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Patterns of total suspended solids concentration and the influence of antecedent conditions on hydrograph response to precipitation events on Beaver Creek, Ontario

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Patterns of total suspended solids concentration and the influence of antecedent conditions on hydrograph response to precipitation events on Beaver Creek, Ontario.

by

Matthew Peter Roy Mittler

THESIS

Submitted to the Department of Geography & Environmental Studies

in partial fulfillment of the requirements for

Master of Environmental Studies

Wilfrid Laurier University

Waterloo, Ontario, Canada 2006

“There is one area that we do have concerns about and we feel that we cannot let it continue in your life without comment. A university education is a costly venture both time wise and financially. Are you making the best choices for yourself selecting courses that entail climbing fences, digging in sand pits and watching water splash on shore? Get real Matt! A degree in DIRT! Like father like son!”

~ P. Mittler

Abstract

This study explored relationships between suspended solids concentration and discharge, the influence of antecedent conditions on event hydrographs and the state of dynamic equilibrium in a second-order stream (Beaver Creek), draining an agricultural basin in southern Ontario, near the City of Waterloo. Beaver creek was monitored for nineteen weeks from July to November of 2005. Thirteen precipitation events of various magnitude and duration were examined within the study period. Discharge and total suspended solids were sampled throughout the events. Cross sectional profiles of six transects were measured prior to and after each event.

Base flow, antecedent conditions and event response were quantified. A strong ($R^2 = 0.79$) positive relationship was found between antecedent conditions and basin response to precipitation events, whereby, wetter conditions in the basin prior to a storm resulted in greater changes in discharge compared to changes in discharge seen with dryer antecedent conditions. Suspended solids/discharge patterns during storm flow were best described using a hysteretic clockwise loop indicating a change in supply source throughout a given event. Rapid changes in suspended solids concentrations were related to decreased detachment by rainfall splash rather than source exhaustion or dilution. Average suspended solids flux showed only a 34% difference between input and output from the study area. Also, cross sectional bed profiles showed that over the duration of this study the creek was in a state of low morphological activity.

For design of monitoring programs as well as planning development within a basin, knowledge of storm sediment patterns, the influence of antecedent conditions on basin response to a precipitation event and resulting sediment flux in agricultural creeks is significant. These patterns should be taken as benchmarks for continued assessment of the impacts of human activities around water ways.

Acknowledgements

The completion of this work would not be possible without the support, guidance and encouragement of many people. I would like to take this opportunity to express my gratitude.

Dr. Mike English – Thank you for the opportunity to pursue this research endeavour, your continued guidance and support, and the many experiences that have come along with and from this journey.

My Parents – To you a very special thanks. You gave me roots and wings, guidance and never ending support in many ways and I could not have done this without you.

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The Lord – All great and wonderful gifts come from you. You placed this opportