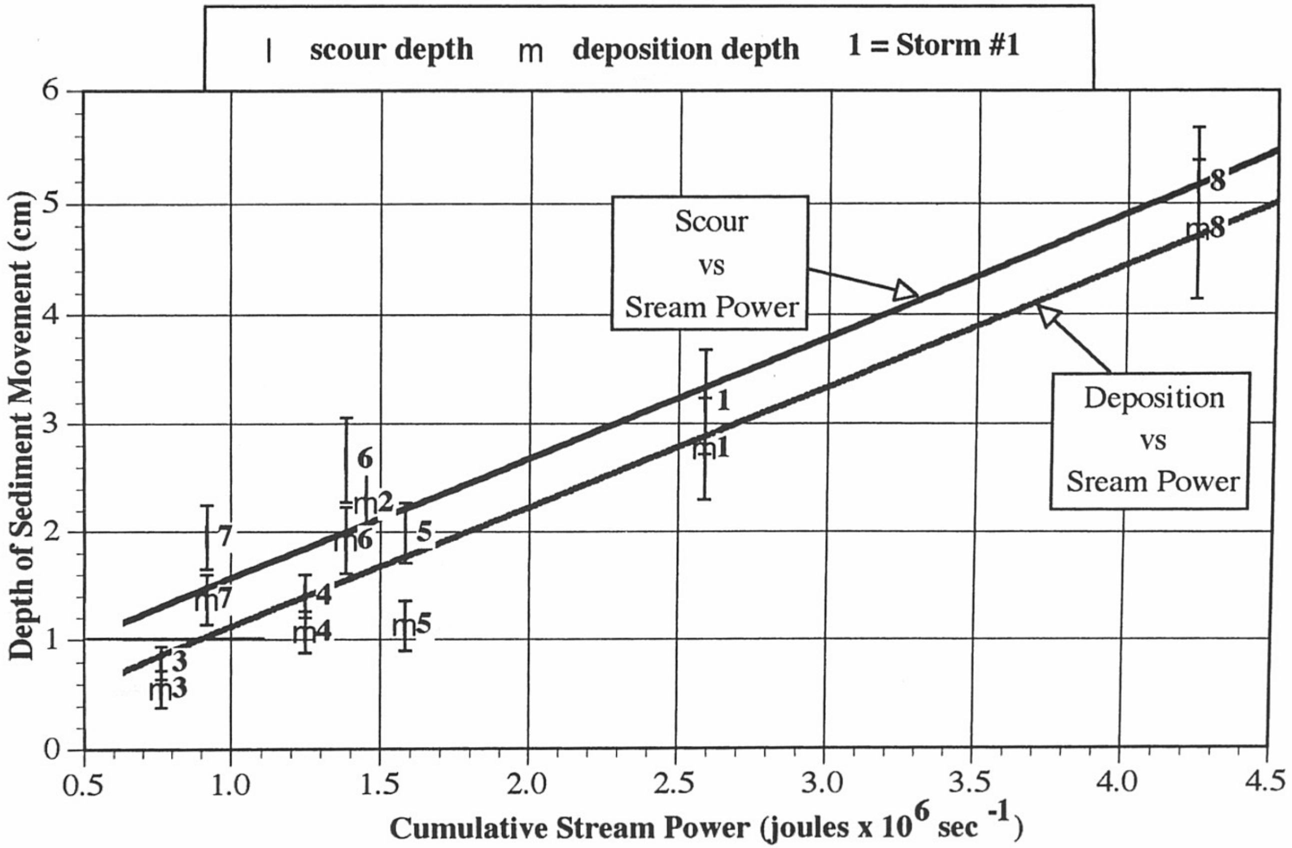


Figure 5.3 Results of Regression Analysis of Scour & Deposition Depths Versus Cumulative Stream Power.

r^2 *(scour)* $= 0.90 \quad f(x) = 1.11 * 10^{-6} * x + 4.57 * 10^{-2}$

r^2 *(deposition)* $= 0.89 \quad f(x) = 1.10 * 10^{-6} * x + 1.46 * 10^{-2}$

Error bars represent standard error of the mean

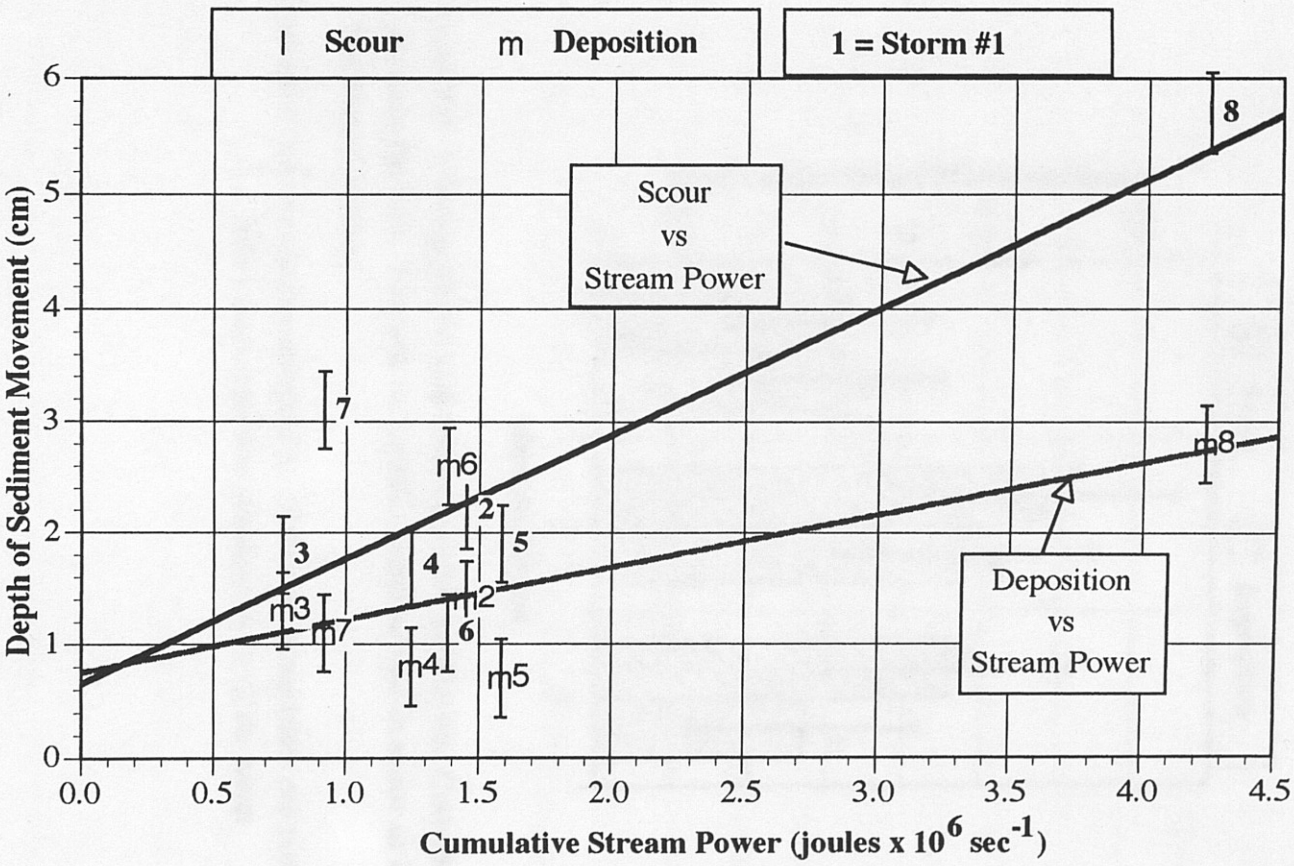


Figure 5.4 Scour and Deposition Versus Cumulative Stream Power for Control Pool # 25.

r^2 *(scour) = .73* $f(x) = 1.11 * 10^{-6} * x + 6.50 * 10^{-1}$

r^2 *(deposition) = .43* $f(x) = 4.70 * 10^{-7} * x + 7.49 * 10^{-1}$

Error bars represent the standard error of the mean

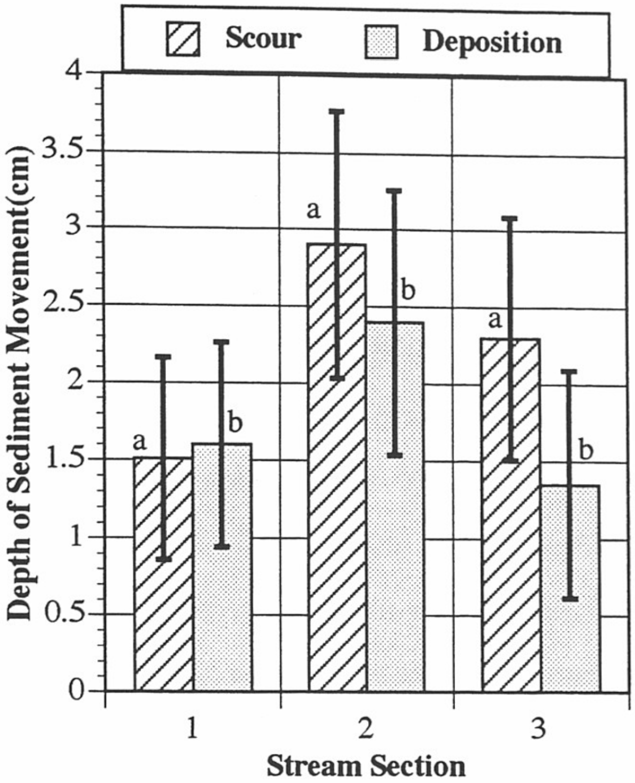


Figure 5.5 Average Scour and Deposition for All Storms, Considered for Each Stream Section. There is no significant difference in scour or deposition depths between sections.

Letters above bars indicate statistical equality. (Bars with same letter are not significantly different)
Error bars represent standard error of the mean

Sediment Density and Particle Size Distribution

Sediment Density One hundred thirty eight cores were collected during the study period and analyzed for sediment density and pollutant concentrations. The density of the stream channel sediment was determined from the core samples by measuring the dry sediment mass (grams) and dividing by a known core volume (cm^3). This density therefore includes the void spaces between sediment grains yielding apparently low density values. The mean density and standard error of the mean was determined for each storm event. The density of sediment ranged from 0.93 grams cm^{-3} (se=0.06, n=9) for storm 1 to 1.76 grams cm^{-3} (se=0.12, n=9) for storm 5. The overall mean of the individual storm means was 1.40 grams cm^{-3} (se=0.07, n=8) (Table 5.3, Figure 5.6).

A Kruskal-Wallis nonparametric statistical test was performed to determine if the sediment density differed among storm events. The test concluded that sediment densities were not all the same (H=19.34, Chi^2=14.07) at the 95% confidence interval (alpha=0.05, df=7). Using the Tukey-Kramer nonparametric statistical test, it was determined that all densities were statistically the same with the exception that storm one had a sediment density that was significantly less than the sediment density measured for all other storm events

Sediment Density-Depth Fraction Comparison The sediment cores were divided into two depth fractions to determine if there was any difference in density with depth. Table 5.4 shows the mean densities of the two depth fractions for each storm event. A Wilcoxon signed ranks test indicates that at the 95% confidence interval the density of sediment in the two fractions were not statistically different from one another (p=0.161, alpha=0.05).

Particle Size Distribution Particle size analyses were performed to give a general idea of the size distribution of the sediment particles which comprise the stream channel. The particle size distribution was determined for one randomly selected sample

Table 5.3 Mean Sediment Density for 8 Storm Event Samplings.

▨	Sediment Density (g/cubic cm)		
Storm	*mean*	**se*	*n*
1	0.93	0.06	9
2	1.32	0.04	24
3	1.36	0.03	24
4	1.35	0.03	27
5	1.76	0.12	9
6	1.50	0.10	9
7	1.34	0.02	27
8	1.71	0.13	9
mean	1.41	0.07	138

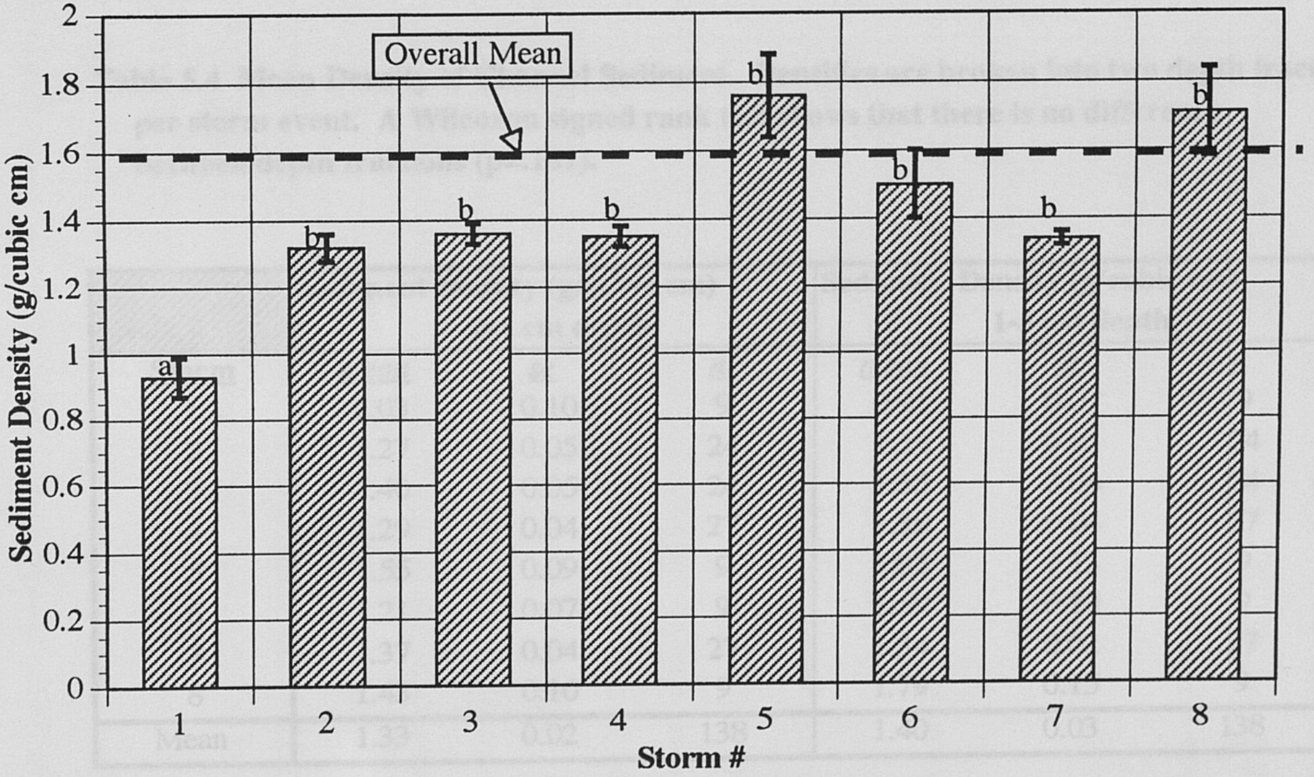


Figure 5.6 Mean Channel Sediment Density for 8 Storm Event Samplings on Englesby Brook.

Error bars represent the standard error of the mean.

Letters above bars represent statistical equality by Tukey-Kramer test.

Table 5.4 Mean Density of Channel Sediment. Densities are broken into two depth fractions per storm event. A Wilcoxon signed rank test shows that there is no difference between depth fractions (p=.161).

	Sediment Density (g/cubic cm) 0-1 cm depth			Sediment Density (g/cubic cm) 1-5 cm depth		
Storm	*mean*	*se*	*n*	*mean*	*se*	*n*
1	1.03	0.10	9	0.91	0.07	9
2	1.27	0.05	24	1.34	0.03	24
3	1.40	0.05	24	1.35	0.04	24
4	1.29	0.04	27	1.38	0.04	27
5	1.55	0.09	9	1.82	0.13	9
6	1.21	0.07	9	1.59	0.10	9
7	1.37	0.04	27	1.34	0.02	27
8	1.43	0.10	9	1.79	0.15	9
Mean	1.33	0.02	138	1.40	0.03	138

(se= standard error of the mean)

from each storm event, yielding a total of eight samples. The mean particle size distribution for the eight samples is shown in Figure 5.7 . The mean particle size is 0.74 mm, se=0.76, n=8 (0.42 phi, se=0.551, n=8) with approximately 80% of all particles falling within the sand size particle range (0.063 mm - 2.0 mm). Less than 2% of all particles fell in the silt and clay size range (< 0.063 mm). Because of the small number of grain size analyses performed, no statistical comparisons have been made across storm events or along the length of the stream.

Total Phosphorus (TP)

The concentration of total phosphorus (TP) in the channel sediments of Englesby Brook was determined in order to justify the hypothesis that stream channel sediments are a low flow storage area for pollutants. For each storm event one to three sediment cores were taken in each of the randomly selected study pools and were analyzed for concentrations of TP. Table 5.5 and Figure 5.8 summarize these mean concentrations of TP for each storm event. Each storm mean was determined from all samples taken during that storm event. Mean TP concentrations ranged from 0.41 mg g^{-1} sediment (se=0.06, n=24) for storm four to 0.62 mg g^{-1} sediment (se=0.16, n=9) for storm eight. The overall mean TP concentration for all sediment samples and for all storms is calculated to be 0.48 mg g^{-1} sediment (se=0.03, n=277) (Table 5.5).

Storm to Storm Comparisons of Sediment TP Concentrations A Kruskal-Wallis statistical test was performed on the mean sediment TP concentrations among the eight storm events. The Kruskal-Wallis test concluded that at the 95% confidence interval there was no significant difference in the sediment TP concentrations of the eight storm events (H=5.22, Chi^2=14.07, alpha=0.05, df=7) (Figure 5.8). A Kruskal Wallis test performed on the mean TP concentrations found in the sediments of

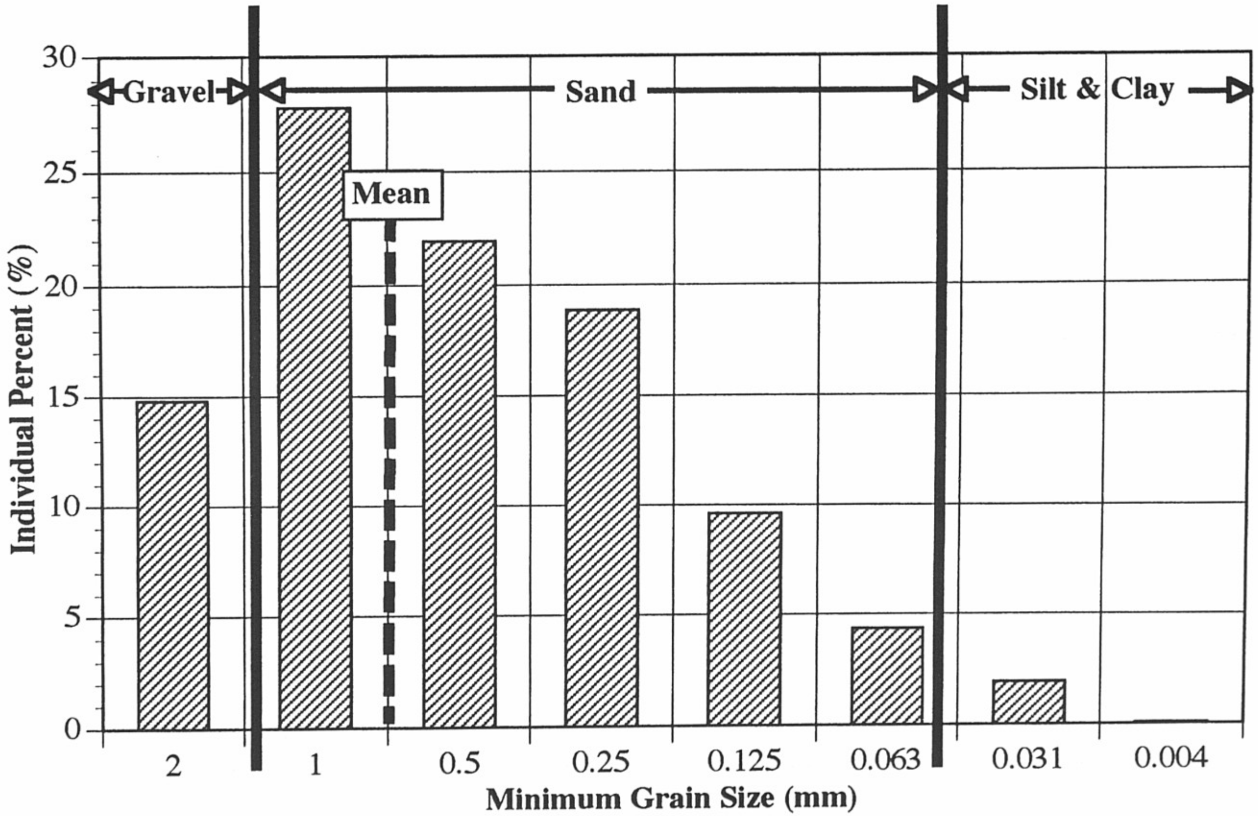


Figure 5.7 Mean Grain Size Distribution for Channel Sediments in Englesby Brook.
$n = 8$ random samples

Table 5.5 Sediment TP Concentrations for 0-1 cm and 1-5 cm Depths. A Wicoxon signed rank test shows that there is no difference between depth fractions (p=.955).

▨	TP Concentration (mg/gram sediment) 0-1 cm depth			TP Concentration (mg/gram sediment) 1-5 cm depth		
Storm	*mean*	*se*	*n*	*mean*	*se*	*n*
1	0.53	0.11	9	0.46	0.11	9
2	0.46	0.08	24	0.51	0.06	24
3	0.44	0.04	24	0.42	0.06	24
4	0.42	0.06	27	0.41	0.06	27
5	0.59	0.15	9	0.45	0.11	9
6	0.38	0.10	9	0.55	0.11	9
7	0.53	0.06	27	0.50	0.06	27
8	0.62	0.16	9	0.56	0.12	9
Total Mean	0.48	0.03	138	0.47	0.03	138

(se=standard error of the mean)

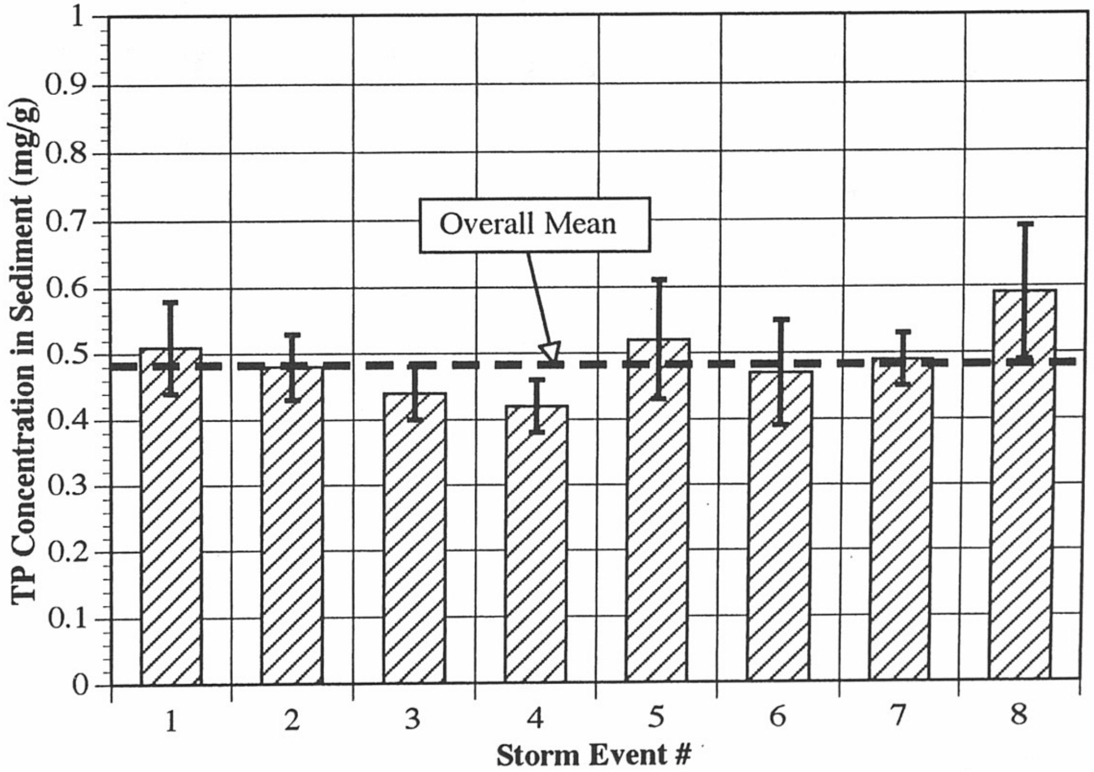


Figure 5.8 **Mean TP Concentrations in Channel Sediments of Englesby Brook. There was no significant difference in concentrations between storm events.**

Error bars represent standard error of the mean

control pool #25 for the eight storm events also concluded that there was no difference in TP concentrations (H=1.73, Chi^2=7.815, alpha=0.05, df=3).

TP-Depth Fraction Comparison Sample cores were split into two fractions (0-1 cm depth and 1-5 cm depth) to determine if there were any differences in TP concentrations with depth (Table 5.5). The Wilcoxon signed rank test was used to compare the two fractions and concluded that the TP concentrations of the two fractions are not statistically different at the 95% confidence interval (p=.955, alpha=0.05).

Fecal Coliform Bacteria (FC)

The concentration of the fecal coliform bacteria (FC) in the channel sediments of Englesby Brook was determined in order to justify the hypothesis that stream channel sediments are a low flow storage area for FC. Preceding each storm event one sample was taken from the sediments of each of the eight randomly selected pools and the control pool (pool #25). Table 5.6 shows the mean concentration of FC found in the sediments for each of the eight storm events and the mean value for all storm events. The FC concentrations ranged from 334 FC $gram^{-1}$ (se=63, n=9) for storm one to 691 FC $gram^{-1}$ (se=139, n=9) for storm five with an overall mean of 456 FC $gram^{-1}$ (se=37, n=69).

FC-Storm to Storm Comparisons A Kruskal-Wallis statistical test compared the mean FC levels among the eight storm events. The test found no significant difference among the storm events at the 95% confidence interval (H=9.86, Chi^2=14.07, alpha = .05, df=7) (Figure 5.9).

Table 5.6 Sediment FC Concentrations for All Storm Events. A Kruskal-Walls statistical test shows all means are equal.

▨	Fecal Colifom Bacteria (#/gram sediment)		
Storm	*mean*	*se*	*n*
1	334	63	9
2	444	102	7
3	378	129	8
4	394	92	9
5	691	139	9
6	571	114	9
7	438	78	9
8	456	69	9
Total	456	37	69

(se=standard error of the mean)

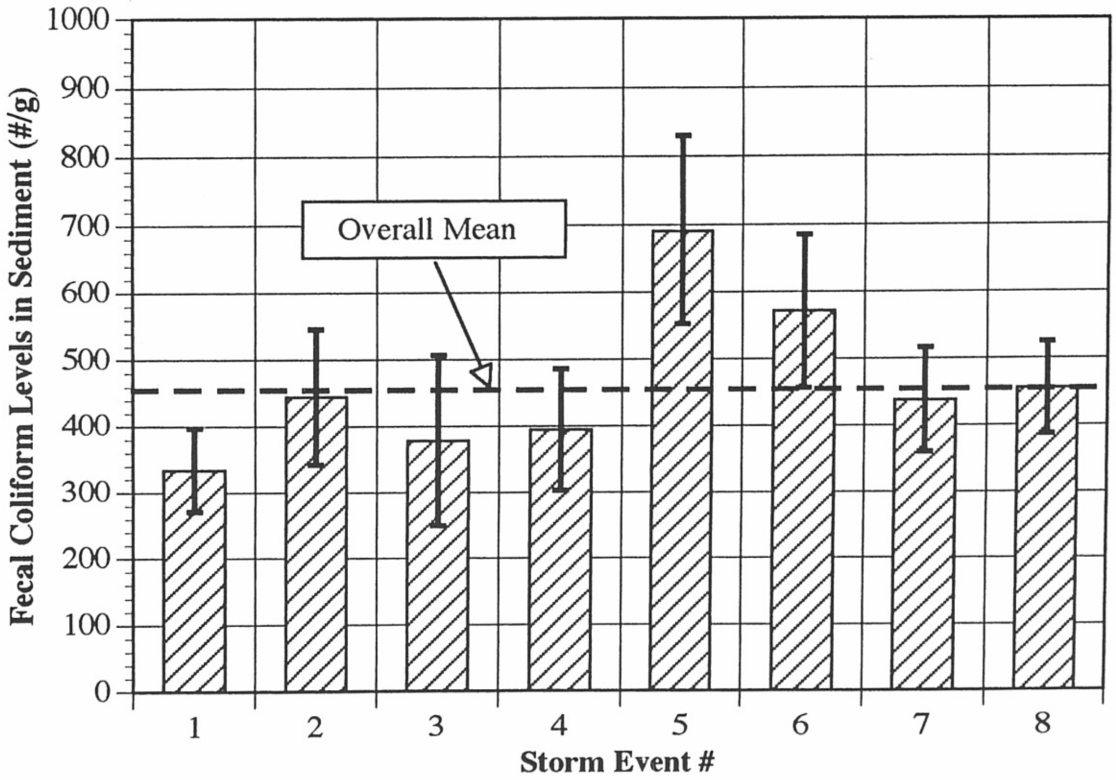


Figure 5.9 Mean Fecal Coliform Levels in Channel Sediments of Englesby Brook. There was no significant difference in the concentration means between storms.

Error bars represent standard error of the mean.

Individual Storm Event Data

Detailed descriptions of each individual storm event data and statistical tests are presented in Appendix C. Because of the low number of samples of TP per pool, statistical comparisons of TP within individual storm events was limited to several storms in which multiple cores were taken per pool. No statistical comparisons of FC concentrations could be made within individual storm events.

The Tukey-W test was used to compare both scour depths and deposition depths between pools within the same storm. At the 95% confidence interval, there was no significant difference in scour for five of the eight storm events and no significant difference in deposition for six of the eight storm events (Table 5.7). Those storms that indicated significant scour or deposition differences between pools displayed differences only in one or two out of the eight pools per storm event.

The Tukey-W statistical test was used to compare both scour and deposition depths among morphological sections. At the 95% confidence interval scour depths in section two (Figure 3.2) were significantly greater than in section one for six of the eight storm events but deposition depths in section two were greater than in section one for only 3 of the eight storm events (Table 5.7). Generally, scour in section two is often greater than in sections one or three but deposition can not be distinguished between the three morphological sections.

The Wilcoxon signed rank test was used to compare scour depth to deposition depth within each storm event. In five of the eight storm events there was no significant difference detected between scour depths and deposition depths (95% confidence interval). In three of the eight storm events, scour depths were significantly greater than deposition depths (95% confidence interval) (Table 5.7).

Total P concentrations were compared within several storm events in which multiple samples were taken per pool. The Kruskal-Wallis test applied to the TP

Table 5.7 Individual Storm Event Statistical Comparison Summary. Statistical comparisons were made within storm events (across rows).

	Scour Pool to Pool Statistical Comparisons									Morphological Section Statistical Comparisons			Scour > Deposition
Storm	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*1*	*2*	*3*	
1	*a	a	ab	ab	a	c	ab	b	-	a	b	b	no
2	a	a	a	a	a	a	a	a	-	a	b	a	no
3	a	a	a	a	a	a	a	a	-	a	b	-	no
4	a	a	a	a	a	a	a	a	a	a	b	b	yes
5	ab	ab	ab	ab	c	ab	ab	bc	a	a	b	a	yes
6	a	ab	ab	ab	ab	b	ab	c	ab	a	b	b	yes
7	a	a	a	a	a	a	a	a	a	a	a	a	no
8	a	a	a	a	a	a	a	a	a	a	a	a	no
	This section compares mean scour among pools of the same storm event. If pools within the same storm contain the same letter, they are statistically equal.									This section compares mean scour among morohological sections within the same storm event. If sections contain the same letter, they are statistically equal.			Yes indicates that the mean scour is statistically greater than mean deposition within a given storm event. No indicates no difference.

	Deposition Pool to Pool Statistical Comparisons									Morphological Section Statistical Comparisons		
Storm	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*1*	*2*	*3*
1	c	c	c	c	c	c	c	c	-	c	d	d
2	c	c	c	c	c	c	c	c	-	c	c	c
3	c	c	c	c	c	c	c	c	-	c	c	-
4	c	c	c	c	c	c	c	c	c	c	c	c
5	d	d	d	d	f	e	d	d	d	c	d	c
6	d	d	d	d	d	d	d	d	d	c	d	d
7	c	d	d	d	d	d	d	d	d	b	b	b
8	c	c	c	d	c	c	c	c	c	b	b	c
	This section compares mean deposition among pools of the same storm event. If pools within the same storm contain the same letter, they are statistically equal.									This section compares mean deposition among morohological sections within the same storm event. If sections contain the same letter, they are statistically equal.		

concentrations within each of these storm events concluded that there was no significant difference in concentrations between pools (H=5.17 to 13.64, Chi^2=14.07, alpha=0.05). No statistical comparisons of FC concentrations could be made within storm events because only one sample was taken per pool.

In summary, there was no definitave difference between scour depths among pools of the same storm nor between deposition depths among pools of the same storm. There was frequently no difference detected between scour and deposition depths within the same storm. Scour in morphological section two was often greater than in sections one and three but deposition was often not greater. Finally, there was no significant difference in TP concentrations between pools of the same storm event.

Chapter 6

Discussion

Introduction

Analytical results indicate that significant amounts of TP and FC are temporarily stored in the channel sediments of Englesby Brook. Analyses of scour and deposition suggest that channel sediments and related pollutants are moving downstream during periods of increased stream flow. Based upon correlations of stream hydrology with sediment scour it is possible to predict long-term transport of channel sediments and related pollutants.

Pollutant Storage in Englesby Brook Channel Sediments

Phosphorus

TP-Sediment Concentration The mean concentration of TP in the channel sediments of Englesby Brook was determined for each specific storm event. However, within each storm event, there was no statistical difference between mean sediment TP concentrations of various study pools. Furthermore, when cores were split into two depth fractions (0-1 cm and 1-5 cm), there was no significant difference in mean sediment P concentrations with depth. Finally, on the larger scale, there was no significant difference in the mean concentrations of TP between storm events. The results of the statistical tests indicate that the TP concentration of the channel sediments remained relatively constant throughout the study period.

Although statistical tests conclude that TP concentrations are constant, there were notable variations in the mean sediment TP concentrations over the study period (0.41 to

0.62 mg g^{-1} or ± 20%). The variation in sediment TP concentrations show no trends over time (Figure 5.8) and no correlation to the length of time since the last storm event (Table 5.1). Huber and Dickinson (1988) showed that an increase in the length of time between storm events leads to an increase in the buildup of pollutants on the watershed and resulted in higher concentrations of pollutants in runoff waters during subsequent storm events. If the water TP concentrations were responsible for changing the TP concentrations in the sediments, one would expect to find the highest sediment TP concentration after the storm event following the longest pre-storm dry period. This trend however does not appear in the data. Storm four which followed a storm event having a six day pre-storm dry period has the lowest TP concentration (0.41 mg g^{-1}). Storm five which followed a storm event having a three day pre-storm dry period has the second highest TP concentration (0.51 mg g^{-1}).

It is likely that the fluctuations in sediment TP concentrations are due to variability in the sampling and analysis of the sediments. Cores taken in fine-grained sediments are expected to yield higher TP concentrations than those taken in coarse sediments because the fine grained materials provide greater surface area for pollutant adsorption (Stone & Mudroch 1989). The particle size distribution analysis revealed that there was a great amount of variance in particle size throughout the stream (standard error = 102% of the mean, n=8). This variance in particle size could account for the variation in sediment TP concentrations throughout the study period.

The fluctuations in sediment TP concentrations can also be accounted for in the laboratory analysis of TP. The persulfate digestion process used in the laboratory analysis yielded TP concentrations between 84 and 92% of the standard samples from the U.S. Bureau of Standards. This variance in yield can explain as much as 16% of the sediment TP variations found in the experimental data.

Due to the relatively large variance in both sediment particle size and persulfate digestion yield it can be concluded that the best estimate of the TP concentrations in the sediments of Englesby Brook during the period of study is the overall mean of all samples analyzed (0.48 mg g^{-1}). This overall mean is calculated on 276 samples and the large sample size should help to minimize the random errors. Because there were no strong correlations between sediment TP concentrations and time or depth, it can be assumed that the TP concentrations remained constant throughout the study period.

TP- Reservoir An active reservoir of TP in the channel sediments of Englesby Brook has been estimated from the sediment TP and scour depth analyses. This active TP reservoir describes the TP associated with stream channel sediments which are mobilized during periods of increased stream flow. Therefore, the depth of the active TP reservoir will be defined as the maximum, mean scour depth observed during the study period. The surface area of the reservoir is assumed to be the total surface area of all 56 pools in Englesby Brook.

The calculation of the active reservoir of TP in the stream channel sediments is detailed in Appendix D1. The total surface area of all 56 pools along the stream (1,810 m^2) multiplied by the maximum mean scour depth observed (5.18 cm = 0.0518 m) gives a total "active sediment" volume of 94 m^3 (9.4 x 10^7 cm^3). Multiplying this volume of sediment by the mean density of the sediment for all storm events (1.40 g cm^{-3}) gives a total mass of the "active sediment" for Englesby Brook of 1.25 x 10^5 kg. This total mass of active sediment multiplied by the mean sediment TP concentration (0.48 mg g^{-1}) gives approximately 63 kg of TP stored in the active stream channel sediments of Englesby Brook.

During storm events increased stream velocity results in the downstream transport of sediment and related TP. This TP will likely be discharged into Lake Champlain over the course of several years. As the export of sediment related TP is occurring the TP reservoir is being replenished from urban stormwater runoff containing high TP concentrations . It is likely that the stream is in a state of equilibrium with respect to inputs and outputs of TP because the Englesby Brook Watershed has not seen significant land use changes over the past decade and the sediments in the stream are likely to remain at a TP equilibrium until input levels of TP are changed through surface water management programs. It is postulated that the 63 kg reservoir of TP will remain constant over time, continually being simultaneously depleted and replenished during storm events.

Fecal Coliform Bacteria

FC-Sediment Concentration High concentrations of FC have been identified in the channel sediments of Englesby Brook. Statistical comparisons of sediment FC concentrations among the pools within individual storm events were not possible due to the small sample population sizes (one per pool). However, statistical tests comparing mean FC concentrations between storm events showed no significant differences in the concentrations. From these tests it can be concluded that the FC concentration of the channel sediments remained constant throughout the study period. This conclusion is consistent with findings by Van Donsel and Geldreich (1971) who indicated that sediment levels of FC are steady over time and may be the best indicator of long-term water quality.

FC concentrations in the channel sediments of Englesby Brook averaged 456 FC gram^{-1} with a standard error of approximately 8% of the mean. However, mean concentrations for individual storms ranged from 334 to 691 FC gram^{-1} with standard errors from 15 to 34% of the mean. As with sediment TP concentrations, there were fluctuations in the mean FC concentrations for the individual storm events which could not be correlated to time. For example, storm four followed a storm event having a six day pre-storm dry period and has a low FC concentration (395 FC g^{-1}). Storm five, which followed a storm event having a short, three day pre-storm dry period, has the highest FC concentration (691 FC g^{-1}). The variations can most easily be explained by the inconsistent nature of sampling living organisms. Sampling of FC often results in concentrations with high variability (Thomman & Mueller 1987). Because of the small sample sizes (one per pool), the overall mean FC concentration are used as the best estimate of sediment FC concentrations throughout the study period.

FC-Reservoir Like the sediment TP reservoir, the reservoir of FC in the stream channel sediments is defined as the FC associated with the "active sediment layer". The reservoir of FC in the stream channel sediments has been calculated for Englesby Brook (Appendix D2). The total surface area of all 56 pools along the stream (1,810 m^2) multiplied by the "active sediment" depth (5.18 cm) gives a total "active sediment" volume of 94 m^3. This volume of active sediment is multiplied by the mean density of the sediment (1.40 g cm^{-3})to give a total mass of the "active sediment" of 1.25×10^5 kg. The total active sediment mass is multiplied by the mean sediment FC concentration (456 FC g^{-1}) to give a mean of 5.9×10^{10} FC stored in the active stream channel sediments of Englesby Brook during the study period.

The FC concentrations measured in the sediments of Englesby Brook are likely to include FC suspended in the pore-waters and FC that are adsorbed to the sediment particles. Because FC may be considered as fine-grained organic particulates ($\leq$ one micron in size), those FC which are suspended in the sediment pore-waters will be exposed to the flowing stream waters as the surrounding sediments are mobilized. These FC will then be transported downstream along with the fine-grained suspended sediments. The FC which are adsorbed to larger sediment particles will be transported downstream along with the sediment substrate as mobilization occurs.

The reservoir of FC can be considered a short-term source of FC to Lake Champlain, assuming transport of the channel sediments occurs. Because FC are fine-grained particulates, those FC which are not adsorbed to larger sediment particles or which become dislodged during transport, may be exported from the stream during a single storm event. The remaining FC will be transported along with the more coarse-grained sediment particles.

Like the TP reservoir, the FC reservoir is likely replenished during periods of stormwater runoff. However, biological factors can play an important role in controlling the concentration of sediment FC. FC have been documented to multiply in sediments (LaLiberte & Grimes 1981) so the number of FC in the sediment reservoir could be growing throughout the study period. FC are also known to die-off over time, lowering the FC concentration between storm events. Although this study did not investigate FC growth or die-off dynamics, the relatively constant concentration of sediment FC throughout the study period may indicate a dynamic equilibrium of the FC population.

Sediment Transport in Englesby Brook

The quantification of the mobilization of stream channel sediments in Englesby Brook is critical to understanding the transport of pollutants through this fluvial system. The simple fact that scour was observed in all pools during all storm events proves that sediment and related pollutants are moving downstream. The actual scour chain data represent a direct measurement of the mobilization of sediments at discrete points along the stream.

Scour versus Deposition Statistical analyses concluded that in six out of eight storm events there was no significant difference between mean scour and mean deposition depths within individual storms. However, when scour and deposition depths from all storm events were combined, the mean scour depth is greater than mean deposition depth. These different conclusions most likely result from the size of the populations being considered.

For statistical tests conducted on populations within the same storm event, the size of the population is small, making statistical differences indistinguishable at the 90-95% level of confidence. When the scour and deposition measurements for all storms are combined, the large population size more clearly defines the mean and differences in populations become statistically significant. It can therefore be concluded that within individual storm events the sample population size may be too small to determine if differences exist between scour and deposition depths at the 90 to 95% confidence level. However, the large population size ($n \approx 512$) resulting from the consolidation of all scour and deposition measurements more clearly defines the population means. The well defined means leads to the conclusion that for the entire study period, scour depths are greater than deposition depths at the 95% confidence interval.

When sediment scour is greater than sediment deposition the stream channel is, by definition, in a state of degradation and there must be more sediment leaving the stream channel than is entering. Field observations appear to confirm the conclusion that Englesby Brook is degrading over the study period. Several areas along the stream, where significant amounts of sediment had agraded at some earlier time, steadily degraded during the study period. It is important to note that all of the storms measured in the study were quite small and unlikely to cause major washoff of sediments from the surface of the watershed or significant bank erosion. Therefore, the conclusion of net stream degradation during the study period may be valid only during the absence of large storm events. Periods having large storm events may experience net agradation due to high sediment inputs from the watershed surface and stream bank erosion.

Field observations have shown that there are areas along the stream where substantial sediment deposition has occurred previous to the study period. However, these areas were measured and observed to be degrading throughout the study period. It is likely that there are periods of significant agradation from spring runoff of snowmelt or major storm events, during which substantial transport of sediment from the watershed surface and from stream bank erosion is occurring.

Scour and Deposition Comparisons Within Storm Events

Within individual storm events, statistical tests conclude that nearly all scour depths and all deposition depths are the same among pools. In the eight storms, four storms displayed no statistical difference among pools and in each of the other four storms statistical tests indicated only one to two pools differed from all others. From these data, it can be concluded that within the accuracy of the scour and deposition measurements, there were no distinct differences in scour or deposition when comparing measured pools of the same storm event.

Differences in scour and deposition depths were compared among the three morphological stream sections as defined in chapter three. In six of the eight individual storm events, both scour and deposition in morphological section two were greater than in section one. In three of the eight storms, scour and deposition in section two were greater than in section three. When combined data from all storms was compared, there was no significant difference in scour or deposition between morphological sections, however, a strong trend of greater scour and deposition in section two does exist.

Section two begins at the base of the steep, upper reaches of the stream and has approximately 70% of all runoff from the watershed traveling through it. The dramatic increases in discharge in this section would make it a logical place for increased scour. Section two's position at a break in slope, where velocities are likely to decrease, make for a logical place for increased deposition. Because there was no definite distinction between the scour or deposition depth measurements in the three morphological sections and because there was no distinct statistical difference in scour and deposition depth measurements between pools, this study will use the overall mean from each storm event as the most dependable estimate of scour and deposition depths due to the large population size.

Scour and Deposition Comparisons Between Storm Events

Statistical comparison of mean scour or deposition depths between storm events concludes that only storm eight, the largest of the measured events, is different from and greater than all other storms. However, regression analysis between total amount of precipitation and both scour depth and deposition depth of sediment displayed strong positive correlations (scour r^2=.82, deposition r^2=.81) (Figure 5.2). Regression analysis between cumulative stream power and both scour depth and deposition depth displayed an even stronger positive correlation (scour r^2=.90, deposition r^2=.89) (Figure 5.3). The stronger correlation between stream power and sediment transport is most likely due to the direct causal effect of the energy of the stream on the transport of sediment (i.e. it takes stream energy to transport stream sediment). It therefore appears that measurements of cumulative stream power may be a good indicator of the amount of scour and deposition occurring in Englesby Brook during the small to moderate storm events measured during this study. For long-term sediment transport prediction in Englesby Brook, long-term, local precipitation records might become the basis for a reasonable estimate of scour and deposition for events of similar size as those measured during this study, assuming no changes in land use occur. Extrapolation of the relationships between watershed hydrology and sediment movement are possible for storm events greater than those measured during this study, however large errors are likely to occur.

A control pool was measured for scour depth and deposition depth during each storm event (except for storm one), to assure that the trends in scour and deposition depths were dependent on stream hydrology and not on pool selection. The regression analysis shown in Figure 5.4 (cumulative stream power versus scour and deposition depths in pool 25) shows that scour and deposition depths in the control pool follow the same trends as the overall storm means shown in Figure 5.3. The correlations are weaker in the individual control pool (scour r^2=.73, deposition r^2=.43) than in the storm event means due to the smaller number of measurements taken for the individual control pool. The trend of increased sediment scour and deposition with increased stream power found in the overall means is supported by similar trends displayed in the control pool correlations.

Limitations of Scour and Deposition Measurements

Measurement of sediment transport through the use of scour chains has several distinct limitations. First, reading of the calibrated stakes beneath the surface of the water is difficult and results in a resolution of approximately ± 0.25 cm. With an average scour of 2.43 cm throughout the study period, the resulting error is approximately ± 10%. This estimate of error in measurement agrees with the errors found in the data summary which reveals an overall mean scour depth of 2.43 cm ± 0.33 cm (approximately 13.6%). Second, there is likely a small amount of locally induced scour caused by the presence of the chains and stakes which would result in slightly high estimates of sediment mobilization and export. Third, the chains only measure sediment mobilization in pool sections of the stream. It is likely that the riffle sections account for an additional several percent export of sediment. Finally, the measured data give no insight into the distance of sediment transport which only allows for direct calculations of entrainment at a single point along the stream. Any estimates of total sediment and pollutant discharge using the scour chain data are rough at best.

Interpretations of Sediment Transport and Pollutant Data

Measured sediment scour and deposition depths are direct measurements of sediment motion at discrete points along the stream. Conclusions which are drawn from these data must assume that the measurements at the scour chains are representative of the scour and deposition of the surrounding stream channel . In order to attempt long-term predictions of sediment movement in the stream channel conclusions must also assume that the scour and deposition measurements taken in eight randomly selected pools are representative of the scour and deposition for the entire length of the stream . The conclusions and calculations which are discussed in this section are extremely approximate, yet will give some insight into the relative magnitudes of the processes moving sediment and pollutants through Englesby Brook. The large errors associated with these calculations are indicated by the significant figures shown. Estimates of true errors would be highly speculative.

Total Sediment and Pollutant Mobilization

Sediment and pollutant mobilization is the amount of sediment and pollutants which are set in motion during a storm event, without consideration of travel distance or whether the scoured materials are transported just out of a stream pool or out of the stream entirely. The total amount of sediment, TP, and FC mobilized has been calculated for the entire study period. Appendix D3 details the sediment and pollutant mobilization calculations.

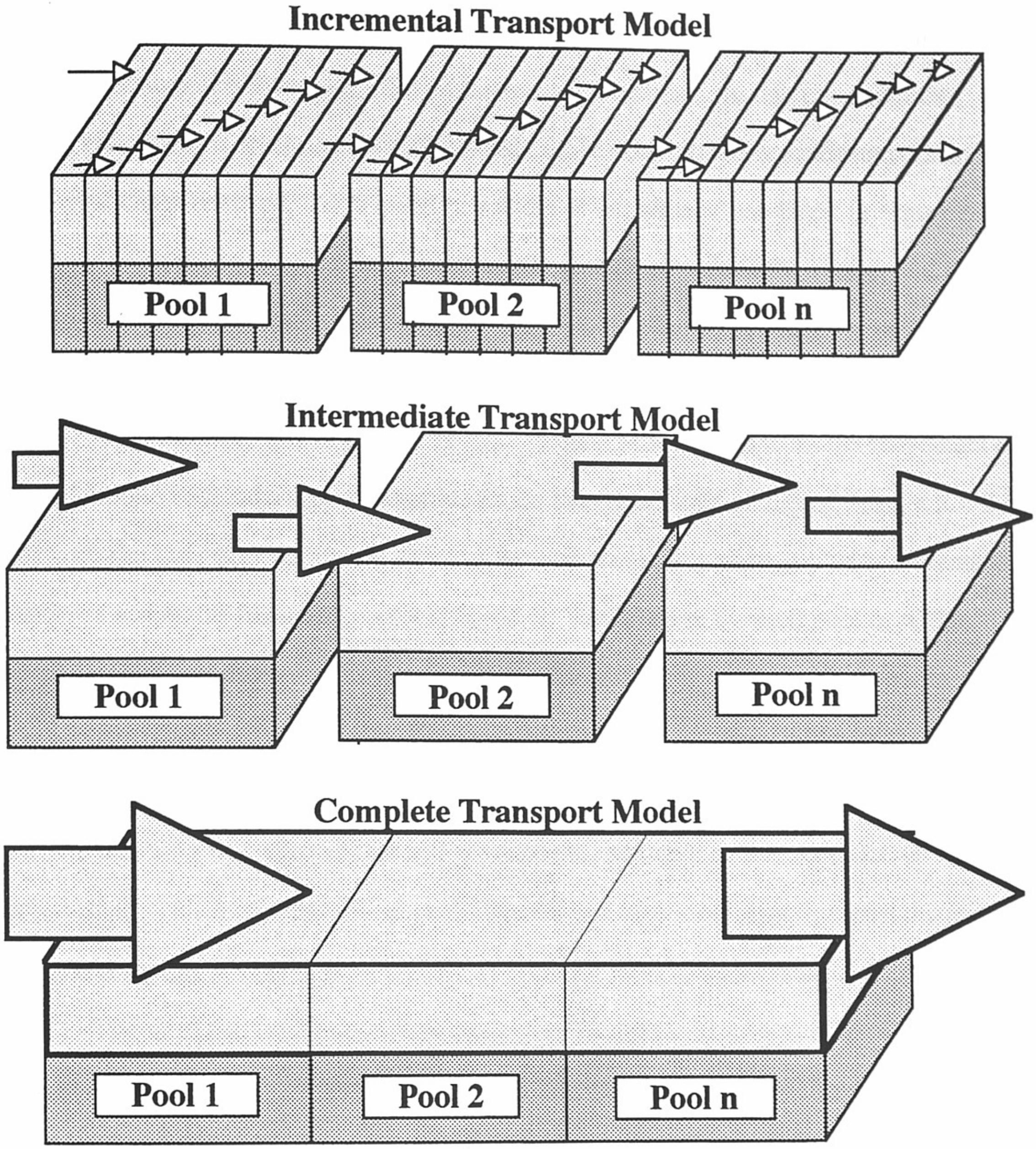
The total sediment mobilized during the study period was 4.9×10^5 kg (ranging from 2×10^4 kg for storm three, to 1×10^5 kg for storm eight). The resulting TP mobilized is calculated to be 240 kg (ranging from 10 kg for storm three, to 63 kg for storm eight). The resulting FC mobilized is calculated to be 2.2×10^{11} FC (ranging from 8.6×10^9 FC for storm three, to 5.9×10^{10} FC for storm eight).

These results indicate a substantial amount of sediment and pollutants are mobilized in Englesby Brook even during relatively small storm events. It is likely that during a single storm event, the coarse fraction of these mobilized sediments (97.6%) and associated pollutants will be re-deposited down stream. The fine fraction (2.4%) will likely be transported entirely through the stream channel. Over the course of many storm events, all mobilized sediments and pollutants should be transported through the system, thus implicating the transport of stream channel sediments as an important mechanism for transporting pollutants through fluvial environments to receiving waters.

Sediment and Pollutant Transport

A rough estimate of mean annual sediment and pollutant transport is possible from the data collected in this study. The calculations require a number of assumptions, however, the results are consistent with values found in the literature. Several interpretive models can be used to describe the motion of different sediment size fractions through a fluvial system. The difference in these models is based only on the probable travel distance of a sediment particle of a specific size fraction during a single storm event.

Sediment Transport Models As stated earlier, the scour measurements represent the mobilization of sediments and related pollutants at discrete points. These measurements can be interpreted using three different interpretive models (Figure 6.1). In the "Incremental Transport Model" the larger sediments move only a short distance



Incremental Transport Model

Intermediate Transport Model

Complete Transport Model

Figure 6.1 **Illustration of Sediment Transport Models. The size of the arrows indicate the relative distance of sediment transport. The incremental transport model shows scoured sediment (light stipple) moves only a short distance within a given pool before deposition occurs. The intermediate model shows sediment is scoured from one pool and is deposited in the next pool down-stream. The complete transport model shows that scoured sediment from all pools is exported from the stream.**

(equal to several mean grain diameters) away from the measured points before they are re-deposited. The Incremental Transport Model probably explains the transport of the coarsest sediment particles (≥ 2 mm) which moves as bedload. In this interpretation, stream channel sediments and pollutants would move down stream a maximum distance of several centimeters per storm event (the width of one slice of one block in Figure 6.1), and only those particles which had incrementally made their way to the very end of the stream, would be exported to the lake (the volume of one lightly stipple slice in Figure 6.1).

A second interpretive model, the"Intermediate Model", describes the movement of highly mobile bedload material classified as the sand sized fraction (0.0625 mm $< x <$ 2 mm). In the Intermediate Model, the average scour measurement for a pool represents the export of sediments from that pool which will be deposited in the next pool or within several pools downstream. Those sediments mobilized in the last one or two pools would be discharged into the lake. The rational behind the distance of transport in this model is that there is a high probability that over the course of several pools, a sediment particle traveling with the bedload will get deposited behind a cobble, boulder, or woody debris dam. This interpretive model would result in a mean sediment transport distance of several to tens of meters per small storm event for sand sized particles.

The third and final interpretive model the "Complete Transport Model", best describes the movement of the fine-grained sediment fraction (≤ 0.0625 mm). In this model all fine-grained sediment from the entire system is entrained in the flowing water, transported through the entire stream, and is discharged to the lake. Because more than 97% of the stream channel sediments are of sand size or greater, it is not likely that there will be a high degree of channel sediment transported in suspension.

Channel Sediment Export Estimations Because of the different size fractions of the stream channel sediments, it is necessary to integrate the three transport models to describe the movement of channel sediments and associated TP and FC through Englesby Brook. During a small sized storm event, the coarse grained particles move several centimeters, the medium sized particles move several to tens of meters (one to two pools), and the fine grained particles move up to several kilometers (total export in suspension). Using these assumptions, total sediment export from the stream channel sediments of Englesby Brook can be estimated.

The export of coarse grained sediments from the stream channel was calculated using the "Incremental Transport Interpretive Model" in which sediments are only transported a distance equal to several mean grain diameters downstream. The coarse grained sediment export volume was assumed to be equal to a section of sediment which has a thickness of 1.0 cm, a width equal to the average width of the stream, and a depth equal to the mean scour depth for that storm. This volume was then multiplied by the 14.8 % coarse fraction to get the total export (Appendix D4). The mass of coarse sediment was then calculated using the mean sediment mass for all storms.

For the mid-sized particle fraction (0.0625 mm < x < 2 mm), the "Intermediate Transport Interpretive Model" was used which assumes export of a volume of sediment which is equal to the mean scour depth for a storm event multiplied by the mean pool channel area. From the particle size analyses it was determined that 83.6% of the channel sediment was mid-sized. This size fraction percentage was then multiplied by the mean sediment scour volume giving the mid-sized export estimate (Appendix D4).

The export of fine-grained sediments from the stream channel was calculated using the "Complete Transport Interpretive Model". This fine-grained sediment export was estimated as 2.6% of the total sediment mobilized (Appendix D4). This 2.6% is assumed to be completely transported from the system.

The sum of the export values from the three models estimates the total export of sediment from the stream channel sediments to Lake Champlain. Appendix D4 details the sediment export calculations for storm one. The calculation implies that a large percentage (66.6%) of the total sediment export (3,301 kg) is fine-grained sediment (2,100 kg) which would be transported as suspended load. Export of medium-grained sediments (1,200 kg) is about half the fine-grained sediment export, and coarse-grained sediment export is minimal (1 kg). The medium and coarse-grained fractions would likely be transported as bedload. Because of the small size of the measured storm events, it is logical to expect the majority of the sediment transport to be fine-grained. The small storm events may not create enough stream energy to move substantial portions of the medium and coarse fractions. The total export estimates for all storms are shown in Table 6.1. The export fractions are in similar proportions for all storm events shown.

For each storm event, the total sediment export estimates were divided by the duration of the hydrograph to get the average sediment discharge rates (lbs sec^{-1}). These sediment discharge rates were plotted on Figure 6.2 (large stars represent sediment export estimates from this study) adapted from Yang & Stall (1976). Yang and Stall (1976) measured sediment discharge in a small stream in South Carolina and then compared the measurements to calculated values using the a number of sediment transport equations reported in the literature. The estimated sediment export values from this study all fall on the low end of the scale of Figure 6.2. The estimated values from this study agree, within an order of magnitude, with the estimates by the various sediment transport equations. It should be noted that all of the sediment transport equations are based on steady flow conditions, where as the flow values determine for this study where the average flow over a changing hydrograph.

Table 6.1 Sediment Export Estimates for 8 Storm Events. Estimates are broken down by grain size fraction. A sample calculation for storm #1 is shown in Appendix D4.

	Sediment Export Estimates (kg)			
Storm	*Fine Grained*	*Medium Grained*	*Coarse Grained*	*Total*
1	2108	1196	1	3305
2	1482	841	1	2324
3	520	295	0	815
4	922	523	0	1445
5	1311	744	1	2056
6	1759	998	1	2758
7	1285	729	1	2015
8	3413	1936	2	5351
mean	1600	908	1	2509

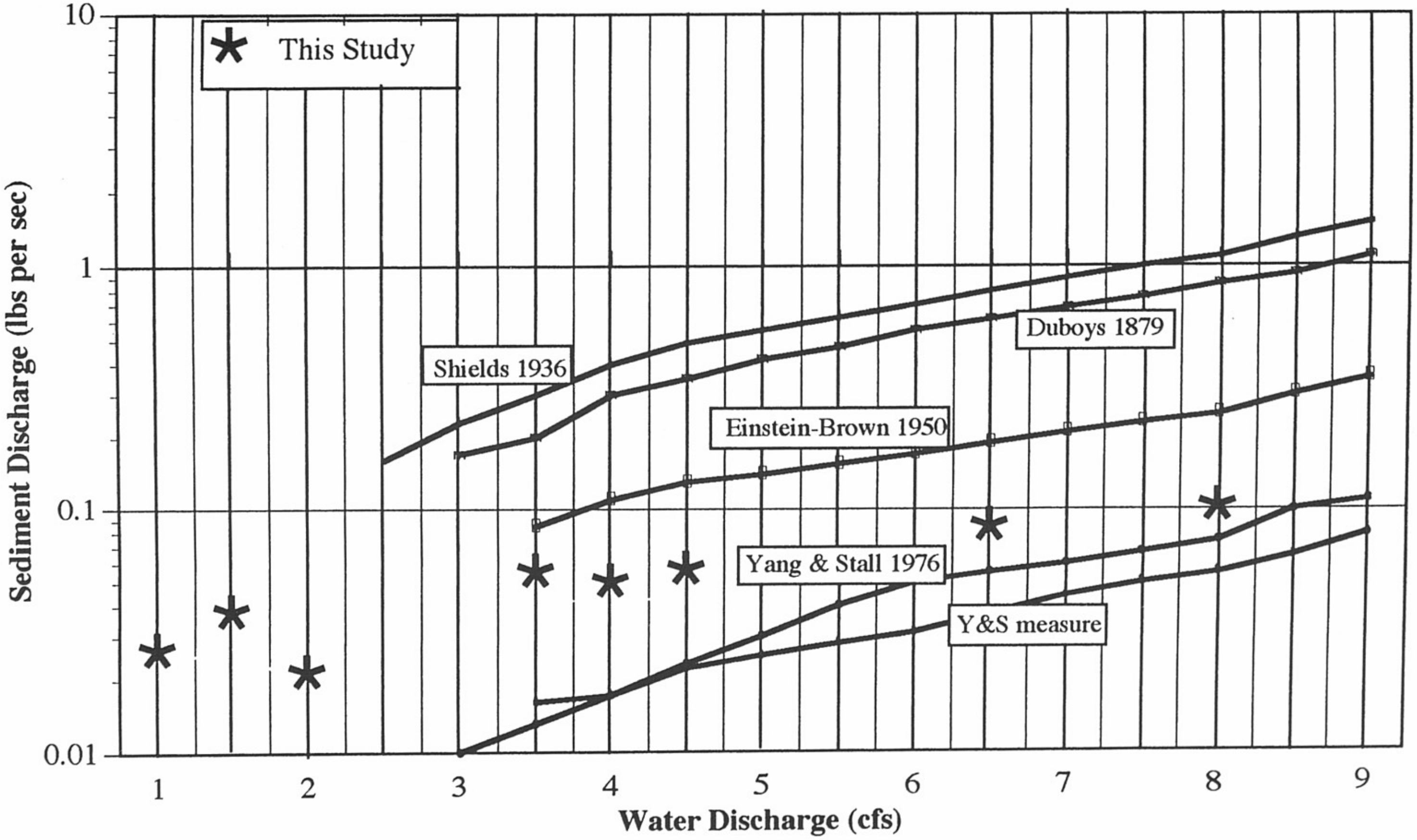


Figure 6.2 Comparison Between Englesby Brook Estimated Sediment Export (stars), and Sediment Discharge Values Measured and Computed by Yang and Stall 1976. Yang and Stall measured sediment discharge in a natural stream in South Carolina, and then computed sediment discharge using literature equations.

Adapted from Yang and Stall 1976.

Pollutant Export From Stream Channel Sediments Approximate total pollutant export values have been estimated for each of the eight storm events (Appendix D5) by multiplying the measured sediment concentrations of TP and FC by the estimated total sediment export values from the previous section (Table 6.2 & 6.3). From the total pollutant export estimates, the pollutant export values have been estimated for each sediment size fraction (Table 6.2 & 6.3) based on the relative surface area available for adsorption. To estimate available surface area, it has been assumed that all particles are spherical.

The TP export from the stream channel sediments has an estimated mean of 1.2 kg TP per storm and ranged from 0.4 to 2.6 kg per storm. FC export has an estimated mean of 1.1 x 10^9 FC per storm and ranged from 3.7 x 10^8 to 2.4 x 10^9 FC per storm. These export estimates are for small to moderate storm events. The export rates would be expected to be higher during periods of higher flows when greater amounts of sediment are exported. However, because pollutants tend to be most strongly associated with fine-grained sediments (Table 6.2 & 6.3), and because higher stream flows will generally increase transport of the coarse-grained sediment fraction, pollutant export rates should increase at a slower rate as the flows increase.

From the per storm pollutant export rates a yearly, small storm export rate of pollutants from the stream channel sediments can be estimated. This export rate does not consider high flow events which may occur from large storm events or from spring runoff. Although this export rate is not a total sediment related pollutant loading rate, it can give insight into the importance of sediment and pollutant mobilization during small to moderate storm events.

The month of July, 1994 was the only complete month of monitoring during the study period and will therefore be used to aproximate a yearly small storm export rate. During the month of July, 1994, a total of 2.06 inches of rainfall was measured. The

Table 6.2 TP Export Estimates for 8 Storm Events. Estimates are broken down by grain size fraction. A sample calculation for storm #1 is shown in Appendix D5.

▨	Fractional TP Export Estimates (kg)			
Storm	*Total*	*Fine Grained*	*Medium Grained*	*Coarse Grained*
1	1.59	1.58	0.01	0.00
2	1.12	1.11	0.01	0.00
3	0.39	0.39	0.00	0.00
4	0.69	0.69	0.00	0.00
5	0.99	0.98	0.01	0.00
6	1.32	1.31	0.01	0.00
7	0.97	0.96	0.01	0.00
8	2.57	2.55	0.01	0.00
mean	1.21	1.20	0.01	0.00

Table 6.3 FC Export Estimates for 8 Storm Events. Estimates are broken down by grain size fraction. A sample calculation for storm #1 is shown in Appendix D5.

▨	Fractional FC Export Estimates (#)			
Storm	*Total*	*Fine Grained*	*Medium Grained*	*Coarse Grained*
1	1.51E+09	1.50E+09	8.44E+06	6.03E+05
2	1.06E+09	1.05E+09	5.93E+06	4.24E+05
3	3.72E+08	3.69E+08	2.08E+06	1.49E+05
4	6.59E+08	6.55E+08	3.69E+06	2.64E+05
5	9.38E+08	9.32E+08	5.25E+06	3.75E+05
6	1.26E+09	1.25E+09	7.04E+06	5.03E+05
7	9.19E+08	9.13E+08	5.15E+06	3.68E+05
8	2.44E+09	2.43E+09	1.37E+07	9.76E+05
mean	1.14E+09	1.14E+09	6.41E+06	4.58E+05

average rainfall from the thirty-year normal, monthly precipitation records from the Burlington International Airport is 3.21 inches (for the months of April through November). Precipitation events during the months of December through March will not be considered because during these months precipitation is generally in the form of snow and the stream is typically frozen. Because precipitation during July, 1994 was well below the long-term monthly average our yearly, small storm export estimate will be considered to be near minimum.

To estimate minimum, monthly, small storm export rates from the stream channel sediments, the pollutant export estimates for the storms measured during the month of July (storms two through six) were summed. The minimum, small storm export rates of TP and FC to Lake Champlain from the stream channel sediments of Englesby Brook are estimated to be 4.5 kg TP month^{-1} and 4.3 x 10^{9} FC month^{-1}. These monthly estimates are then multiplied by eight months (April through November) to give minimum, small storm export estimates of 36 kg TP year^{-1} and 3.4 x 10^{10} FC year^{1}. When these loading rates are compared to the active TP and FC reservoirs (63 kg and 6 x 10^{10} respectively), approximately 57% of the TP and the FC are exported from the stream channel sediments by small storm events during a one year period. This implies that if the pollutant reservoirs were not continually replenished, the pollutant reservoir could be depleted in slightly less than two years even without the aid of large storm events or spring snowmelt runoff.

In order to detemine the possible significance of the estimated, minimum, small storm pollutant export from the channel sediments, a comparison has been made to TP export estimates calculated from values found in the literature. Pitt (1994), determined TP loading rates from a medium density residential watershed to be 0.26 kg acre^{-1} yr^{-1} (0.58 lbs acre^{-1} yr^{-1}). This loading rate multiplied by the 544 acres which make up the Englesby Brook Watershed yields a yearly TP loading rate of 143 kg yr^{-1}. Budd and

Meals (1994) estimated urban TP loading coefficients of 0.40 kg acre^{-1} yr^{-1} to 0.77 kg acre^{-1} yr^{-1} which yield TP exports of 217 kg yr^{-1} to 420 kg yr^{-1} for Englesby Brook. The minimum, small storm pollutant export estimate (36 kg yr^{-1}) suggests that pollutants mobilized with stream channel sediments during small storm events may be responsible for the export of at least 8 to 25% of the total yearly TP export.

Chapter 7

Conclusions

In this thesis, Englesby Brook has been monitored for eight small storm events (0.06" to 1.30" of precipitation). Sediment scour and deposition depths, sediment TP and FC concentrations, sediment density, particle size distribution, as well as streamflow and precipitation were measured. The following conclusions have been formulated from the Englesby Brook data:

1. There are high concentrations of TP and FC in the channel sediments of Englesby Brook. Mean TP concentrations were 0.48 mg g^{-1} and mean FC concentrations were 456 FC g^{-1} during the study period. These concentrations remained constant throughout the study period, indicating that TP and FC were stored in the stream channel sediments from June through September, 1994.

2. Mean sediment TP and FC concentrations are not significantly different among pools during the same storm event or among the eight different storm events, at the 95% confidence interval. Therefore, the overall mean TP and FC concentrations for all storm events are a good estimate of the concentrations throughout the study period.

3. In all eight storm events, mean sediment scour depths were greater than zero (0.79 - 5.18 cm) indicating that sediment is being transported away from the scour chains. Therefore, sediments and adsorbed pollutants are being transported downstream during the measured stormflow periods. Sediment and pollutant transport occurs even during storm events yielding relatively low streamflow.

4. Mean scour depths over the period of study are significantly greater than mean deposition depths at the 95% confidence interval. Thus, the stream channel was degrading throughout the study period. For degradation to occur, there must be a greater amount of sediment leaving the stream channel than is entering. Therefore, stream channel sediments were exported during the study period and sediment related TP and FC must also have been exported.

5. Correlations of mean sediment scour depths with precipitation and cumulative stream power yield r^2 values of 0.82 and 0.90 respectively. Both precipitation and cumulative stream power can provide good estimates of mean scour and deposition depths in the channel sediments of Englesby Brook. t

6. A mass of active sediment, defined as the total mass of sediment in the stream which is likely to be mobilized during small to moderate storm events, has been estimated to be 1.25 x 10^5 10^4 kg.

7. From the estimated active sediment mass, the reservoirs of TP and FC contained in the stream channel are estimated to be 63 kg P and 5.9 x 10^{10}FC. These estimates are the masses of TP and FC respectively, which are likely to be mobilized during small to moderate storm events.

8. Three conceptual models for describing the transport of stream channel sediments have been presented in this thesis. The three models suggest that (a) the coarse sediments (> 2.0 mm) are only transported a short distance before being re-deposited, (b) the medium sized particles ($0.0625 \text{ mm} \leq x \leq 2.0 \text{ mm}$) travel through several pools before being re-deposited, and (c) the fine-grained

sediments are suspended and quickly transported out of the stream. These generalized models can give insight into understanding the motion of sediments in fluvial systems.

9. Rough estimates of sediment export have been made using the three conceptual models. The sediment export estimates had a mean of 2509 kg per storm event of which approximately 64% was transported as fine-grained suspended sediment, 36% was transported as sand sized bedload, and less than 1% was transported as coarse bedload. Because all of the storm events were small, it is expected that stream energy would be relatively low and that coarse bedload transport would also be low. The calculated sediment export values agreed well with the values calculated from the equations from the literature (Yang and Stall 1976),

10. The export of TP and FC from the stream channel sediments of Englesby Brook have been roughly estimated to be 1.2 kg TP per storm and 1.1 x 10^9 FC per storm. These estimates have then been used to approximate minimum, yearly export coefficients of 36 kg TP yr^{-1} and 3.4 x 10^{10} FC yr^{-1} from the stream channel sediments of Englesby Brook. The minimum sediment TP export rate amounts to approximately 8 to 25% of the estimated TP export from the entire watershed indicating that the stream channel sediments may be an important source of pollutants to Lake Champlain.

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Appendix A

Stream Reach Characteristics

Section#	Pool #	Width (ft)	Length (ft)	Channel Area (sq ft)	Bank Full Depth (ft)
1	1	13.6	12.1	164.6	1.0
1	2	6.0	22.0	132.0	0.7
1	3	8.0	15.8	126.4	1.1
1	4	12.7	14.2	180.3	0.6
1	5	5.5	72.1	396.6	0.7
1	6	6.1	98.2	599.0	1.5
1	7	5.7	31.9	181.8	0.5
1	8	5.8	29.1	168.8	1.2
1	9	5.7	25.7	146.5	0.5
1	10	7.0	17.8	124.6	1.0
1	11	8.2	37.0	303.4	1.2
1	12	5.0	45.0	225.0	1.5
1	13	5.3	30.2	160.1	1.4
1	14	6.2	45.2	280.2	0.6
1	15	7.2	30.1	216.7	0.9
1	16	10.7	22.0	235.4	0.7
1	17	9.2	40.5	372.6	1.4
1	18	10.5	39.5	414.8	0.6
1	19	8.5	22.0	187.0	0.4
1	20	6.4	16.6	106.2	1.5
1	21	5.4	33.9	183.1	1.4
1	22	3.8	35.1	133.4	1.2
1	23	5.2	16.0	83.2	1.0
2	24	6.6	39.9	263.3	2.9
2	25	7.0	77.8	544.6	2.2
2	26	7.4	37.8	279.7	1.9
2	27	7.6	22.4	170.2	2.5
2	28	7.5	67.0	502.5	2.8
2	29	7.5	36.1	270.8	1.5
2	30	5.6	32.1	179.8	1.8
2	31	5.8	22.7	131.7	2.3
2	32	5.2	46.4	241.3	2.2
2	33	7.0	27.0	189.0	1.7
2	34	7.0	15.9	111.3	2.5
2	35	7.0	100.1	700.7	2.8
2	36	5.1	22.0	112.2	2.1
2	37	8.8	66.0	580.8	1.6
2	38	8.9	65.3	581.2	2.3
2	39	6.0	50.8	304.8	2.5
2	40	5.2	50.1	260.5	2.2
2	41	4.0	41.0	164.0	2.2

2	42	7.0	40.1	280.7	2.6
2	43	8.0	90.0	720.0	2.1
2	44	9.2	100.0	920.0	2.2
2	45	8.8	80.7	710.2	2.9
3	46	7.4	40.2	297.5	2.0
3	47	7.0	150.8	1055.6	2.2
3	48	na	na	na	na
3	49	10.1	152.0	1535.2	2.5
3	50	9.2	98.5	906.2	1.5
3	51	10.7	58.6	627.0	1.8
3	52	6.0	18.2	109.2	2.8
3	53	8.3	63.0	522.9	2.2
3	54	6.4	48.2	308.5	2.7
3	55	10.5	70.3	738.2	1.8
3	56	10.6	72.0	763.2	1.6

Appendix B

Sediment and Pollutant Laboratory Data

Storm #	Pool#	core#	sample #	sediment wet weight (g)	sediment dry weight (g)	Absorbence 1/50 dillution	Absorbence	sample [P] (mg/l)	mass P (mg)	sediment sample mass (g)	Sed [P] (mg/g)	[FC] #/g
1	1	1	a	17.7	12.8	0.005	0.250	2.685	0.134	0.220	0.610	230
1	1	1	b	76.9	62.4	0.000	0.000	0.000	0.000	0.210	0.000	-
1	7	7	a	27.7	19.5	0.001	0.050	0.599	0.030	0.190	0.158	410
1	7	7	b	55.1	43.2	0.004	0.200	2.181	0.109	0.260	0.419	-
1	16	16	a	28.6	21.8	0.005	0.250	2.685	0.134	0.200	0.671	240
1	16	16	b	90.9	72.1	0.005	0.250	2.685	0.134	0.310	0.433	-
1	23	23	a	15.7	11.5	0.001	0.050	0.599	0.030	0.200	0.150	90
1	23	23	b	99.1	76.6	0.003	0.150	1.668	0.083	0.220	0.379	-
1	34	34	a	25.7	21	0.001	0.050	0.599	0.030	0.240	0.125	150
1	34	34	b	111.8	92.4	0.003	0.150	1.668	0.083	0.220	0.379	-
1	36	36	a	30.9	23.1	0.011	0.550	5.598	0.280	0.250	1.120	380
1	36	36	b	99.4	77.2	0.006	0.300	3.182	0.159	0.210	0.758	-
1	38	38	a	37.9	30.7	0.005	0.250	2.685	0.134	0.240	0.559	390
1	38	38	b	115.2	95.4	0.009	0.450	4.643	0.232	0.200	1.161	-
1	50	50	a	29.3	22.2	0.006	0.300	3.182	0.159	0.290	0.549	730
1	50	50	b	87.9	64.8	0.003	0.150	1.668	0.083	0.280	0.298	-
1	52	52	a	32.8	25.1	0.011	0.550	5.598	0.280	0.330	0.848	390
1	52	52	b	104.3	79.5	0.002	0.100	1.143	0.057	0.210	0.272	-
2	4	2	a	22.8	16	0.012	0.600	6.071	0.304	0.200	1.518	800
2	4	2	b	103.8	70.3	0.006	0.300	3.182	0.159	0.200	0.796	-
2	4	37	a	27.4	22.9	0.003	0.150	1.668	0.083	0.210	0.397	-
2	4	37	b	132.2	114.2	0.004	0.200	2.181	0.109	0.220	0.496	-
2	4	50	a	38.4	31.7	0.016	0.800	7.937	0.397	0.240	1.654	-

2	4	50	b	134.6	119	0.003	0.150	1.668	0.083	0.190	0.439	-
2	12	6	a	37	30.7	0.003	0.150	1.668	0.083	0.200	0.417	80
2	12	6	b	136.7	112.6	0.004	0.200	2.181	0.109	0.220	0.496	-
2	12	23	a	30.7	22.8	0.004	0.200	2.181	0.109	0.210	0.519	-
2	12	23	b	120.2	95.6	0.004	0.200	2.181	0.109	0.220	0.496	-
2	12	34	a	26.7	20.8	0.005	0.250	2.685	0.134	0.230	0.584	-
2	12	34	b	135.1	105.5	0.004	0.200	2.181	0.109	0.200	0.545	-
2	25	29	a	32.6	26.8	0.001	0.050	0.599	0.030	0.260	0.115	464
2	25	29	b	126.3	102.8	0.001	0.050	0.599	0.030	0.240	0.125	-
2	25	26	a	32.2	27.9	0.002	0.100	1.143	0.057	0.200	0.286	-
2	25	26	b	145.5	121.6	0.008	0.400	4.161	0.208	0.250	0.832	-
2	25	21	a	33.6	28.4	0.002	0.100	1.143	0.057	0.260	0.220	-
2	25	21	b	142.7	121.5	0.005	0.250	2.685	0.134	0.220	0.610	-
2	33	40	a	25.5	23.8	0.007	0.350	3.674	0.184	0.260	0.707	304
2	33	40	b	111.1	101.6	0.002	0.100	1.143	0.057	0.190	0.301	-
2	33	51	a	17.3	16.3	0.001	0.050	0.599	0.030	0.210	0.143	-
2	33	51	b	109.7	102.8	0.003	0.150	1.668	0.083	0.250	0.334	-
2	33	45	a	25.6	25.2	0.001	0.050	0.599	0.030	0.200	0.150	-
2	33	45	b	106.8	102.7	0.002	0.100	1.143	0.057	0.220	0.260	-
2	37	35	a	24.6	22.5	0.005	0.250	2.685	0.134	0.250	0.537	800
2	37	35	b	105.4	98	0.005	0.225	2.434	0.122	0.190	0.641	-
2	37	30	a	24.7	21.1	0.002	0.100	1.143	0.057	0.200	0.286	-
2	37	30	b	125.9	106.5	0.002	0.100	1.143	0.057	0.200	0.286	-
2	37	17	a	31	25.2	0.003	0.150	1.668	0.083	0.210	0.397	-
2	37	17	b	141.4	115.7	0.006	0.300	3.182	0.159	0.260	0.612	-
2	40	20	a	27.2	24.9	0.002	0.100	1.143	0.057	0.210	0.272	368
2	40	20	b	106.3	98.3	0.001	0.050	0.599	0.030	0.220	0.136	-
2	40	18	a	21.6	19.9	0.001	0.050	0.599	0.030	0.220	0.136	-
2	40	18	b	107.9	96.8	0.003	0.150	1.668	0.083	0.240	0.348	-
2	40	43	a	26.4	25.3	0.004	0.200	2.181	0.109	0.220	0.496	-

2	40	43	b	105.9	100.8	0.001	0.050	0.599	0.030	0.220	0.136	-
2	46	3	a	37.7	31.5	0.002	0.100	1.143	0.057	0.200	0.286	304
2	46	3	b	145.2	124.3	0.003	0.150	1.668	0.083	0.220	0.379	-
2	46	1	a	36.7	31.7	0.004	0.200	2.181	0.109	0.270	0.404	-
2	46	1	b	139.8	126.4	0.004	0.200	2.181	0.109	0.200	0.545	-
2	46	41	a	32.5	27.3	0.001	0.050	0.599	0.030	0.210	0.143	-
2	46	41	b	119.8	106.3	0.002	0.100	1.143	0.057	0.220	0.260	-
2	54	32	a	42.6	36.6	0.002	0.100	1.143	0.057	0.200	0.286	na
2	54	32	b	147.2	124.9	0.007	0.350	3.674	0.184	0.200	0.918	-
2	54	19	a	38.6	29.6	0.003	0.150	1.668	0.083	0.220	0.379	-
2	54	19	b	164.8	128.8	0.010	0.500	5.122	0.256	0.240	1.067	-
2	54	42	a	41.5	33.3	0.002	0.100	1.143	0.057	0.220	0.260	-
2	54	42	b	127.1	100.4	0.010	0.500	5.122	0.256	0.210	1.220	-
3	1	7	a	29.2	23.5	0.002	0.100	1.143	0.057	0.240	0.238	200
3	1	7	b	125.2	97.9	0.002	0.100	1.143	0.057	0.230	0.249	-
3	1	36	a	30	24.4	0.003	0.150	1.668	0.083	0.240	0.348	-
3	1	36	b	144.4	120	0.003	0.125	1.408	0.070	0.260	0.271	-
3	1	22	a	38	28.6	0.007	0.350	3.674	0.184	0.210	0.875	-
3	1	22	b	122.1	95.3	0.005	0.250	2.685	0.134	0.230	0.584	-
3	3	28	a	31	22.6	0.001	0.050	0.599	0.030	0.210	0.143	320
3	3	28	b	134.7	116	0.001	0.050	0.599	0.030	0.240	0.125	-
3	3	38	a	31.6	25.7	0.004	0.200	2.181	0.109	0.240	0.454	-
3	3	38	b	87.4	60.8	0.005	0.250	2.685	0.134	0.210	0.639	-
3	3	15	a	30.9	26	0.003	0.150	1.668	0.083	0.220	0.379	-
3	3	15	b	132.2	106.8	0.004	0.200	2.181	0.109	0.230	0.474	-
3	10	9	a	42.6	38.7	0.004	0.200	2.181	0.109	0.240	0.454	120
3	10	9	b	121.9	89.8	0.006	0.300	3.182	0.159	0.230	0.692	-
3	10	11	a	29.7	24.8	0.003	0.150	1.668	0.083	0.260	0.321	-
3	10	11	b	138.6	116.4	0.001	0.050	0.599	0.030	0.200	0.150	-

3	10	49	a	40	32.3	0.002	0.100	1.143	0.057	0.230	0.249	-
3	10	49	b	140.7	117.6	0.001	0.050	0.599	0.030	0.200	0.150	-
3	11	16	a	38.9	31.4	0.005	0.250	2.685	0.134	0.240	0.559	160
3	11	16	b	141.2	122.8	0.002	0.100	1.143	0.057	0.360	0.159	-
3	11	24	a	39.4	31.5	0.005	0.250	2.685	0.134	0.220	0.610	-
3	11	24	b	139.3	110.4	0.004	0.200	2.181	0.109	0.200	0.545	-
3	11	44	a	38.5	31.3	0.002	0.100	1.143	0.057	0.240	0.238	-
3	11	44	b	131.9	104.7	0.003	0.150	1.668	0.083	0.230	0.363	-
3	18	4	a	36.2	29.4	0.006	0.300	3.182	0.159	0.220	0.723	300
3	18	4	b	136	112.6	0.004	0.200	2.181	0.109	0.260	0.419	-
3	18	46	a	28.8	23.9	0.004	0.200	2.181	0.109	0.220	0.496	-
3	18	46	b	155.4	138.3	0.003	0.150	1.668	0.083	0.270	0.309	-
3	18	47	a	33.6	28.9	0.003	0.150	1.668	0.083	0.200	0.417	-
3	18	47	b	128.6	104.7	0.004	0.200	2.181	0.109	0.210	0.519	-
3	25	8	a	36.3	31.5	0.003	0.150	1.668	0.083	0.220	0.379	130
3	25	8	b	141.2	118.7	0.002	0.100	1.143	0.057	0.220	0.260	-
3	25	14	a	32.3	28.3	0.006	0.300	3.182	0.159	0.280	0.568	-
3	25	14	b	128	112.2	0.001	0.050	0.599	0.030	0.210	0.143	-
3	25	27	a	32.4	29.2	0.002	0.100	1.143	0.057	0.250	0.229	-
3	25	27	b	131.3	116.3	0.003	0.150	1.668	0.083	0.230	0.363	-
3	33	10	a	35.9	31.6	0.003	0.150	1.668	0.083	0.280	0.298	1200
3	33	10	b	129	109	0.006	0.300	3.182	0.159	0.290	0.549	-
3	33	25	a	43	35.2	0.003	0.150	1.668	0.083	0.210	0.397	-
3	33	25	b	137.2	114.9	0.006	0.300	3.182	0.159	0.240	0.663	-
3	33	48	a	46.7	37.8	0.008	0.400	4.161	0.208	0.220	0.946	-
3	33	48	b	137.4	112.1	0.004	0.200	2.181	0.109	0.200	0.545	-
3	37	12	a	31.5	25.7	0.005	0.250	2.685	0.134	0.290	0.463	553.33
3	37	12	b	135.7	111.5	0.002	0.100	1.143	0.057	0.210	0.272	-
3	37	39	a	29.8	24.5	0.002	0.100	1.143	0.057	0.210	0.272	-
3	37	39	b	132.9	110.2	0.002	0.100	1.143	0.057	0.210	0.272	-

3	37	13	a	19.9	16.1	0.008	0.400	4.161	0.208	0.220	0.946	-
3	37	13	b	129.1	106.5	0.014	0.700	7.008	0.350	0.240	1.460	-
4	3	72	a	36.79	34.58	0.001	0.050	0.599	0.030	0.250	0.120	660
4	3	72	b	142.88	98.59	0.005	0.250	2.685	0.134	0.270	0.497	-
4	3	36	a	30.35	24.58	0.006	0.300	3.182	0.159	0.260	0.612	-
4	3	36	b	129.66	97.25	0.003	0.150	1.668	0.083	0.200	0.417	-
4	3	37	a	29.93	29.33	0.002	0.100	1.143	0.057	0.210	0.272	-
4	3	37	b	131.40	93.29	0.001	0.050	0.599	0.030	0.200	0.150	-
4	11	66	a	32.00	21.44	0.011	0.550	5.598	0.280	0.240	1.166	140
4	11	66	b	118.03	83.80	0.004	0.200	2.181	0.109	0.200	0.545	-
4	11	52	a	27.51	23.93	0.002	0.100	1.143	0.057	0.230	0.249	-
4	11	52	b	120.69	101.38	0.007	0.350	3.674	0.184	0.210	0.875	-
4	11	41	a	36.53	33.24	0.001	0.050	0.599	0.030	0.210	0.143	-
4	11	41	b	122.53	109.05	0.003	0.150	1.668	0.083	0.210	0.397	-
4	13	40	a	27.13	24.42	0.003	0.150	1.668	0.083	0.220	0.379	100
4	13	40	b	129.85	123.36	0.006	0.300	3.182	0.159	0.240	0.663	-
4	13	43	a	28.42	19.04	0.007	0.350	3.674	0.184	0.210	0.875	-
4	13	43	b	139.58	94.91	0.001	0.050	0.599	0.030	0.190	0.158	-
4	13	66	a	40.82	39.19	0.001	0.050	0.599	0.030	0.220	0.136	-
4	13	66	b	136.37	103.64	0.007	0.350	3.674	0.184	0.230	0.799	-
4	25	63	a	39.32	24.38	0.001	0.050	0.599	0.030	0.190	0.158	560
4	25	63	b	118.37	112.45	0.003	0.150	1.668	0.083	0.260	0.321	-
4	25	70	a	31.94	24.59	0.004	0.200	2.181	0.109	0.240	0.454	-
4	25	70	b	148.46	132.13	0.005	0.250	2.685	0.134	0.280	0.479	-
4	25	71	a	28.07	21.33	0.001	0.050	0.599	0.030	0.210	0.143	-
4	25	71	b	132.94	113.00	0.001	0.050	0.599	0.030	0.260	0.115	-
4	33	72	a	34.89	23.03	0.000	0.000	0.000	0.000	0.230	0.000	110
4	33	72	b	149.10	143.14	0.002	0.100	1.143	0.057	0.210	0.272	-
4	33	69	a	34.34	26.10	0.003	0.150	1.668	0.083	0.230	0.363	-

4	33	69	b	139.01	136.23	0.005	0.250	2.685	0.134	0.260	0.516	-
4	33	68	a	33.93	24.43	0.008	0.400	4.161	0.208	0.220	0.946	-
4	33	68	b	135.14	122.98	0.002	0.100	1.143	0.057	0.270	0.212	-
4	35	17	a	30.79	23.09	0.004	0.200	2.181	0.109	0.230	0.474	800
4	35	17	b	142.34	135.22	0.009	0.450	4.643	0.232	0.200	1.161	-
4	35	19	a	32.75	22.93	0.002	0.100	1.143	0.057	0.240	0.238	-
4	35	19	b	124.82	121.08	0.005	0.250	2.685	0.134	0.250	0.537	-
4	35	26	a	34.48	21.03	0.006	0.300	3.182	0.159	0.200	0.796	-
4	35	26	b	119.78	112.59	0.002	0.100	1.143	0.057	0.200	0.286	-
4	39	31	a	36.85	27.27	0.003	0.150	1.668	0.083	0.210	0.397	130
4	39	31	b	137.50	122.38	0.002	0.100	1.143	0.057	0.200	0.286	-
4	39	35	a	33.25	30.59	0.006	0.300	3.182	0.159	0.220	0.723	-
4	39	35	b	130.02	83.21	0.002	0.100	1.143	0.057	0.210	0.272	-
4	39	50	a	36.34	27.98	0.002	0.100	1.143	0.057	0.220	0.260	-
4	39	50	b	127.35	113.34	0.001	0.050	0.599	0.030	0.230	0.130	-
4	43	12	a	27.11	26.84	0.003	0.150	1.668	0.083	0.220	0.379	590
4	43	12	b	125.48	106.66	0.001	0.050	0.599	0.030	0.200	0.150	-
4	43	53	a	39.54	33.21	0.002	0.100	1.143	0.057	0.200	0.286	-
4	43	53	b	141.42	110.31	0.005	0.250	2.685	0.134	0.210	0.639	-
4	43	18	a	32.15	23.79	0.002	0.100	1.143	0.057	0.210	0.272	-
4	43	18	b	123.50	108.68	0.001	0.050	0.599	0.030	0.200	0.150	-
4	51	22	a	37.73	25.28	0.002	0.100	1.143	0.057	0.200	0.286	460
4	51	22	b	126.83	93.85	0.008	0.400	4.161	0.208	0.200	1.040	-
4	51	21	a	31.50	23.00	0.001	0.050	0.599	0.030	0.190	0.158	-
4	51	21	b	124.59	117.11	0.000	0.000	0.000	0.000	0.280	0.000	-
4	51	20	a	31.80	28.62	0.009	0.450	4.643	0.232	0.220	1.055	-
4	51	20	b	135.78	120.84	0.001	0.050	0.599	0.030	0.220	0.136	-
5	13	2	a	31.2	21.6	0.009	0.450	4.643	0.232	0.20	1.161	350
5	13	2	b	140.3	112.4	0.007	0.350	3.674	0.184	0.20	0.918	-

5	13	31	a	32.6	24.4	0.002	0.100	1.143	0.057	0.21	0.272	-
5	13	31	b	134.7	104.5	0.011	0.550	5.598	0.280	0.20	1.399	-
5	13	41	a	38.9	31.3	0.007	0.350	3.674	0.184	0.21	0.875	-
5	13	41	b	118.6	91.2	0.006	0.300	3.182	0.159	0.20	0.796	-
5	18	70	a	36.5	29.1	0.001	0.050	0.599	0.030	0.20	0.150	1300
5	18	70	b	139.5	116.3	0.002	0.100	1.143	0.057	0.23	0.249	-
5	18	71	a	41	34.9	0.003	0.150	1.668	0.083	0.26	0.321	-
5	18	71	b	147.2	126.5	0.001	0.050	0.599	0.030	0.20	0.150	-
5	18	72	a	31.1	24.6	0.006	0.300	3.182	0.159	0.21	0.758	-
5	18	72	b	124.5	95.2	0.006	0.300	3.182	0.159	0.24	0.663	-
5	22	1	a	32.8	26.5	0.003	0.150	1.668	0.083	0.29	0.288	120
5	22	1	b	131.8	105	0.005	0.250	2.685	0.134	0.20	0.671	-
5	22	17	a	39.8	32.5	0.008	0.400	4.161	0.208	0.18	1.156	-
5	22	17	b	137	117.5	0.002	0.100	1.143	0.057	0.20	0.286	-
5	22	26	a	31.8	25.7	0.002	0.100	1.143	0.057	0.21	0.272	-
5	22	26	b	139.2	113.6	0.003	0.150	1.668	0.083	0.21	0.397	-
5	25	6	a	34.9	29.9	0.001	0.050	0.599	0.030	0.23	0.130	630
5	25	6	b	135.2	110.1	0.005	0.250	2.685	0.134	0.22	0.610	-
5	25	37	a	36.8	30.9	0.005	0.250	2.685	0.134	0.22	0.610	-
5	25	37	b	129.7	109.1	0.005	0.250	2.685	0.134	0.22	0.610	-
5	25	43	a	28.6	25.1	0.000	0.000	0.000	0.000	0.21	0.000	-
5	25	43	b	118.9	102.5	0.007	0.350	3.674	0.184	0.26	0.707	-
5	32	67	a	25.6	21.6	0.002	0.100	1.143	0.057	0.20	0.286	340
5	32	67	b	148.5	120.9	0.002	0.100	1.143	0.057	0.24	0.238	-
5	32	68	a	30.1	25.3	0.002	0.100	1.143	0.057	0.23	0.249	-
5	32	68	b	132.6	109.4	0.002	0.100	1.143	0.057	0.20	0.286	-
5	32	69	a	32.4	27.3	0.002	0.100	1.143	0.057	0.21	0.272	-
5	32	69	b	136.2	112.5	0.004	0.200	2.181	0.109	0.21	0.519	-
5	33	64	a	39.8	32.8	0.002	0.100	1.143	0.057	0.22	0.260	520
5	33	64	b	135.7	111.1	0.003	0.150	1.668	0.083	0.21	0.397	-

5	33	65	a	38	31.7	0.002	0.100	1.143	0.057	0.20	0.286	-
5	33	65	b	134.8	110	0.009	0.450	4.643	0.232	0.20	1.161	-
5	33	66	a	37	30.5	0.006	0.300	3.182	0.159	0.20	0.796	-
5	33	66	b	140.1	119	0.003	0.150	1.668	0.083	0.20	0.417	-
5	34	34	a	35.7	29.2	0.002	0.100	1.143	0.057	0.23	0.249	1300
5	34	34	b	134.4	117.2	0.003	0.150	1.668	0.083	0.29	0.288	-
5	34	42	a	37.4	32.6	0.008	0.400	4.161	0.208	0.20	1.040	-
5	34	42	b	137.6	113.9	0.001	0.050	0.599	0.030	0.20	0.150	-
5	34	50	a	25.5	22.7	0.003	0.150	1.668	0.083	0.24	0.348	-
5	34	50	b	118.7	101.4	0.007	0.350	3.674	0.184	0.21	0.875	-
5	53	60	a	31.3	24	0.006	0.300	3.182	0.159	0.21	0.758	780
5	53	60	b	114.3	89.1	0.002	0.100	1.143	0.057	0.20	0.286	-
5	53	61	a	32.5	26.5	0.002	0.100	1.143	0.057	0.20	0.286	-
5	53	61	b	135.6	109	0.002	0.100	1.143	0.057	0.20	0.286	-
5	53	62	a	36.8	29.8	0.004	0.200	2.181	0.109	0.23	0.474	-
5	53	62	b	119.1	90.6	0.003	0.150	1.668	0.083	0.20	0.417	-
5	55	45	a	35.4	27.9	0.003	0.150	1.668	0.083	0.20	0.417	880
5	55	45	b	127	96.9	0.002	0.100	1.143	0.057	0.21	0.272	-
5	55	51	a	32.6	26.2	0.004	0.200	2.181	0.109	0.23	0.474	-
5	55	51	b	140.6	115.3	0.002	0.100	1.143	0.057	0.21	0.272	-
5	55	63	a	31.6	24.6	0.006	0.300	3.182	0.159	0.25	0.636	-
5	55	63	b	136.4	106.3	0.002	0.100	1.143	0.057	0.20	0.286	-
6	1	18	a	39.7	29.4	0.004	0.200	2.181	0.109	0.23	0.474	240
6	1	18	b	204.1	147.0	0.002	0.100	1.143	0.057	0.20	0.286	-
6	7	19	a	32.8	25.2	0.002	0.100	1.143	0.057	0.22	0.260	90
6	7	19	b	162.7	136.7	0.003	0.150	1.668	0.083	0.20	0.417	-
6	16	3	a	20.8	16.6	0.001	0.050	0.599	0.030	0.21	0.143	855
6	16	3	b	104.1	80.2	0.004	0.200	2.181	0.109	0.24	0.454	-
6	23	12	a	38.0	29.3	0.001	0.050	0.599	0.030	0.23	0.130	630

6	23	12	b	182.5	155.2	0.007	0.350	3.674	0.184	0.24	0.765	-
6	34	6	a	31.7	22.2	0.008	0.400	4.161	0.208	0.20	1.040	440
6	34	6	b	152.0	135.3	0.006	0.300	3.182	0.159	0.20	0.796	-
6	36	5	a	36.7	30.1	0.001	0.050	0.599	0.030	0.19	0.158	480
6	36	5	b	190.8	145.0	0.003	0.150	1.668	0.083	0.24	0.348	-
6	38	65	a	29.2	21.3	0.005	0.250	2.685	0.134	0.19	0.707	800
6	38	65	b	143.1	127.4	0.003	0.150	1.668	0.083	0.22	0.379	-
6	50	41	a	25.2	21.9	0.002	0.100	1.143	0.057	0.23	0.249	1200
6	50	41	b	117.9	93.1	0.010	0.500	5.122	0.256	0.20	1.281	-
6	52	22	a	33.8	24.3	0.002	0.100	1.143	0.057	0.23	0.249	400
6	52	22	b	168.4	136.4	0.002	0.100	1.143	0.057	0.24	0.238	-
7	1	28	a	39.9	34.3	0.008	0.400	4.161	0.208	0.22	0.946	270
7	1	28	b	195.1	175.6	0.002	0.100	1.143	0.057	0.20	0.286	-
7	7	29	a	42.5	38.3	0.001	0.050	0.599	0.030	0.20	0.150	110
7	7	29	b	215.4	152.9	0.004	0.200	2.181	0.109	0.20	0.545	-
7	16	53	a	43.3	34.2	0.000	0.000	0.000	0.000	0.21	0.000	300
7	16	53	b	224.4	190.8	0.002	0.100	1.143	0.057	0.23	0.249	-
7	23	51	a	28.5	25.0	0.010	0.500	5.122	0.256	0.22	1.164	510
7	23	51	b	133.8	99.0	0.002	0.100	1.143	0.057	0.24	0.238	-
7	34	61	a	44.7	33.5	0.003	0.150	1.668	0.083	0.20	0.417	600
7	34	61	b	231.8	173.8	0.007	0.350	3.674	0.184	0.20	0.918	-
7	36	57	a	42.3	34.3	0.008	0.400	4.161	0.208	0.19	1.095	430
7	36	57	b	202.7	166.2	0.001	0.050	0.599	0.030	0.24	0.125	-
7	38	71	a	39.8	35.0	0.004	0.200	2.181	0.109	0.20	0.545	800
7	38	71	b	197.4	144.1	0.009	0.450	4.643	0.232	0.22	1.055	-
7	50	47	a	33.2	23.9	0.008	0.400	4.161	0.208	0.23	0.904	700
7	50	47	b	156.0	112.3	0.001	0.050	0.599	0.030	0.20	0.150	-
7	52	46	a	29.5	23.9	0.001	0.050	0.599	0.030	0.23	0.130	220
7	52	46	b	139.1	114.0	0.004	0.200	2.181	0.109	0.21	0.519	-

8	1	7	a	46.3	37.1	0.001	0.050	0.599	0.030	0.23	0.130	110
8	1	7	b	227.3	175.0	0.007	0.350	3.674	0.184	0.20	0.918	-
8	7	1	a	33.3	25.0	0.015	0.750	7.474	0.374	0.22	1.699	290
8	7	1	b	169.2	130.3	0.006	0.300	3.182	0.159	0.20	0.796	-
8	16	17	a	23.1	20.1	0.005	0.250	2.685	0.134	0.21	0.639	460
8	16	17	b	123.5	101.3	0.002	0.100	1.143	0.057	0.24	0.238	-
8	23	21	a	39.8	35.4	0.004	0.200	2.181	0.109	0.23	0.474	610
8	23	21	b	190.3	140.9	0.010	0.500	5.122	0.256	0.24	1.067	-
8	34	4	a	46.2	34.7	0.008	0.400	4.161	0.208	0.20	1.040	400
8	34	4	b	239.6	210.8	0.002	0.100	1.143	0.057	0.20	0.286	-
8	36	54	a	32.8	24.0	0.003	0.150	1.668	0.083	0.19	0.439	750
8	36	54	b	155.2	133.5	0.007	0.350	3.674	0.184	0.24	0.765	-
8	38	61	a	42.5	31.0	0.004	0.200	2.181	0.109	0.19	0.574	680
8	38	61	b	211.0	173.0	0.001	0.050	0.599	0.030	0.22	0.136	-
8	50	15	a	37.5	31.1	0.001	0.050	0.599	0.030	0.23	0.130	510
8	50	15	b	177.6	136.7	0.005	0.250	2.685	0.134	0.20	0.671	-
8	52	13	a	26.4	22.7	0.004	0.200	2.181	0.109	0.23	0.474	290
8	52	13	b	123.4	102.4	0.001	0.050	0.599	0.030	0.24	0.125	-

Appendix C

Description of Individual Storm Event Data

Introduction

This appendix describes the data for each of the eight individual storm events. Precipitation values given are the arithmetic average of the three rain gauges located within the watershed (Figure 4.1). Total runoff values are those measured at the Shelburne Road gauging station. The runoff values have been increased by 30% to account for the lower 30% of the watershed which is located below the gauging station. The mean scour and deposition per pool are calculated using the eight measured values within each pool for a given storm event. The overall mean scour and deposition per storm event is calculated using all scour and deposition measurements from all pools measured during that storm event. Because of the low number of samples of TP and FC per pool, statistical comparisons of TP within individual storm events was limited to several storms in which multiple cores were taken per pool. No statistical comparisons of FC concentrations could be made within individual storm events.

Description of Storm One Data.

Hydrology Storm one began on June 29, 1994 yielding a total rainfall amount of 0.96 inches in four distinct periods of high intensity. The total runoff volume was calculated by a simulation model (Cassell et al. 1994) to be 325,800 ft^3 and total stream power expended was 1,739,631 joules. The precipitation hyetograph and computer generated stream flow hydrographs can be seen in Figure C.1.

Sediment Transport Mean scour depths for the randomly selected pools studied in storm one ranged from 0.5 cm (se=0.3, n=8) in pool one to 7.5 cm (se=1.1, n=8) in pool thirty six (Table C.1, Figure C.2). The overall mean scour depth was 3.20

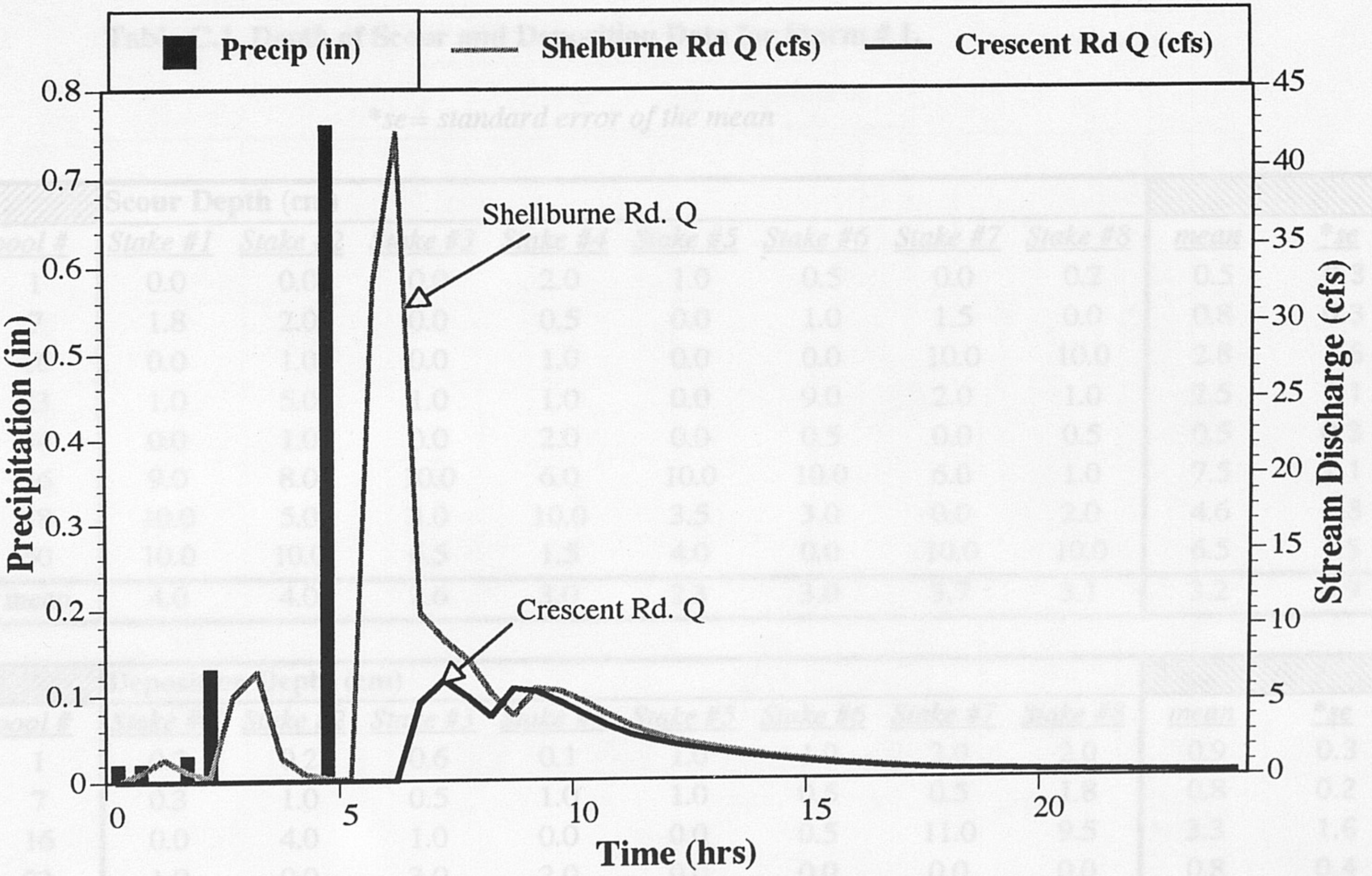

Figure C.1 Storm #1 Hydrology. Hyetograph(bars) and hydrographs (lines) for storm in Englesby Brook Watershed on June 29, 1994.

Table C.1 Depth of Scour and Deposition Data for Storm # 1.

**se= standard error of the mean*

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
1	0.0	0.0	0.0	2.0	1.0	0.5	0.0	0.2	0.5	0.3
7	1.8	2.0	0.0	0.5	0.0	1.0	1.5	0.0	0.8	0.3
16	0.0	1.0	0.0	1.0	0.0	0.0	10.0	10.0	2.8	1.6
23	1.0	5.0	1.0	1.0	0.0	9.0	2.0	1.0	2.5	1.1
34	0.0	1.0	0.0	2.0	0.0	0.5	0.0	0.5	0.5	0.3
36	9.0	8.0	10.0	6.0	10.0	10.0	6.0	1.0	7.5	1.1
38	10.0	5.0	3.0	10.0	3.5	3.0	0.0	2.0	4.6	1.3
50	10.0	10.0	6.5	1.5	4.0	0.0	10.0	10.0	6.5	1.5
mean	4.0	4.0	2.6	3.0	2.3	3.0	3.7	3.1	3.2	0.9

	Deposition Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
1	0.2	0.2	0.6	0.1	1.0	1.0	2.0	2.0	0.9	0.3
7	0.3	1.0	0.5	1.0	1.0	0.5	0.5	1.8	0.8	0.2
16	0.0	4.0	1.0	0.0	0.0	0.5	11.0	9.5	3.3	1.6
23	1.0	0.0	3.0	2.0	0.0	0.0	0.0	0.0	0.8	0.4
34	2.5	1.5	5.0	0.0	2.0	2.0	0.0	0.5	1.7	0.6
36	4.0	15.5	0.0	0.0	13.0	0.0	0.0	9.0	5.2	2.3
38	8.0	10.0	5.0	5.0	3.5	1.0	3.0	3.0	4.8	1.0
50	10.0	10.0	0.0	0.0	6.0	0.0	8.0	4.0	4.8	1.6

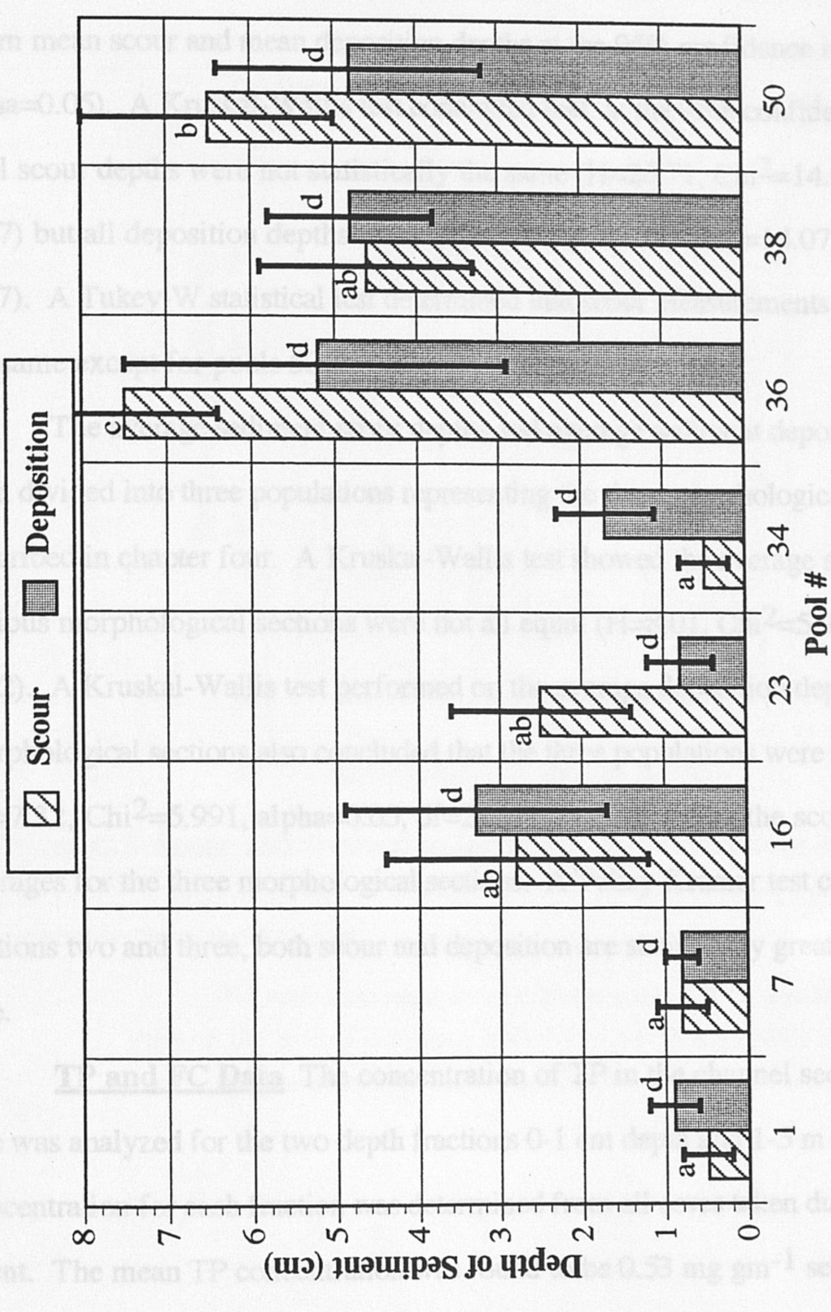

Figure C.2 Mean Scour and Deposition Values for Storm #1. Mean scour and depsition are not statistically different at the 95% confidence interval (p=.2495).

**Letters above bars represent statistical equality (*

Error bars represent standard error of the mean □

cm (se=0.48, n=64). The mean deposition depths ranged from 0.8 cm (se=0.2, n=8) in pool seven to 5.2 cm (se=2.3, n=8) in pool thirty six (Table C.1, Figure C.2). The overall mean deposition depth was 2.77 cm (se=0.47, n=64).

A Wilcoxon signed rank test indicated that there is no difference between the storm mean scour and mean deposition depths at the 95% confidence interval (p=0.2459, alpha=0.05). A Kruskal-Wallis test concluded that, at the 95% confidence interval, mean pool scour depths were not statistically the same (H=26.71, Chi^2=14.07, alpha=.05, df=7) but all deposition depths were the same (H=12.89, Chi^2=14.07, alpha=.005, df=7). A Tukey-W statistical test determined that scour measurements in all pools were the same except for pools 50 and 36 (Figure C.2).

The average sediment scour depths and average sediment deposition depths were each divided into three populations representing the three morphological stream sections described in chapter four. A Kruskal-Wallis test showed the average scour depths for the various morphological sections were not all equal (H=8.01, Chi^2=5.991, alpha=0.05, df=2). A Kruskal-Wallis test performed on the average deposition depths for these morphological sections also concluded that the three populations were not all equal (H=7.32, Chi^2=5.991, alpha=0.05, df=2). Figure C.3 shows the scour and deposition averages for the three morphological sections. A Tukey-Kramer test concluded that in sections two and three, both scour and deposition are statistically greater than in section one.

TP and FC Data The concentration of TP in the channel sediments for storm one was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.53 mg gm^{-1} sediment (se=0.11, n=9) for the 0-1 cm depth fraction and 0.46 mg gm^{-1} sediment (se=0.11, n=9) for the 1-5 cm depth fraction, with an overall weighted mean of 0.47 mg gm^{-1}(se=0.11, n=9).

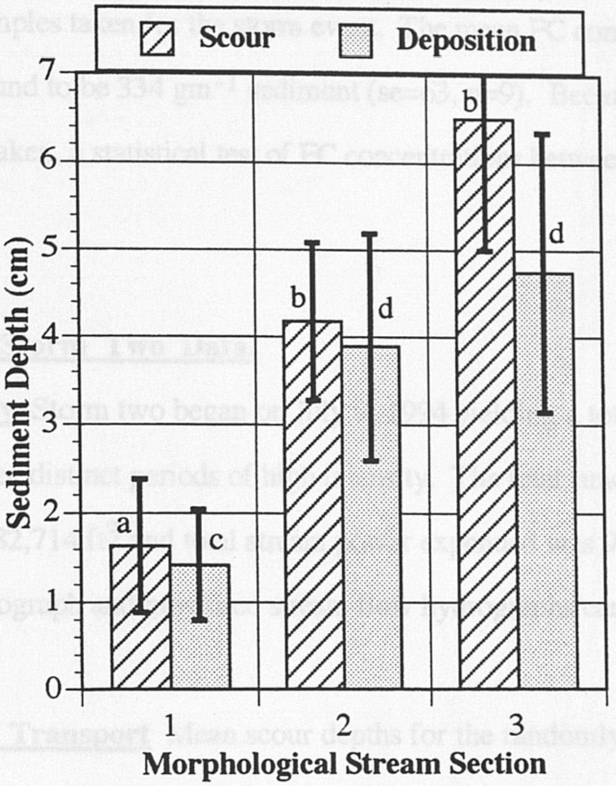

Figure C.3 Scour and Deposition for Storm #1, Divided into Morphological Stream Sections. Scour and deposition in sections 2 and 3 are statistically greater than section 1. Ä

** Letters above bars represent statistical equality*
(thos bars having the same letters are not statistically different)
Error bars represent standard error of the mean

Because of the low number of cores taken, statistical tests of TP concentrations between pools and fractions were not possible.

The concentration of FC in the channel sediments for storm one was determined from the scoop sample taken in each pool. The mean FC concentration was determined from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 334 gm^{-1} sediment (se=63, n=9). Because of the low number of cores taken, a statistical test of FC concentrations between pools was not possible.

Description of Storm Two Data.

Hydrology Storm two began on July 9, 1994 yielding a total rainfall amount of 0.55 inches in three distinct periods of high intensity. The total runoff volume was measured to be 182,714 ft^3 and total stream power expended was 975,618 joules. The precipitation hyetograph and measured stream flow hydrographs can be seen in Figure C.4.

Sediment Transport Mean scour depths for the randomly selected pools studied in storm two ranged from 0.5 cm (se=0.3, n=8) in pool 4 to 3.9 cm (se=1.1, n=8) in pool 40 (Table C.2, Figure C.5). The overall mean scour depth was 2.25 cm (se=0.36, n=61). The mean deposition depths ranged from 0.8 cm (se=0.6, n=8) in pool 54 to 4.1 cm (se=1.2, n=7) in pool 40 (Table C.2, Figure C.5). The overall mean deposition depth was 2.27 cm (se=0.36, n=60). Three scour and four deposition measurements were discarded due to entrapment of debris or washout of stakes.

A Wilcoxon signed rank test indicated that there is no difference between scour and deposition at the 95% confidence interval (p=0.3895, alpha=0.05). Kruskal-Wallis tests concluded that at the 95% confidence interval, all average pool scour depths were not statistically the same (H=14.38, Chi^2=14.07, alpha=0.05, df=7) nor were all average

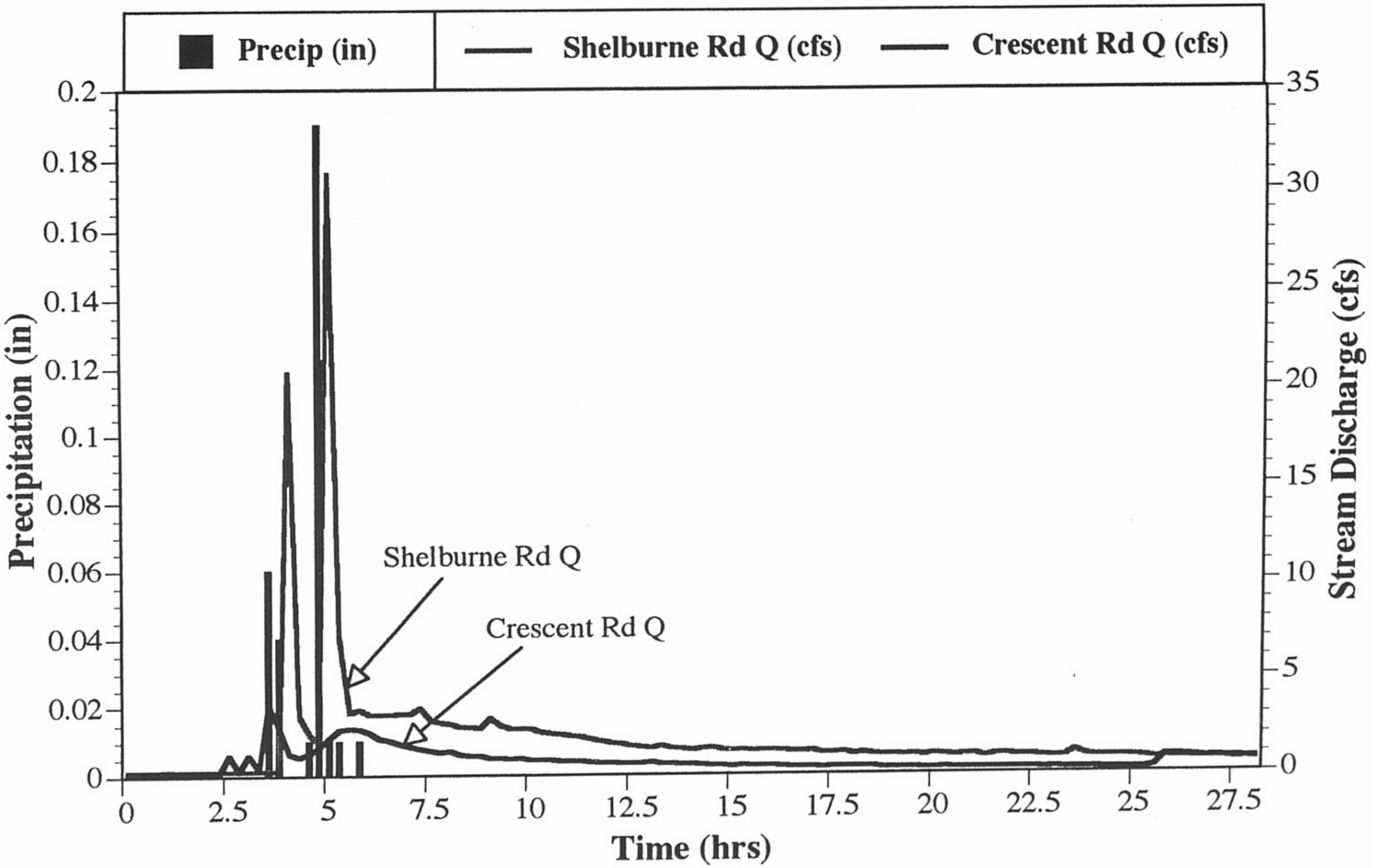

Figure C.4 Storm #2 Hydrology. Hyetograph (bars) and hydrographs (lines) for storm in Englesby Brook Watershed on July 9, 1994. □

Table C.2 Depth of Scour and Deposition Data for Storm #2.

**se = standard error of the mean*

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
4	0.0	0.0	2.0	0.0	1.0	0.0	1.0	0.0	0.5	0.3
12	0.0	4.0	6.0	4.5	0.0	0.0	0.0	0.5	1.9	0.9
25	4.0	na	4.0	1.0	na	na	1.0	1.0	2.2	0.7
33	0.0	1.0	3.5	1.0	0.0	12.0	10.0	0.0	3.4	1.7
37	5.0	10.0	0.0	1.0	1.0	5.0	5.0	1.5	3.6	1.2
40	5.5	5.5	1.0	4.0	2.5	1.0	2.0	10.0	3.9	1.1
46	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0	0.8	0.2
54	0.0	2.0	0.5	1.0	0.0	3.0	4.0	3.0	1.7	0.5
mean	1.9	3.4	2.1	1.7	0.6	3.1	3.0	2.1	2.2	0.8

	Deposition Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
4	0.0	0.0	2.0	0.0	4.0	3.0	0.0	0.0	1.1	0.6
12	5.5	3.0	0.0	3.5	15.0	2.0	0.0	3.0	4.0	1.7
25	0.0	na	5.0	2.0	na	na	0.0	0.0	1.4	1.0
33	2.0	0.0	5.5	5.5	0.0	6.0	5.0	0.0	3.0	1.0
37	0.0	0.0	0.0	0.0	4.0	3.0	6.0	3.5	2.1	0.8
40	8.5	6.5	0.0	6.0	2.5	4.0	1.0	na	4.1	1.2
46	3.0	2.0	0.0	2.0	0.0	3.0	2.5	0.0	1.6	0.5
54	0.0	0.0	4.5	0.0	0.0	0.0	0.0	2.0	0.8	0.6
mean	2.4	1.6	2.1	2.4	3.6	3.0	1.8	1.2	2.3	0.9

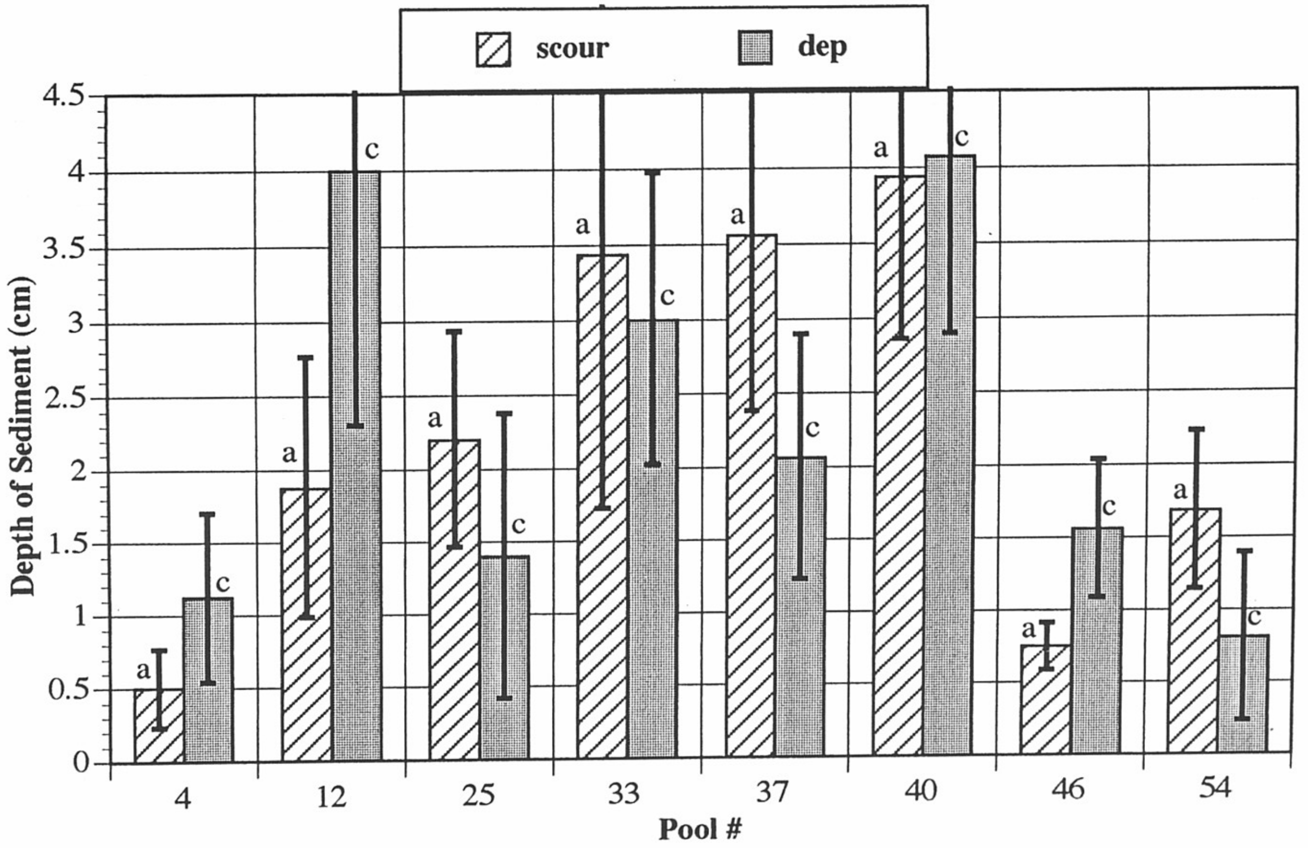

Figure C.5 Mean Scour and Deposition Values for Storm #2. Mean scour and deposition are not statistically different at the 95% confidence interval (p=..3895).

*Letters above bars represent statistical equality (

those bars having the same letters are not statistica

rror bars represent standard error of the mean deposition depths the same(H=15.08, Chi^{2}=14.07, alpha=0.05, df=7). However, a Tukey-W statistical test performed on the same populations determined that there was no difference in the populations with respect to scour or deposition. This difference in conclusions is due to the fact that the Tukey-W test is more conservative in its conclusions than the Kruskal-Wallis test. The fact that the H-values calculated for the Kruskal-Wallis tests were very close to the critical Chi^{2}-values, makes the use of two different tests subject to discrepancies.

The average sediment scour depths and average sediment deposition depths were each divided into three populations representing the three morphological stream sections (Figure C.6) A Kruskal-Wallis showed the average scour depths for the various morphological sections were not all equal (H=9.22, Chi^{2}=5.991, alpha=0.05, df=2). A Kruskal-Wallis test performed on the average deposition depth for these morphological sections also concluded that the three populations were not all equal (H=8.65, Chi^{2}=5.991, alpha=.05, df=2). Figure C.6 shows the scour and deposition averages for the three morphological sections. A Tukey-Kramer test between each section shows that in section two, both scour and deposition are statistically greater than in sections one and three.

<u>TP and FC Data</u> The concentration of TP in the channel sediments for storm two was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.46 mg gm^{-1} sediment (se=0.08, n=24) for the 0-1 cm depth fraction and 0.51 mg gm^{-1} sediment (se=0.06, n=24) for the 1-5 cm depth fraction, with an overall weighted mean of 0.50 mg gm^{-1}(se=0.07, n=24). A Kruskal-Wallis statistical test was performed on eight populations representing the eight pools sampled for this storm. Each pool population was comprised of three samples taken from that pool. The test concluded that at the 95% confidence interval,

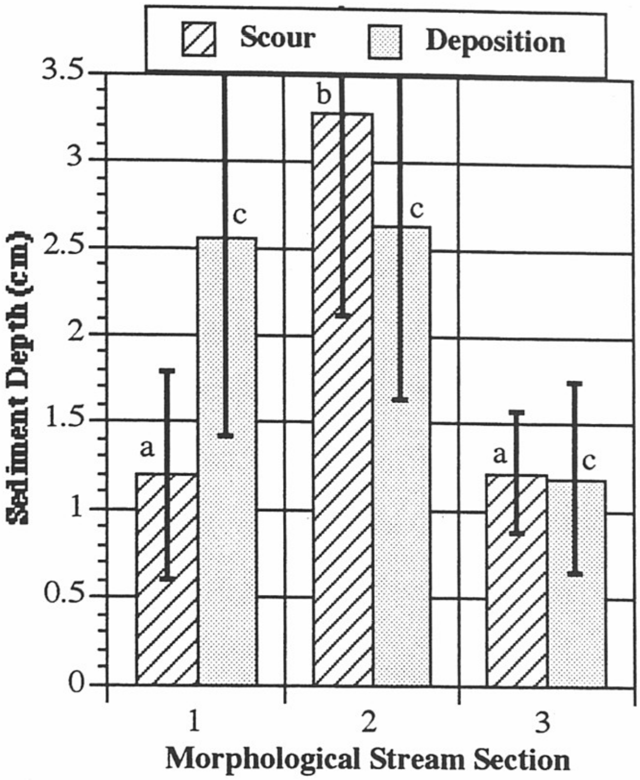

Figure C.6 Scour and Deposition for Storm #2, Divided into Morphological Stream Sections. Scour in section 2 is statistically greater than sections 1 and 3. Deposition is equal in all sections.

** Letters above bars represent statistical equality*
(thos bars having the same letters are not statistically different)
Error bars represent standard error of the mean

there was no significant difference in the TP concentration between pools (H=13.64, Chi^2=14.07, alpha=0.05, df=7).

The concentration of FC in the channel sediments for storm two was determined from the scoop sample taken in each pool. The mean FC concentration was determined from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 444 gm^{-1} sediment (se=102, n=7). Because of the low number of cores taken, a statistical test of FC concentrations between pools was not possible.

Description of Storm Three Data.

Hydrology Storm three began on July 15, 1994 yielding a total rainfall amount of only 0.06 inches over a half hour period. The total runoff volume was measured to be 96,000 ft^3 and total stream power expended was 512,598 joules. Stream flow was measured only at the Crescent Road gauging station, high in the watershed, because the primary flow meter at the Shelburne Road gauging station failed during this event. The total runoff from the event was then calculated from a rating curve relating flow at the two gauging stations. The precipitation hyetograph and measured stream flow hydrographs can be seen in Figure C.7.

Sediment Transport Mean scour depths for the randomly selected pools studied in storm three ranged from 0.1 cm (se=0.1, n=8) in pool 10 to 1.8 cm (se=0.9, n=6) in pool 25 (Table C.3 Figure C.8). The overall mean scour depth was 0.79 cm (se=0.15, n=62). The mean deposition depths ranged from 0.0 cm (se=0.0, n=8) in pool 1 to 1.5 cm (se=0.7 n=8) in pool 18 (Table C.3, Figure C.8). The overall mean deposition depth was 0.55 cm (se=0.17, n=62). Two scour and deposition measurements were discarded due to entrapment of debris or washout of stakes.

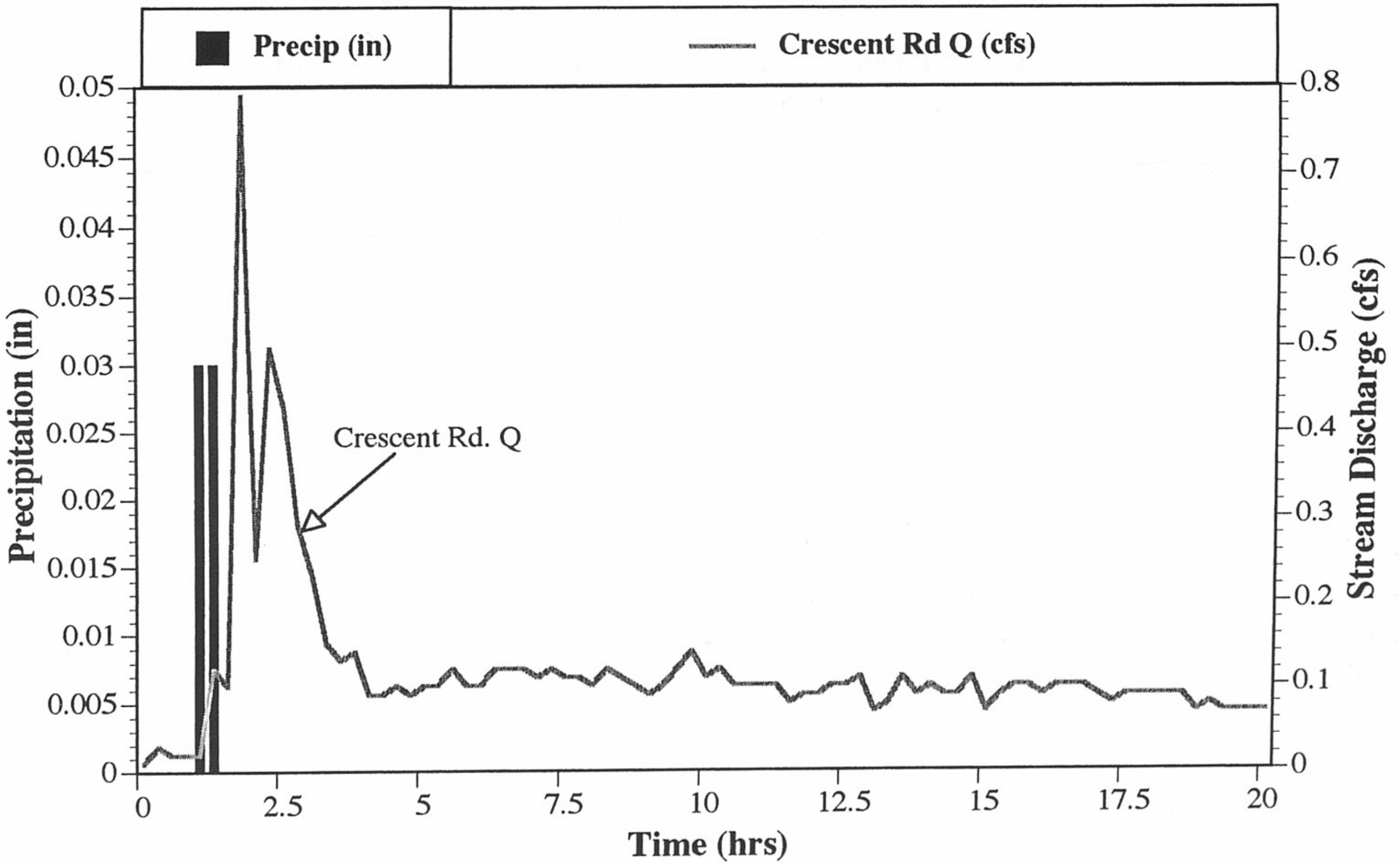

Figure C.7 Storm #3 Hydrology. Hyetograph (bars) and hydrograph (line) for storm in Englesby Brook Watershed on July 15, 1994.

Table C.3 Depth of Scour and Deposition Data for Storm #3.

**se* = *standard error of the mean*

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
1	1.0	1.0	0.5	0.0	0.0	0.5	0.0	0.0	0.4	0.2
3	0.0	1.0	0.0	0.5	3.0	1.0	0.0	0.5	0.8	0.4
10	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
11	0.5	0.0	0.5	0.5	0.0	1.0	1.0	0.0	0.4	0.1
18	1.5	1.0	1.0	1.0	2.0	1.0	0.0	0.0	0.9	0.2
25	0.0	4.0	5.0	1.0	na	na	1.0	0.0	1.8	0.9
31	0.0	0.5	0.0	1.5	0.0	6.0	1.0	1.0	1.3	0.7
37	1.0	0.0	1.5	2.0	0.5	1.0	0.5	0.5	0.9	0.2
mean	0.5	0.9	1.2	0.8	0.8	1.5	0.4	0.3	0.8	0.4

	Deposition Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
18	4.5	0.0	3.0	0.0	1.0	0.0	3.5	0.0	1.5	0.7
25	0.0	1.5	6.0	0.0	na	na	0.0	0.0	1.3	1.0
31	0.5	0.0	0.0	0.0	0.0	5.0	4.0	0.0	1.2	0.7
37	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1

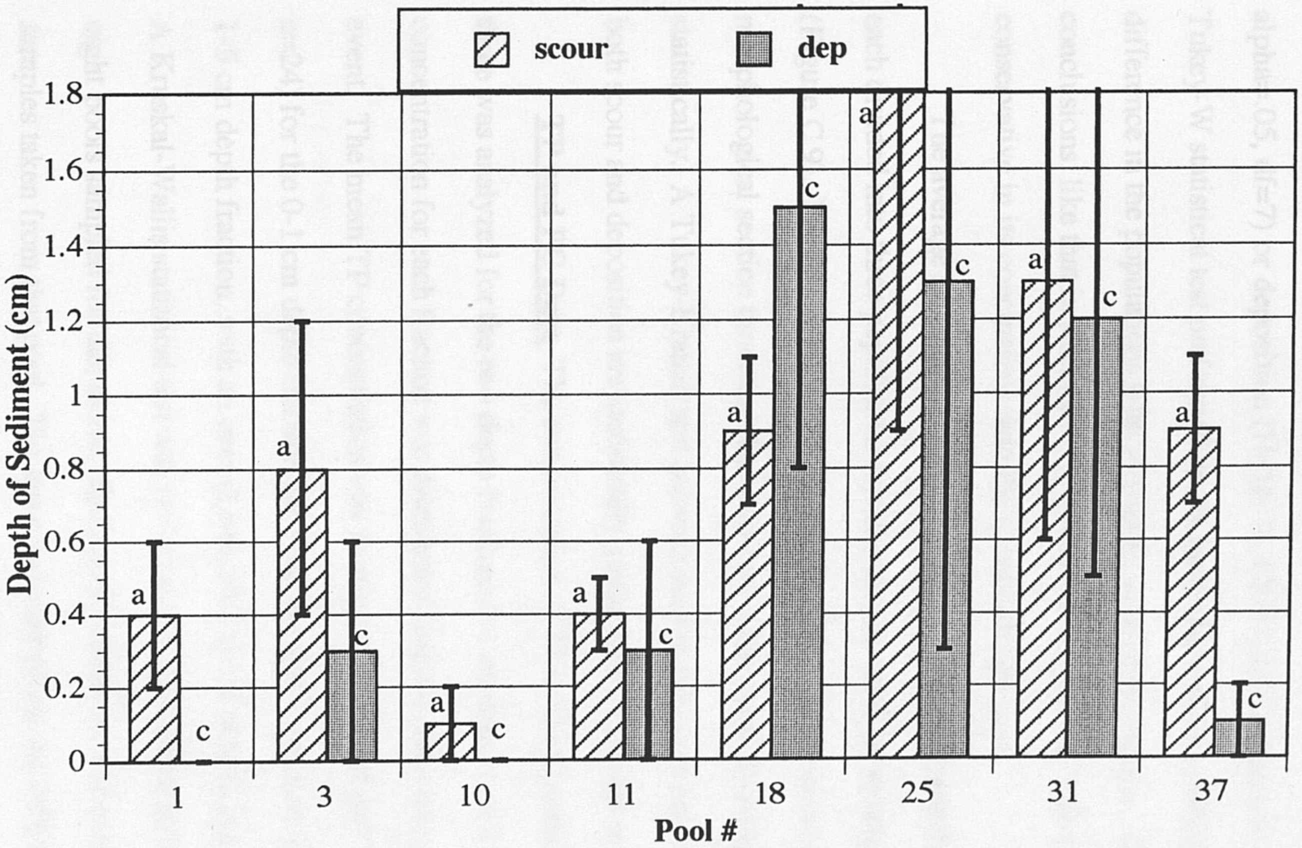

Figure C.8 **Mean Scour and Deposition Values for Storm #3. Mean scour and deposition are not statistically different at the 95% confidence interval (p=.0615).**

**Letters above bars represent statistical equality (*

rror bars represent standard error of the mean

A Wilcoxon signed rank test indicated that there is no difference between the storm mean scour and mean deposition depths at the 95% confidence interval (p=.0615, alpha=.05). Kruskal-Wallis tests concluded that at the 95% confidence interval, the populations were not all the same with respect to scour (H=15.31, Chi^2=14.07, alpha=.05, df=7) or deposition (H=16.06, Chi^2=14.07, alpha=.05, df=7). However, a Tukey-W statistical test performed on the same populations determined that there was no difference in the populations with respect to scour or deposition. This difference in conclusions, like that in storm two, is due to the fact that the Tukey-W test is more conservative in its conclusions than the Kruskal-Wallis test.

The average sediment scour depths and average sediment deposition depths were each divided into three populations representing the three morphological stream sections (Figure C.9). For this storm event, no randomly selected pools were located in morphological section three and thus only two populations could be compared statistically. A Tukey-Kramer test between each section concludes that in section two, both scour and deposition are statistically greater than in section one.

<u>TP and FC Data</u> The concentration of TP in the channel sediments for storm three was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.44 mg gm^{-1} sediment (se=0.04, n=24) for the 0-1 cm depth fraction and 0.42 mg gm^{-1} sediment (se=0.06, n=24) for the 1-5 cm depth fraction, with an overall weighted mean of 0.42 mg gm^{-1}(se=0.05, n=24). A Kruskal-Wallis statistical test was performed on eight populations representing the eight pools sampled for this storm. Each pool population was comprised of three samples taken from that pool. The test concluded that at the 95% confidence interval, there was no significant difference in the TP concentration between pools (H=5.17, Chi^2=14.07, alpha=.05, df=7).

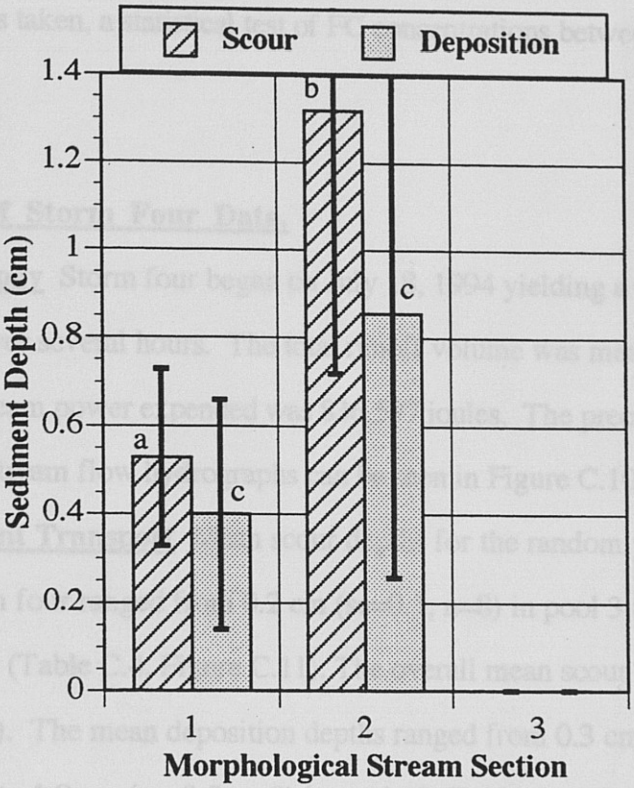

Figure C.9 Scour and Deposition for Storm #3, Divided into Morphological Stream Sections. Scour in section 2 is statistically greater than section 1 and deposition is equal. No random pools were selected from section 3.

** Letters above bars represent statistical equality*
(those bars having the same letters are not statistically different)
Error bars represent standard error of the mean

The concentration of FC in the channel sediments for storm three was determined from the scoop sample taken in each pool. The mean FC concentration was determined from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 378 gm^{-1} sediment (se=129, n=8). Because of the low number of cores taken, a statistical test of FC concentrations between pools was not possible.

Description of Storm Four Data.

Hydrology Storm four began on July 18, 1994 yielding a total rainfall amount of 0.5 inches over several hours. The total runoff volume was measured to be 156,974 ft^3 and total stream power expended was 836,597 joules. The precipitation hyetograph and measured stream flow hydrographs can be seen in Figure C.10.

Sediment Transport Mean scour depths for the randomly selected pools studied in storm four ranged from 0.2 cm (se=0.1, n=8) in pool 3 to 2.5 cm (se=0.7, n=8) in pool 43 (Table C.4, Figure C.11). The overall mean scour depth was 1.40 cm (se=0.20, n=72). The mean deposition depths ranged from 0.3 cm (se=0.2, n=8) in pools 3 and 11 to 1.9 cm (se=0.5, n=8) in pool 18 (Table C.4, Figure C.11). The overall mean deposition depth was 1.07 cm (se=0.19, n=72).

A Wilcoxon signed rank that scour is significantly greater than deposition at the 95% confidence interval (p=.0430, alpha=.05). Kruskal-Wallis tests concluded that at the 95% confidence interval, the populations were not all the same with respect to scour (H=17.97, Chi^2=14.07, alpha=.05, df=7) or deposition (H=18.52, Chi^2=14.07, alpha=.05, df=7). However, a Tukey-W statistical test performed on the same populations determined that there was no difference in the populations with respect to scour or deposition. This difference in conclusions, like that in storms two and three, is

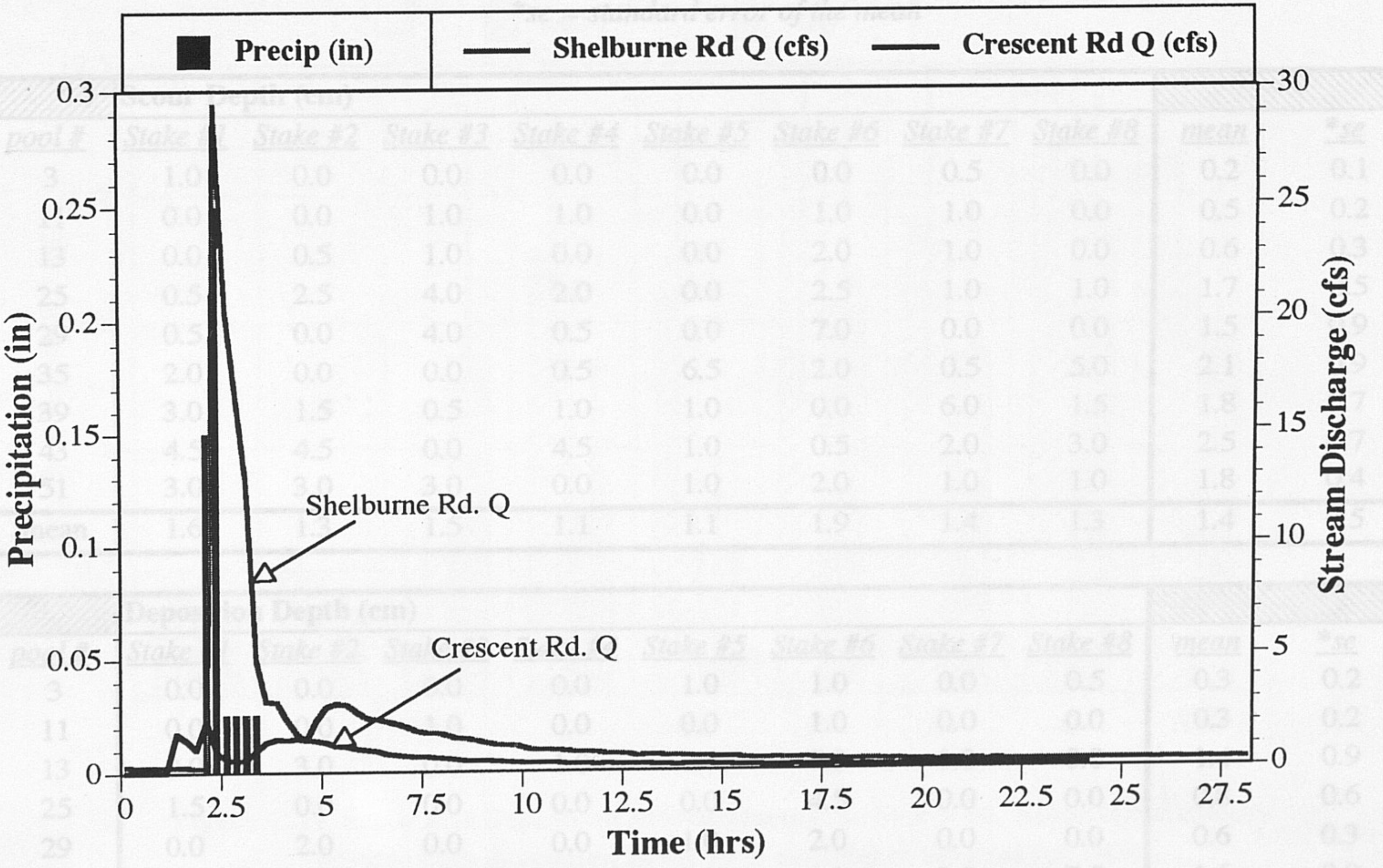

Figure C.10 Storm #4 Hydrology. Hyetograph (bars) and hydrographs (lines) for storm in Englesby Brook Watershed on July 18, 1994.

Table C.4 Depth of Scour and Deposition Data for Storm #4.

**se = standard error of the mean*

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
3	1.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.2	0.1
11	0.0	0.0	1.0	1.0	0.0	1.0	1.0	0.0	0.5	0.2
13	0.0	0.5	1.0	0.0	0.0	2.0	1.0	0.0	0.6	0.3
25	0.5	2.5	4.0	2.0	0.0	2.5	1.0	1.0	1.7	0.5
29	0.5	0.0	4.0	0.5	0.0	7.0	0.0	0.0	1.5	0.9
35	2.0	0.0	0.0	0.5	6.5	2.0	0.5	5.0	2.1	0.9
39	3.0	1.5	0.5	1.0	1.0	0.0	6.0	1.5	1.8	0.7
43	4.5	4.5	0.0	4.5	1.0	0.5	2.0	3.0	2.5	0.7
51	3.0	3.0	3.0	0.0	1.0	2.0	1.0	1.0	1.8	0.4
mean	1.6	1.3	1.5	1.1	1.1	1.9	1.4	1.3	1.4	0.5

	Deposition Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
3	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.5	0.3	0.2
11	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	0.3	0.2
13	0.0	3.0	0.0	1.0	0.0	7.0	0.0	0.0	1.4	0.9
25	1.5	0.0	0.0	0.0	0.0	4.5	0.0	0.0	0.8	0.6
29	0.0	2.0	0.0	0.0	1.0	2.0	0.0	0.0	0.6	0.3
35	0.0	3.0	0.5	0.0	0.5	1.0	0.0	7.5	1.6	0.9
39	1.0	1.5	0.0	1.0	3.0	1.0	3.0	0.5	1.4	0.4
43	2.5	2.5	1.0	4.5	1.5	0.0	1.0	2.0	1.9	0.5
51	1.0	3.5	1.0	0.5	0.0	0.0	4.0	2.0	1.5	0.5

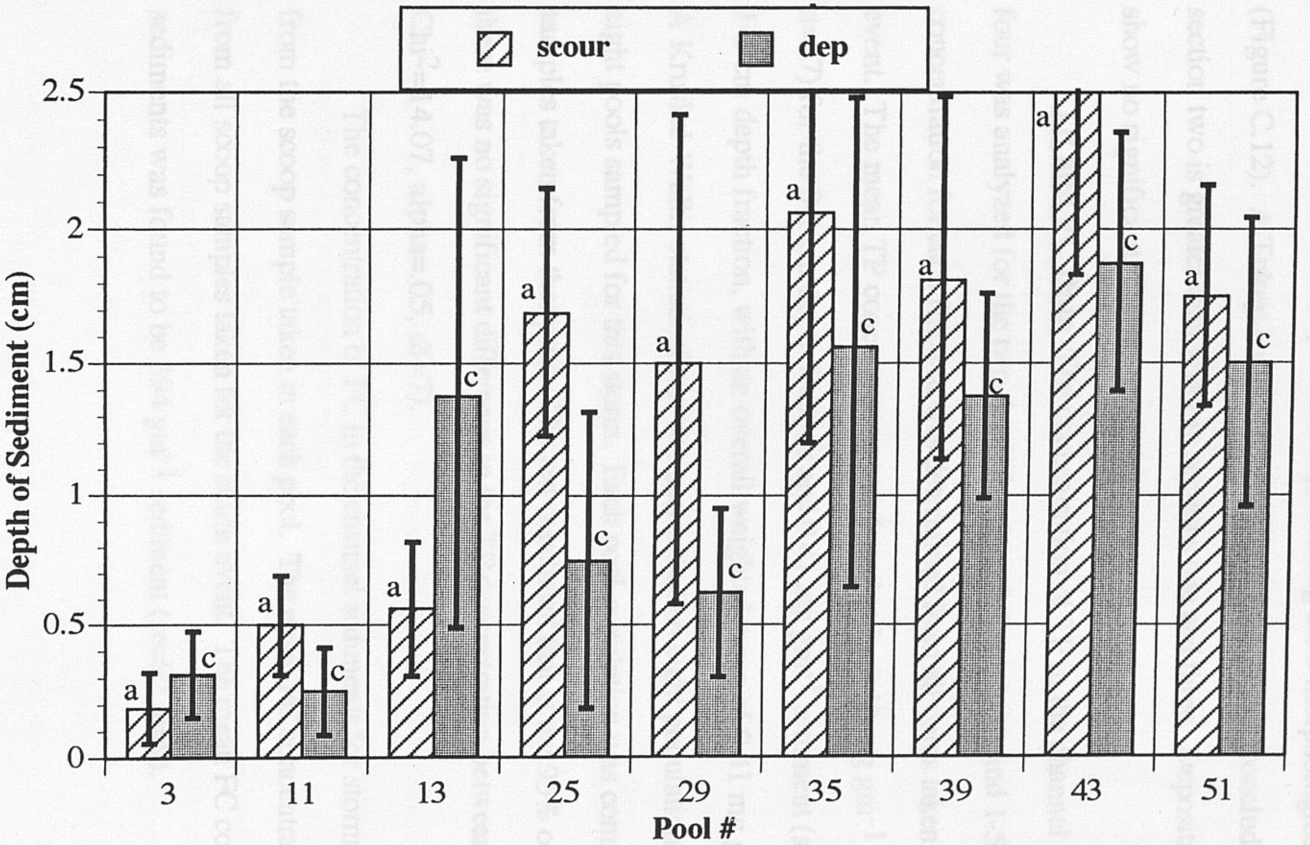

Figure C.11 Scour and Deposition Measurements for Storm #4. Scour is statistically greater than deposition at the 95% confidence interval (p=.0430).

*

Letters above bars represent statistical equality (

those bars having the same letters are not statist

rror bars represent standard error of the mean . Ä due to the fact that the Tukey-W test is more conservative in its conclusions than the Kruskal-Wallis test.

The average sediment scour depths and average sediment deposition depths were each divided into three populations representing the 3 morphological stream sections (Figure C.12). A Tukey-Kramer test between each section concludes that scour in section two is greater than scour in sections one and three. Deposition in all sections show no significant difference.

TP and FC Data The concentration of TP in the channel sediments for storm four was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.42 mg gm^{-1} sediment (se=0.06, n=27) for the 0-1 cm depth fraction and 0.41 mg gm^{-1} sediment (se=0.06, n=27) for the 1-5 cm depth fraction, with an overall weighted mean of 0.41 mg gm^{-1}(se=0.06, n=27). A Kruskal-Wallis statistical test was performed on eight populations representing the eight pools sampled for this storm. Each pool population was comprised of three samples taken from that pool. The test concluded that at the 95% confidence interval, there was no significant difference in the TP concentration between pools (H=7.27, Chi^2=14.07, alpha=.05, df=7).

The concentration of FC in the channel sediments for storm four was determined from the scoop sample taken in each pool. The mean FC concentration was determined from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 394 gm^{-1} sediment (se=92, n=9).

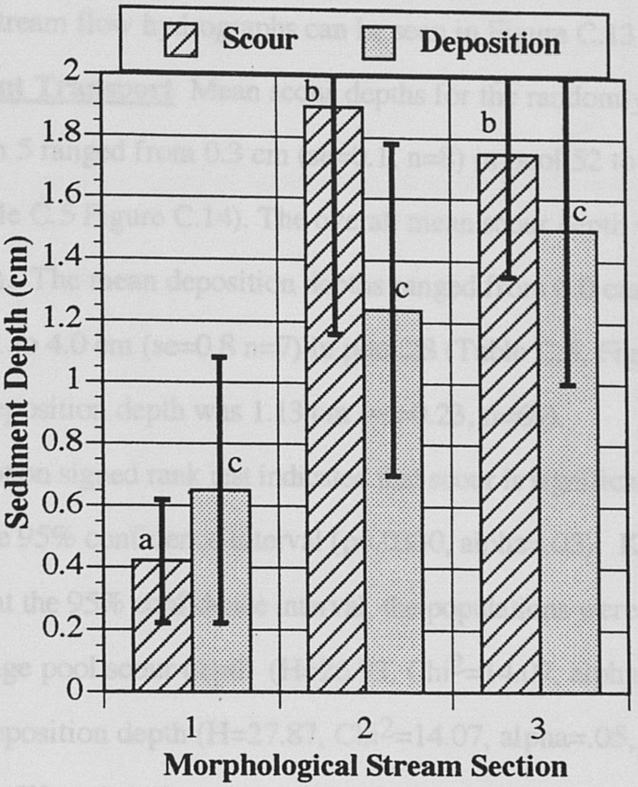

Figure C.12 Scour and Deposition for Storm #4, Divided into Morphological Stream Sections. Scour in sections 2 and 3 are statistically greater than section 1. Deposition is equal in all sections.

** Letters above bars represent statistical equality (those bars having the same letters are not statistically different) Error bars represent standard error of the mean*

Description of Storm Five Data.

Hydrology Storm five began on July 25, 1994 yielding a total rainfall amount of 0.20 inches over several days. The total runoff volume was measured to be 199,154 ft^3 and total stream power expended was 1,063,401 joules. The precipitation hyetograph and measured stream flow hydrographs can be seen in Figure C.13.

Sediment Transport Mean scour depths for the randomly selected pools studied in storm 5 ranged from 0.3 cm (se=0.1, n=8) in pool 52 to 5.4 cm (se=0.8, n=7) in pool 28 (Table C.5 Figure C.14). The overall mean scour depth was 1.99 cm (se=0.28, n=69). The mean deposition depths ranged from 0.0 cm (se=0.0, n=8) in pools 52 and 11 to 4.0 cm (se=0.8 n=7) in pool 28 (Table C.5, Figure C.14). The overall mean deposition depth was 1.13 cm (se=0.23, n=69).

A Wilcoxon signed rank test indicated that scour is significantly greater than deposition at the 95% confidence interval (p=.0330, alpha=.05). Kruskal-Wallis tests concluded that at the 95% confidence interval, the populations were not all the same with respect to average pool scour depth (H=26.93, Chi^2=14.07, alpha=.05, df=7) or average pool deposition depth (H=27.87, Chi^2=14.07, alpha=.05, df=7).

A Tukey-W statistical test was performed on the same populations and concluded that scour in all pools was equal except for pools 28 and 38 (Figure C.14). Scour in pool 28 was determined to be equal to that in pool 38, but greater than scour in all other pools. Scour in pool 38 is statistically greater than that in pool 52. Deposition in all pools was not significantly different with the exception of pools 28 and 31. Deposition in pool 28 is significantly greater than all other pools. Deposition in pool 31 is significantly less than in pool 28 and is not significantly different from pool 15.

The average sediment scour depths and deposition depths were each divided into three populations representing the three morphological stream sections (Figure C.15). A

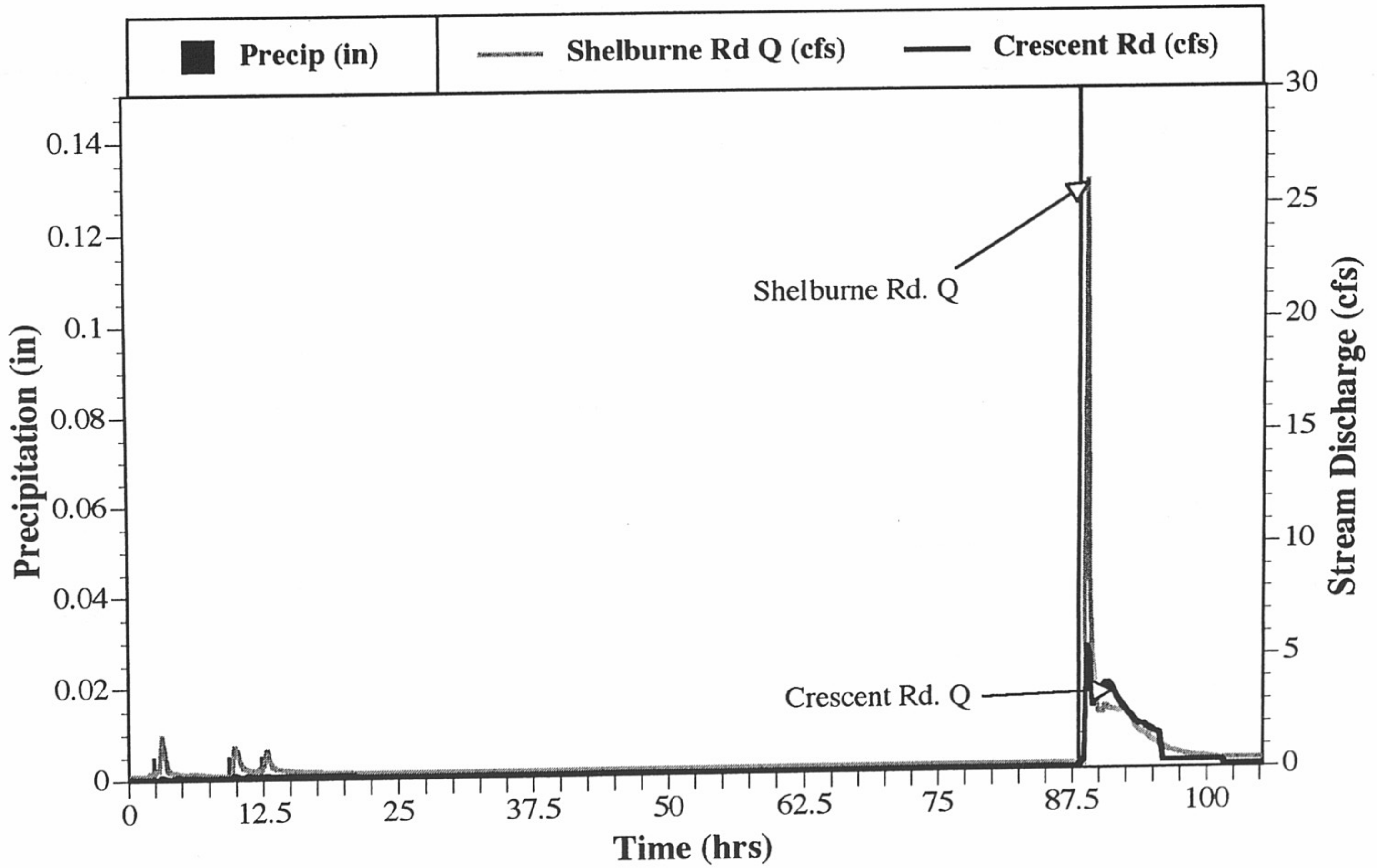

Figure C.13 Storm #5 Hydrology. Hyetograph (bars) and hydrograph (lines) for storm in Englesby Brook Watershed on July 22 through 25, 1994.

Table C.5 Depth of Scour and Deposition for Storm #5.

**se* = *standard error of the mean*

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
5	0.5	0.5	0.0	1.0	5.0	0.5	0.0	0.5	1.0	0.6
10	1.0	0.0	1.5	0.0	1.0	4.5	2.5	0.0	1.3	0.6
15	0.0	7.0	2.0	1.0	2.0	2.5	0.5	0.0	1.9	0.8
25	0.0	2.0	4.0	1.0	7.0	1.0	0.5	0.0	1.9	0.9
28	10.0	5.0	5.5	5.5	na	3.0	4.0	5.0	5.4	0.8
31	1.0	2.0	3.5	2.5	0.5	2.0	na	na	1.9	0.4
36	0.0	0.0	3.0	0.0	4.0	0.0	0.0	0.0	0.9	0.6
38	3.0	2.0	2.0	0.0	4.0	7.0	6.0	6.0	3.8	0.9
52	0.0	0.0	0.5	0.0	0.0	0.5	0.0	1.0	0.3	0.1
mean	1.7	2.1	2.4	1.2	2.9	2.3	1.7	1.6	2.0	0.6

	Deposition Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
5	0.0	0.5	0.0	0.0	0.0	2.5	0.0	0.0	0.4	0.3
10	0.0	1.0	0.5	0.0	0.0	1.5	1.0	0.0	0.5	0.2
15	0.0	0.0	1.0	0.0	3.5	1.5	0.0	1.0	0.9	0.4
25	1.0	0.5	1.0	0.0	2.0	1.0	0.0	0.0	0.7	0.2
28	7.5	2.5	3.0	6.0	na	4.0	2.0	3.0	4.0	0.8
31	10.0	0.0	3.5	2.5	4.0	0.0	na	na	3.3	1.5
36	0.0	1.0	0.0	0.0	0.0	2.0	0.0	2.0	0.6	0.3
38	0.5	2.0	0.0	0.0	0.0	0.0	3.0	0.0	0.7	0.4
52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

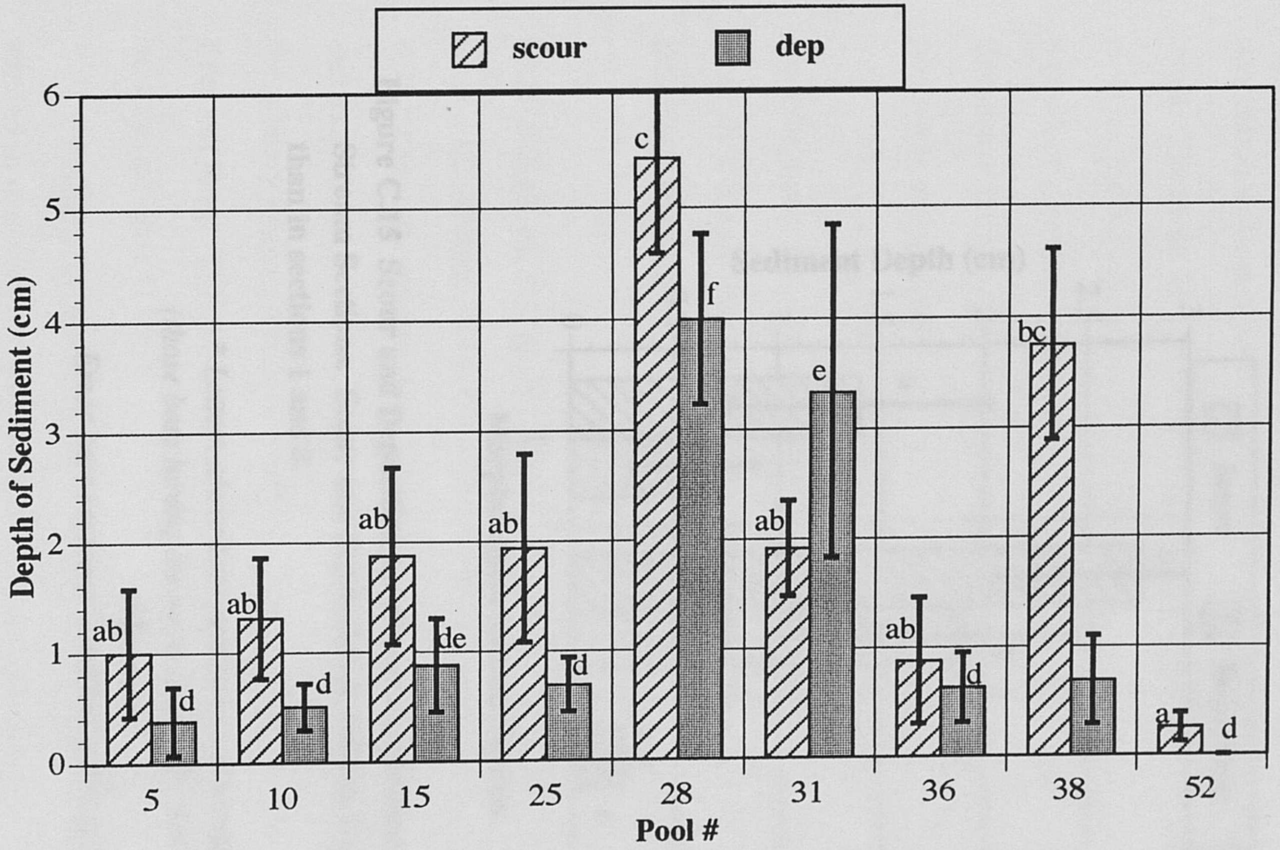

Figure C.14 Scour and Deposition Measurements for Storm #5. Scour is statistically greater than deposition at the 95% confidence interval (p=.0330).

**Letters above bars represent statistical equality*
(those bars having the same letters are not statistically different).
Error bars represent standard error of the mean .

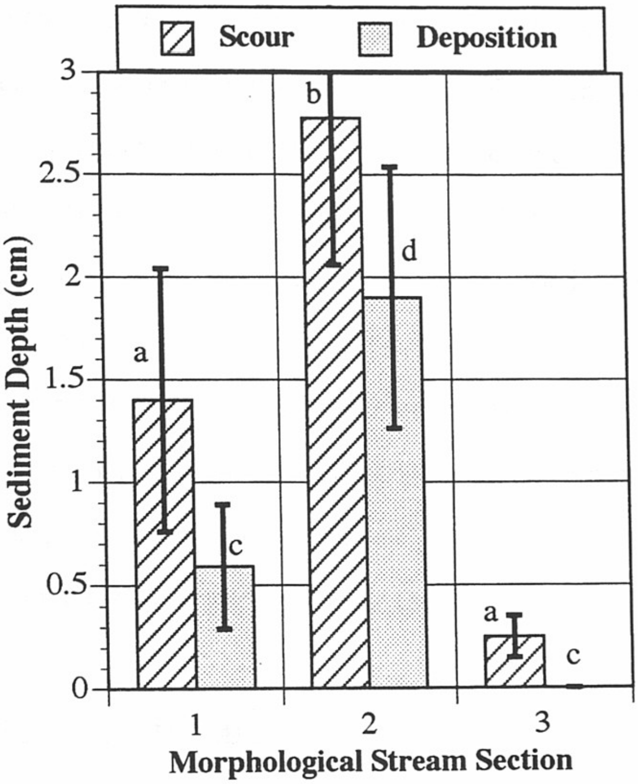

Figure C.15 Scour and Deposition for Storm #5, Divided into Morphological Stream Sections. Scour and deposition in section 2 are statistically greater than in sections 1 and 3.

** Letters above bars represent statistical equality (those bars having the same letters are not statistically different)*

Error bars represent standard error of the mean

Tukey-Kramer test between each section concludes that scour and deposition in section two is greater than scour in sections one and three.

TP and FC Data The concentration of TP in the channel sediments for storm five was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.59 mg gm^{-1} sediment (se=0.15, n=9) for the 0-1 cm depth fraction and 0.45 mg gm^{-1} sediment (se=0.11, n=9) for the 1-5 cm depth fraction, with an overall weighted mean of 0.48 mg gm^{-1}(se=0.13, n=9). Because of the low number of cores taken, a statistical test of TP concentrations between pools was not possible.

The concentration of FC in the channel sediments for storm five was determined from the scoop sample taken in each pool. The mean FC concentration was determined from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 691 gm^{-1} sediment (se=139, n=9).

Description of Storm Six Data.

Hydrology Storm six began on July 26, 1994 yielding a total rainfall amount of 0.75 inches over several days. The total runoff volume was measured to be 174,248 ft^3 and total stream power expended was 930,406 joules. Stream flow was measured only at the primary gauging station at Shelburne Road because of a flow meter malfunction at Crescent Road. The precipitation hyetograph and measured stream flow hydrograph can be seen in Figure C.16.

Sediment Transport Mean scour depths for the randomly selected pools studied in storm six ranged from 0.4 cm (se=0.3, n=8) in pool 9 to 6.8 cm (se=1.9, n=6) in pool 42 (Table C.6 Figure C.17). The overall mean scour depth was 2.67 cm (se=0.39, n=69). The mean deposition depths ranged from 0.0 cm (se=0.0, n=8) in

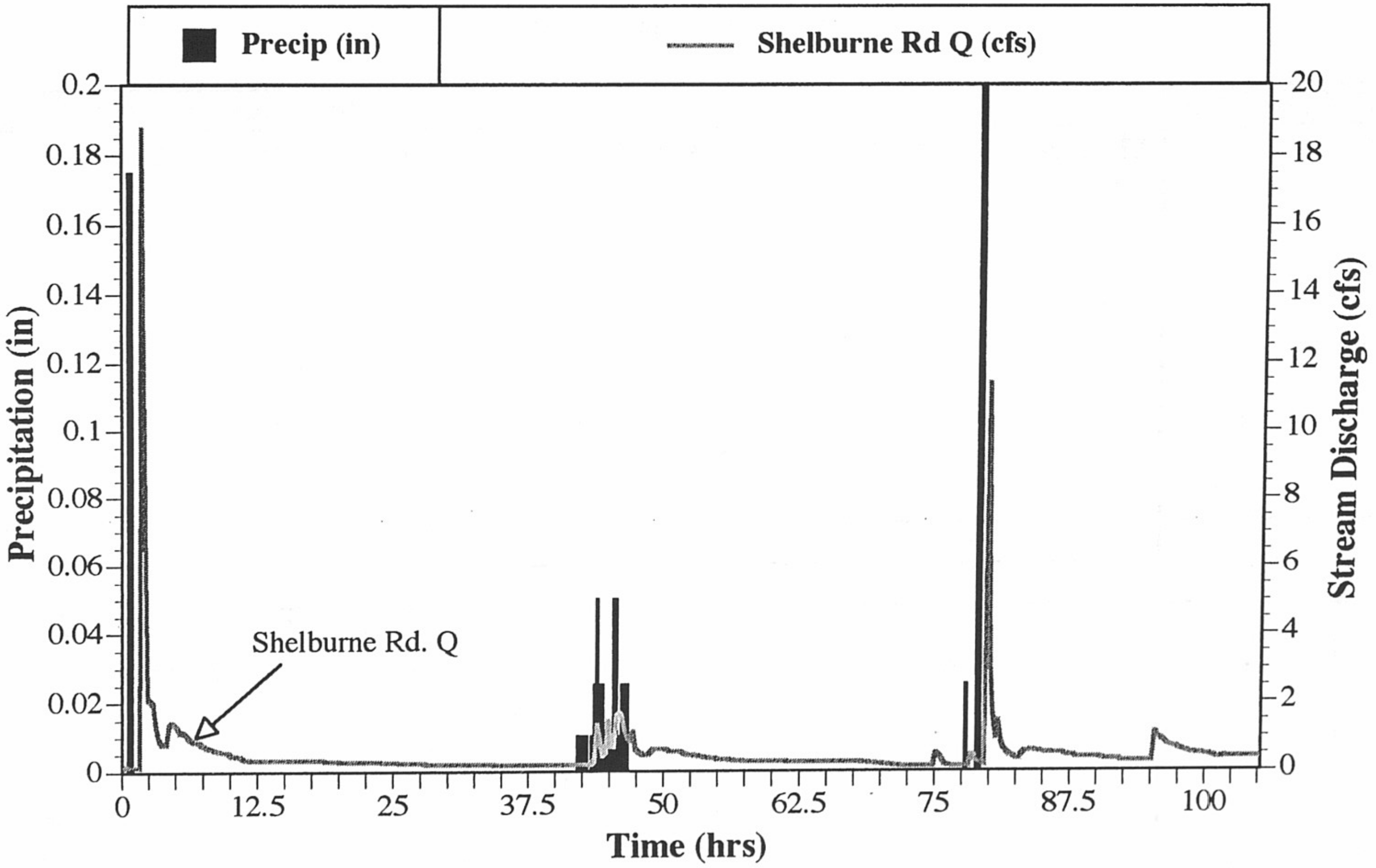

Figure C.16 Storm #6 Hydrology. Hyetograph (bars) and hydrograph (lines) for storm in Englesby Brook Watershed on July 26 through July 31, 1994. Ä

Table C.6 Depth of Scour and Deposition Data for Storm #6.

**se = standard error of the mean*

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
9	2.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.4	0.3
21	0.0	1.0	0.0	0.0	0.0	10.0	1.5	1.0	1.7	1.2
25	1.5	0.0	5.0	1.5	0.0	0.0	0.0	0.5	1.1	0.6
26	4.0	4.0	1.0	na	5.5	2.0	0.0	5.0	3.1	0.8
29	5.0	0.0	1.0	2.0	3.0	1.0	7.0	1.5	2.6	0.8
32	10.0	9.0	2.0	2.0	1.0	2.5	8.5	8.0	5.4	1.3
33	0.5	0.0	1.0	3.5	0.0	2.0	4.0	0.0	1.4	0.6
42	2.0	4.0	na	10.0	13.0	2.0	na	10.0	6.8	1.9
54	3.0	1.5	0.0	2.0	1.5	1.0	6.5	7.0	2.8	0.9
mean	3.1	2.2	1.3	2.6	2.7	2.3	3.4	3.8	2.8	0.9

	Deposition Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.5	0.5	0.5	0.0	na	0.5	0.0	0.3	0.1
25	2.5	3.0	2.0	1.5	1.0	3.0	7.5	0.0	2.6	0.8
26	2.5	3.5	0.0	na	3.5	0.0	0.0	0.0	1.4	0.7
29	1.0	1.5	1.0	1.0	7.0	1.0	4.0	3.5	2.5	0.8
32	na	4.0	6.0	3.5	0.0	2.0	4.5	11.0	4.4	1.3
33	0.5	1.5	0.0	0.0	1.0	0.5	0.0	0.0	0.4	0.2
42	0.0	0.5	na	4.0	9.0	5.0	na	1.0	3.3	1.4
54	2.0	1.5	0.0	7.0	6.5	1.0	0.0	4.8	2.8	1.0

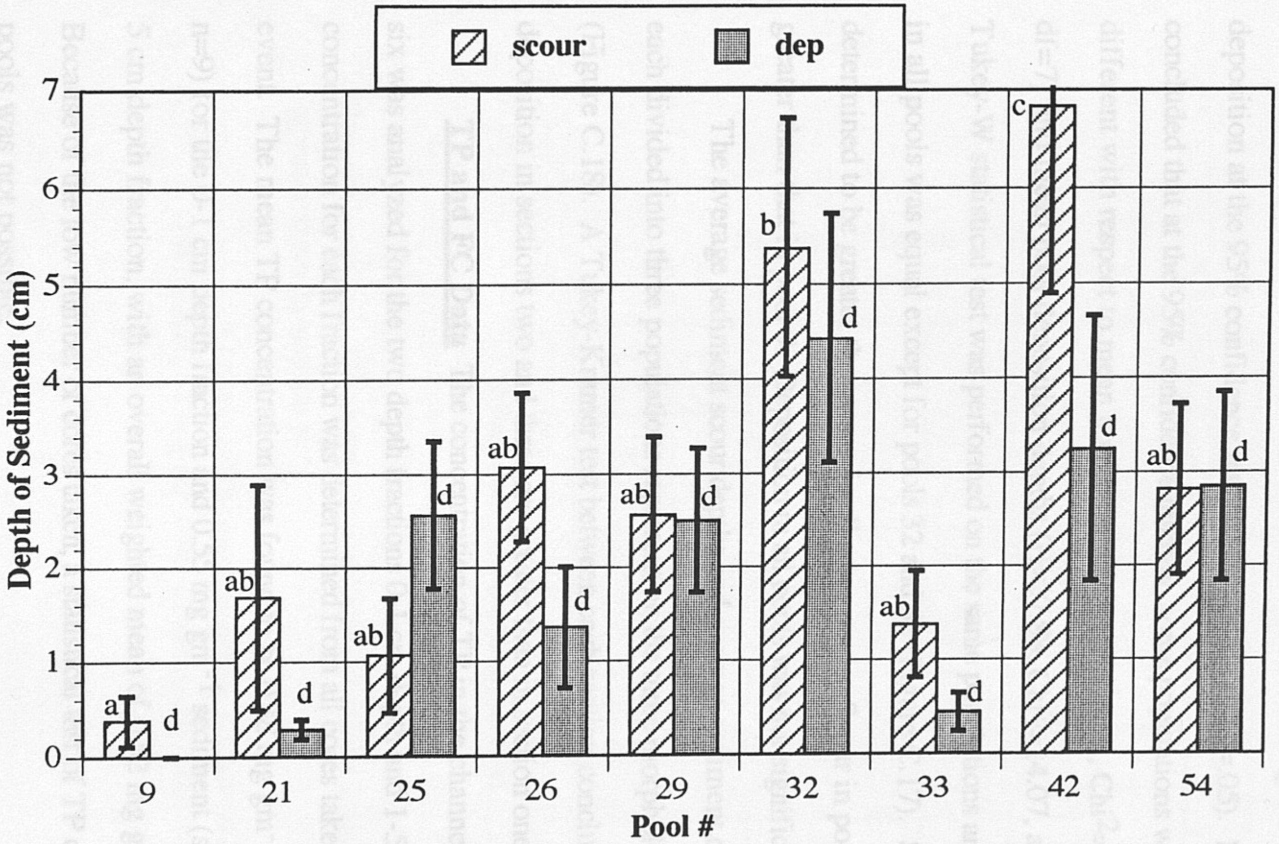

Figure C.17 Scour and Deposition Measurements for Storm #6. Scour is statistically greater than deposition at the 95% confidence interval (p=.0465).

**Letters above bars represent statistical equality (those bars having the same letters are not statistically different). Error bars represent standard error of the mean* pools 9 to 4.4 cm (se=1.3 n=7) in pool 32 (Table C.6, Figure C.17). The overall mean deposition depth was 1.92 cm (se=0.31, n=67). Three scour and four deposition measurements were discarded due to entrapment of debris or washout of stakes.

A Wilcoxon signed rank test indicated that scour is significantly greater than deposition at the 95% confidence interval (p=.0465, alpha=.05). Kruskal-Wallis tests concluded that at the 95% confidence interval, some populations were significantly different with respect to mean pool scour depths(H=26.32, Chi^2=14.07, alpha=.05, df=7) and mean pool deposition depths (H=27.88, Chi^2=14.07, alpha=.05, df=7). A Tukey-W statistical test was performed on the same populations and concluded that scour in all pools was equal except for pools 32 and 42 (Figure C.17). Scour in pool 42 was determined to be greater than scour in all other pools. Scour in pool 32 is statistically greater than that in pool 9. Deposition in all pools was not significantly different

The average sediment scour depths and average sediment deposition depths were each divided into three populations representing the three morphological stream sections (Figure C.18). A Tukey-Kramer test between each section concludes that scour and deposition in sections two and three are greater than in section one.

TP and FC Data The concentration of TP in the channel sediments for storm six was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.38 mg gm^{-1} sediment (se=0.10, n=9) for the 0-1 cm depth fraction and 0.55 mg gm^{-1} sediment (se=0.11, n=9) for the 1-5 cm depth fraction, with an overall weighted mean of 0.52 mg gm^{-1}(se=0.10, n=9). Because of the low number of cores taken, a statistical test of TP concentrations between pools was not possible.

The concentration of FC in the channel sediments for storm 6 was determined from the scoop sample taken in each pool. The mean FC concentration was determined

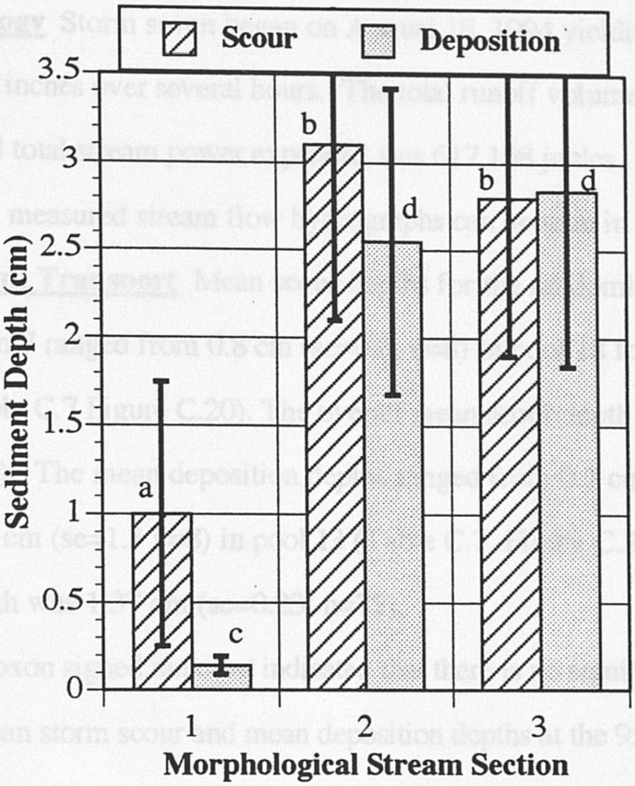

Figure C.18 Scour and Deposition for Storm #6, Divided into Morphological Stream Sections. Scour and deposition in sections 2 and 3 are statistically greater than in section 1.

** Letters above bars represent statistical equality (those bars having the same letters are not statistically different)*

Error bars represent standard error of the mean

from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 571 gm^{-1} sediment (se=114, n=9).

Description of Storm Seven Data.

Hydrology Storm seven began on August 18, 1994 yielding a total rainfall amount of 0.70 inches over several hours. The total runoff volume was measured to be 115,572 ft^3 and total stream power expended was 617,108 joules. The precipitation hyetograph and measured stream flow hydrographs can be seen in Figure C.19

Sediment Transport Mean scour depths for the randomly selected pools studied in storm 7 ranged from 0.8 cm (se=0.3, n=8) in pool 18 to 3.9 cm (se=0.8, n=8) in pool 32 (Table C.7 Figure C.20). The overall mean scour depth was 1.95 cm (se=0.30, n=72). The mean deposition depths ranged from 0.1 cm (se=0.1, n=8) in pools 42 to 3.3 cm (se=1.3 n=8) in pool 13 (Table C.7, Figure C.20). The overall mean deposition depth was 1.37 cm (se=0.23, n=72).

A Wilcoxon signed rank test indicated that there is no significant difference between the mean storm scour and mean deposition depths at the 95% confidence interval (p=.0615, alpha=.05). Kruskal-Wallis tests concluded that at the 95% confidence interval, some populations were significantly different with respect to average pool scour depths (H=18.79, Chi^2=14.07, alpha=.05, df=7) and average pool deposition depths (H=19.36, Chi^2=14.07, alpha=.05, df=7). A Tukey-W statistical test was performed on the same populations and concluded that scour in all pools was not significantly different. This conclusion is contrary to that of the Kruskal-Wallis test because of the conservative nature of the Tukey-W test. The test concluded that deposition in pool 13 was significantly greater than in all other pools (Figure C.20).

The average sediment scour depths and deposition depths were each divided into three populations representing the three morphological stream sections (Figure C.21). A

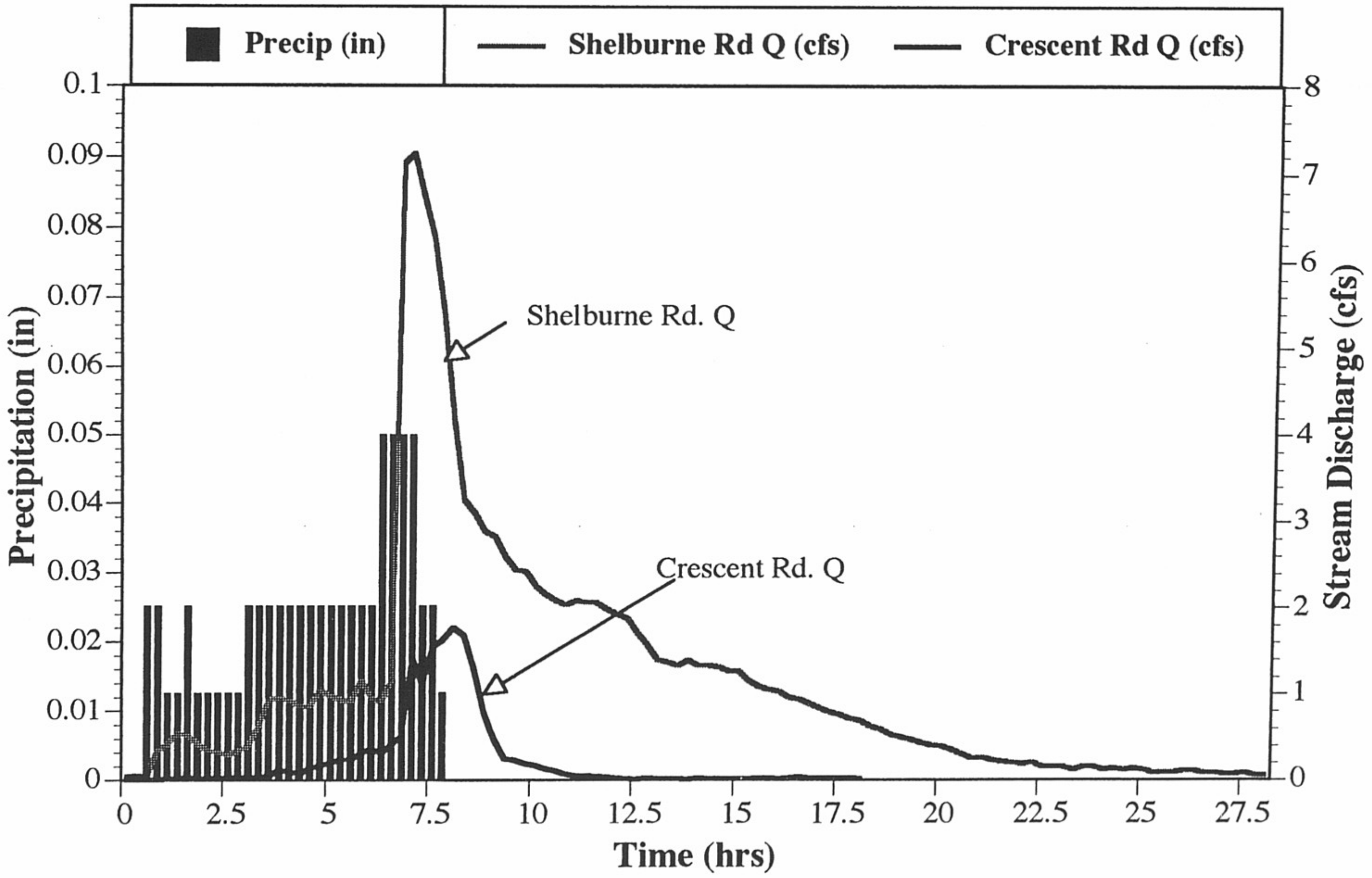

Figure C.19 Storm #7 Hydrology. Hyetograph (bars) and hydrographs (lines) for storm in Englesby Brook Watershed on August 18, 1994.

Table C.7 Depth of Scour and Deposition Data for Storm # 7.

***se= standard error of the mean**

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
13	2.0	2.0	6.5	13.0	0.0	0.0	2.0	0.5	3.3	1.6
18	1.0	0.0	0.0	0.0	1.0	0.0	2.0	2.0	0.8	0.3
22	1.0	3.0	0.0	0.0	1.0	0.0	0.0	0.0	0.6	0.4
25	2.0	2.0	2.5	6.5	5.0	2.0	5.0	0.0	3.1	0.8
32	1.5	3.5	6.0	5.5	3.0	0.5	7.0	4.0	3.9	0.8
34	0.0	0.0	0.0	2.0	0.0	1.0	5.0	2.0	1.3	0.6
42	3.0	2.0	0.0	1.0	3.0	1.0	0.0	2.0	1.5	0.4
53	1.0	11.5	0.5	0.3	2.5	1.0	0.0	1.0	2.2	1.4
55	2.0	0.5	0.0	1.5	1.0	1.5	0.0	1.0	0.9	0.3
mean	1.5	2.7	1.7	3.3	1.8	0.8	2.3	1.4	1.9	0.7

	Deposition Depth (cm)									
pool#	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
13	0.0	3.0	5.5	11.0	3.0	2.0	2.0	0.0	3.3	1.3
18	0.0	0.5	0.0	0.0	0.0	0.0	3.0	0.0	0.4	0.4
22	3.0	6.0	0.0	1.0	1.5	0.0	1.5	0.0	1.6	0.7
25	0.0	0.0	0.0	2.0	3.5	1.0	1.0	1.0	1.1	0.4
32	7.0	0.5	2.0	2.5	0.0	0.0	1.0	3.0	2.0	0.8
34	1.0	2.0	1.0	2.0	1.0	2.0	0.0	0.0	1.1	0.3
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.1	0.1
53	0.0	1.5	4.5	0.0	0.0	2.0	1.0	3.0	1.5	0.6
55	0.0	0.0	0.5	0.0	2.0	3.5	0.0	3.0	1.1	0.5

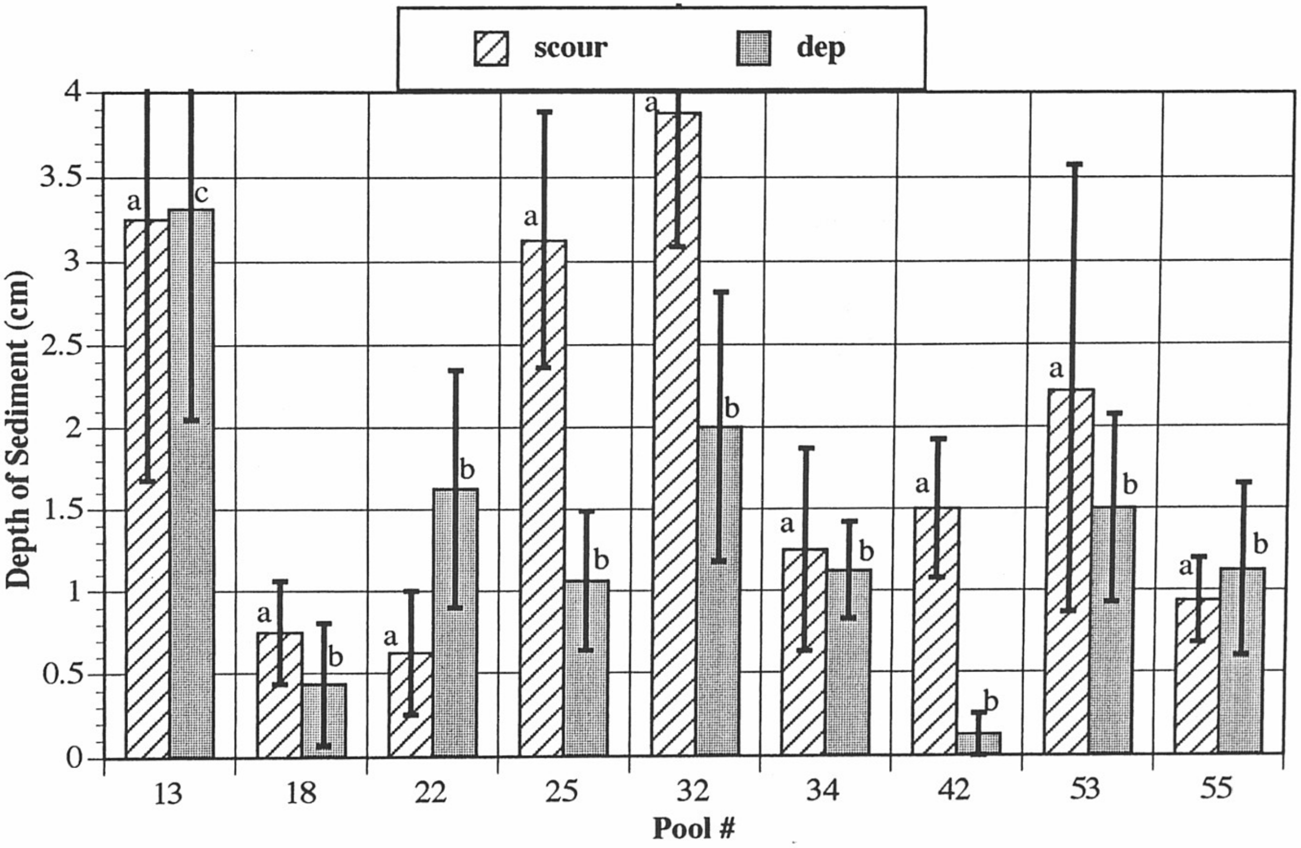

Figure C.20 Scour and Deposition Measurements for Storm #7. Scour and deposition are not statistically different at the 95% confidence interval (p=.0615).

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those bars having the same letters are not statisticall

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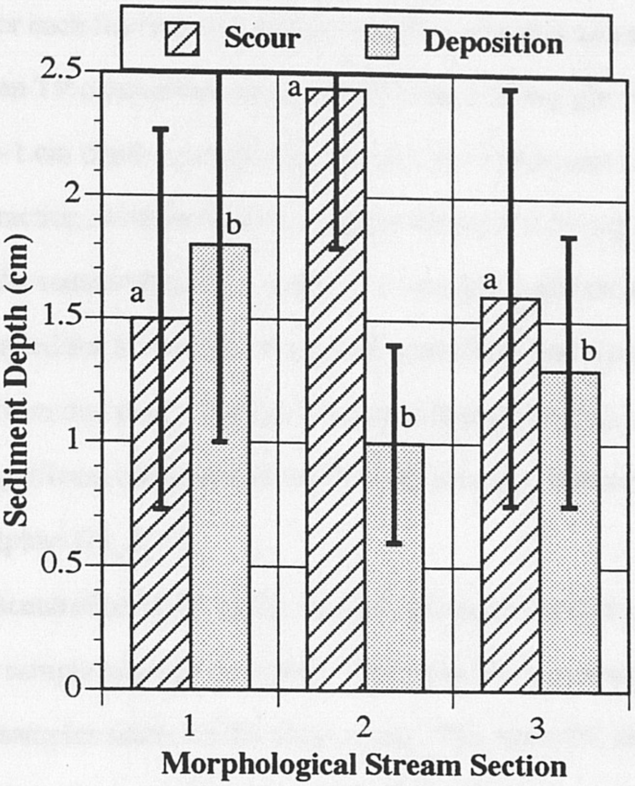

Figure C.21 Scour and Deposition for Storm #7, Divided into Morphological Stream Sections. Scour and deposition in all sections are equal.

** Letters above bars represent statistical equality (those bars having the same letters are not statistically different)*
Error bars represent standard error of the mean

Tukey-Kramer test between each section concludes that for both scour and deposition, the sections are not significantly different.

TP and FC Data The concentration of TP in the channel sediments for storm seven was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.53 mg gm^{-1} sediment (se=0.06, n=27) for the 0-1 cm depth fraction and 0.50 mg gm^{-1} sediment (se=0.06, n=27) for the 1-5 cm depth fraction, with an overall weighted mean of 0.51 mg gm^{-1}(se=0.06, n=27). A Kruskal-Wallis statistical test was performed on eight populations representing the eight pools sampled for this storm. Each pool population was comprised of three samples taken from that pool. The test concluded that at the 95% confidence interval, there was no significant difference in the TP concentration between pools (H=5.22, Chi^2=14.07, alpha=.05, df=7).

The concentration of FC in the channel sediments for storm seven was determined from the scoop sample taken in each pool. The mean FC concentration was determined from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 438 gm^{-1} sediment (se=78, n=9). Because of the low number of cores taken, a statistical test of FC concentrations between pools was not possible.

Description of Storm Eight Data.

Hydrology Storm eight began on August 21, 1994 yielding the highest total rainfall amount of 1.30 inches over nearly 12 hours. The total runoff volume was measured to be 532,372 f^3 and total stream power expended was 2,842,643 joules. Stream flow was measured only at the primary gauging station at Shelburne Road because of a flow meter malfunction at Crescent Road. The precipitation hyetograph and measured stream flow hydrograph can be seen in Figure C.22.

Sediment Transport Mean scour depths for the randomly selected pools studied in storm 8 ranged from 2.1 cm (se=0.5, n=8) in pool 39 to 10.7 cm (se=1.5, n=6) in pool 31 (Table C.8 Figure C.23). The overall mean scour depth was 5.18 cm (se=0.9, n=69). The mean deposition depths ranged from 0.9 cm (se=0.5, n=8) in pools 39 to 11.3 cm (se=3.5 n=6) in pool 31 (Table C.8, Figure C.23). The overall mean deposition depth was 4.76 cm (se=0.62, n=69). Three scour and 3 deposition measurements were discarded due to entrapment of debris or washout of stakes.

A Wilcoxon signed rank test indicates that there is no significant difference between the mean storm scour and mean deposition depths at the 95% confidence interval (p=.3835, alpha=.05). Kruskal-Wallis tests concluded that at the 95% confidence interval, some populations were significantly different with respect to average pool scour (H=21.50, Chi^2=14.07, alpha=.05, df=7) and deposition depths (H=22.25, Chi^2=14.07, alpha=.05, df=7). A Tukey-W statistical test was performed on the same populations and concluded that for both scour and deposition depths, pool 31 was significantly greater than all other pools (Figure C.23).

The average sediment scour depths and average sediment deposition depths were each divided into three populations representing the three morphological stream sections (Figure C.24). A Tukey-Kramer test between each section concludes that scour in all three sections is not significantly different and deposition in section three is significantly less than in sections one and two.

TP and FC Data The concentration of TP in the channel sediments for storm eight was analyzed for the two depth fractions 0-1 cm depth and 1-5 m depth. The mean concentration for each fraction was determined from all cores taken during the storm event. The mean TP concentration was found to be 0.62 mg gm^{-1} sediment (se=0.16,

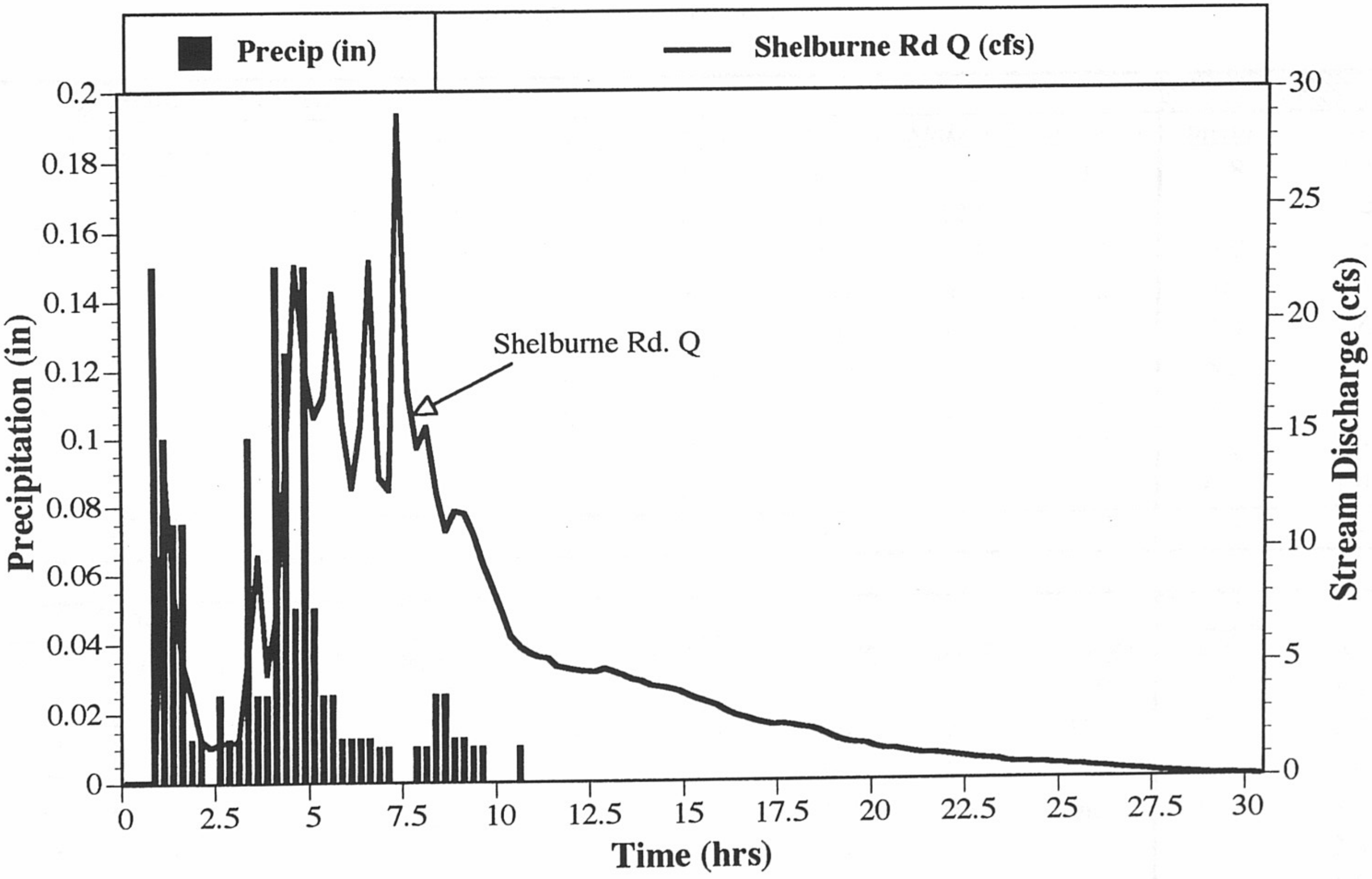

Figure C.22 Storm #8 Hydrology. Hyetograph (bars) and hydrograph (line) for storm in Englesby Brook Watershed on August 21, 1994.

Table C.8 Depth of Scour and Deposition Data for Storm # 8.

**se= standard error of the mean*

	Scour Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
6	5.5	6.5	6.5	0.0	0.5	0.0	0.0	3.0	2.8	1.1
21	7.0	10.0	3.0	0.0	10.0	7.0	12.0	10.0	7.4	1.4
25	5.0	6.0	12.0	12.0	5.5	1.0	3.0	1.0	5.7	1.5
31	10.0	6.0	15.0	15.0	8.0	10.0	na	na	10.7	1.5
33	0.0	0.5	0.0	1.0	0.0	5.0	9.5	11.0	3.4	1.6
35	5.0	1.0	3.0	2.0	na	8.0	8.0	8.0	5.0	1.2
39	4.0	4.0	2.0	0.0	2.0	1.0	2.0	2.0	2.1	0.5
43	8.0	8.0	8.0	6.0	2.0	5.0	5.0	7.5	6.2	0.8
53	4.0	4.0	5.0	1.5	11.0	10.0	0.0	3.0	4.8	1.4
mean	5.4	5.1	6.1	4.2	4.9	5.2	4.9	5.7	5.3	1.2

	Deposition Depth (cm)									
pool #	*Stake #1*	*Stake #2*	*Stake #3*	*Stake #4*	*Stake #5*	*Stake #6*	*Stake #7*	*Stake #8*	*mean*	**se*
6	5.5	8.5	7.5	2.0	6.5	1.0	0.0	3.0	4.3	1.1
21	15.0	15.0	1.0	0.0	5.0	2.0	7.0	12.0	7.1	2.2
25	0.0	2.5	6.0	6.0	6.5	0.0	1.5	0.0	2.8	1.0
31	5.0	1.0	23.0	20.0	8.0	11.0	na	na	11.3	3.5
33	0.0	2.5	0.0	2.0	1.5	5.0	13.5	17.0	5.2	2.3
35	8.0	3.0	2.5	5.0	na	10.0	6.0	6.0	5.8	1.0
39	0.0	0.0	4.0	0.0	1.0	0.0	0.0	2.0	0.9	0.5
43	8.0	5.0	3.0	4.0	4.0	7.0	12.0	5.5	6.1	1.0
53	0.0	8.0	0.0	0.0	1.5	0.0	0.0	0.0	1.2	1.0

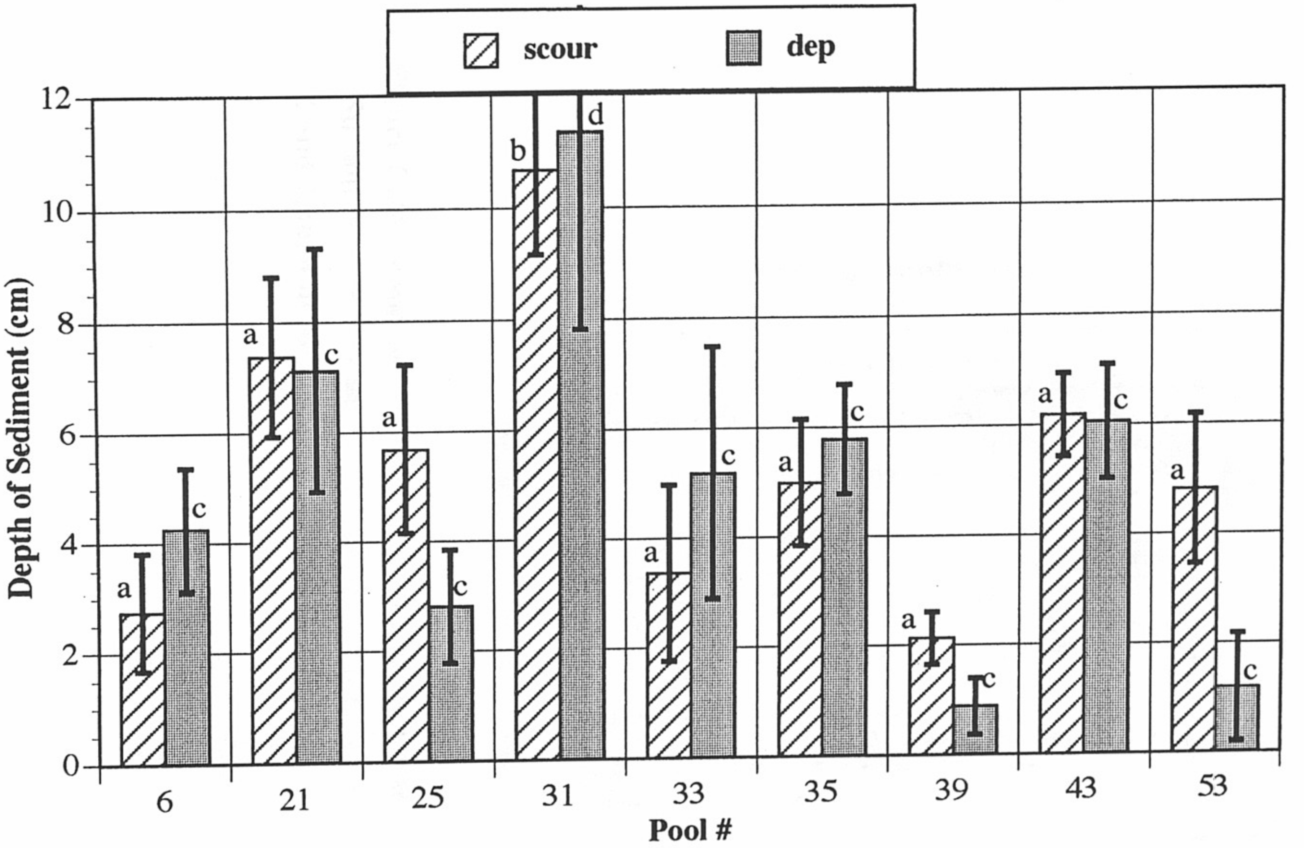

Figure C.23 Scour and Deposition Measurements for Storm #8. Scour and deposition are not statistically different at the 95% confidence interval (p=.3835).

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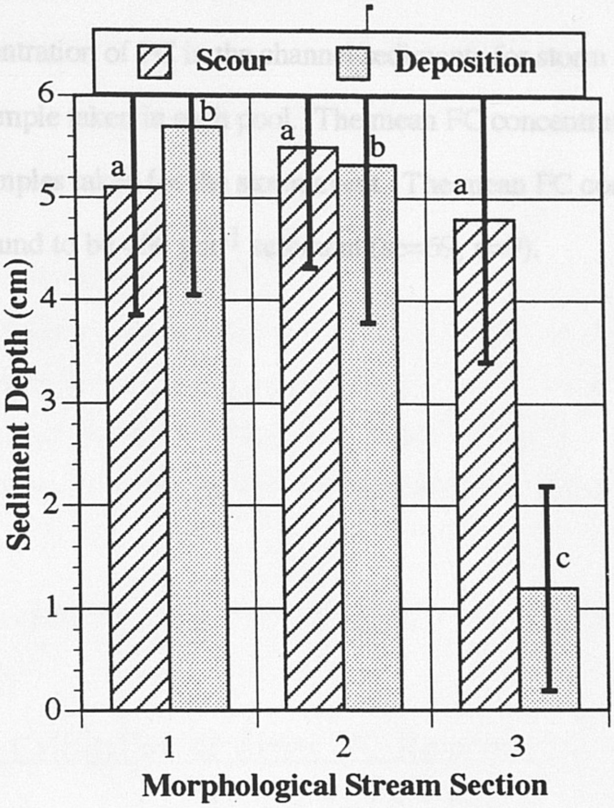

Figure C.24 Scour and Deposition for Storm #8, Divided into Morphological Stream Sections. Scour in all sections is equal. Deposition is greater in sections 1 and 2, than in section 3.

** Letters above bars represent statistical equality*
(those bars having the same letters are not statistically different)
Error bars represent standard error of the mean

n=9) for the 0-1 cm depth fraction and 0.56 mg gm^{-1} sediment (se=0.12, n=9) for the 1-5 cm depth fraction, with an overall weighted mean of 0.58 mg gm^{-1}(se=0.14, n=9). Because of the low number of cores taken, a statistical test of TP concentrations between pools was not possible.

The concentration of FC in the channel sediments for storm eight was determined from the scoop sample taken in each pool. The mean FC concentration was determined from all scoop samples taken for the storm event. The mean FC concentration of the sediments was found to be 456 gm^{-1} sediment (se=69, n=9).

Appendix D

Mathematical Calculations

Appendix D1- Calculation of Active TP Reservoir

$$P_r = A_p * d * \rho_s * P_c$$

where:

$\mathrm{P_r}$ = active TP reservoir (kg of TP)

$\mathrm{A_p}$ = combined surface area of all pools ($\mathrm{m^2}$)

d = maximum mean scour depth observed (cm)

ρ_s = mean density of sediment during study period (g $\mathrm{cm^{-1}}$)

$\mathrm{P_c}$ = mean sediment TP concentration during study period (mg $\mathrm{g^{-1}}$)

$$P_r = (1{,}810 m^2) * (5.2 cm) * (1.4 g\ cm^{-1}) * (0.48 mg\ g^{-1}) = 63 kg$$

Appendix D2- Calculation of Active FC Reservoir

$$FC_r = A_p * d * \rho_s * FC_c$$

where:

FC_r = active FC reservoir (# of FC)

FC_c = mean sediment FC concentration during study period (FC $\mathrm{g^{-1}}$)

$$FC_r = (1{,}810 m^2) * (5.2 cm) * (1.4 g\ cm^{-1}) * (456 FC\ g^{-1}) = 5.9 * 10^{10} FC$$

Appendix D3- Calculation of Mean Sediment and Pollutant Mobilization

$$M_s = S_\mu * A_p * \rho_s * n_e$$

where:

M_s = mass of sediment mobilized (kg)
S_μ = mean scour depth during study period (cm)
n_e = number of storm events during study period

$$M_s = (2.4cm) * (1{,}810m^2) * (1.4g\ cm^{-1}) * (8\ storms) = 4.9 * 10^5 kg$$

and

$$M_p = M_s * P_c$$

where:

M_p = mass of P mobilized (kg)

$$M_p = (4.9 * 10^5 kg) * (0.48mg\ g^{-1}) = 240kg$$

and

$$M_{FC} = M_s * FC_C$$

where:

M_{FC} = number of FC mobilized

$$M_{FC} = (4.9 * 10^5 kg) * (456FC\ g^{-1}) = 2.2 * 10^{11} FC$$

Appendix D4- Estimation of Channel Sediment Export for Storm One (Sample Calculation)

Fine Grained-Continuous Transport Model:

$$E_F = M_{s1} * F$$

where:

E_F = mass of fine grained sediments exported for storm one (kg)
M_{s1} = total mass of sediment mobilized from all pools for storm one (kg)
F = fine grained fraction of sediment (%)

$$E_F = (8.0 * 10^4 kg) * (2.6\%) = 2.1 * 10^3 kg$$

Medium Grained-Intermediate Transport Model:

$$E_m = \frac{M_{s1}}{n_p} * M$$

where:

E_m = mass of medium grained sediments exported for storm one (kg)
M = medium grained fraction of sediment (%)
n_p = total number of pools along stream

$$E_m = \left[\frac{8.0 * 10^4 kg}{56 pools}\right] * 82.6\% = 1,200 kg$$

Coarse Grained-Incremental Transport Model:

$$E_c = W_\mu * d * i * \rho_s * C$$

where:

E_c = mass of coarse grained sediments exported (kg)
W_μ = mean width of all pools (m)
i = incremental transport distance (assumed to be 1cm)
C = coarse grained fraction of sediment (%)

$$E_c = 2.1m * 3.2cm * 1cm * 1.4gcm^{-3} * 14.8\% = 1kg$$

Finally

$$E_{total} = E_F + E_M + E_C$$

where:

E_{total} = total mass of sediments exported (kg)

$$E_{total} = (2,100kg) + (1200) + (1kg) = 3,301kg$$

Appendix D5- Estimation of Pollutant Export from Stream Channel Sediments

$$E_P = E_{total} * P_c$$

where:

E_P = mass of P exported (kg)

$$E_P = 3{,}301kg * 0.48mg\ g^{-1} = 1.6kg$$

and

$$E_{FC} = E_{total} * FC_c$$

where:

E_{FC} = # of FC exported

$$E_P = 3{,}301kg * 456FC\ g^{-1} = 1.51 * 10^9 FC$$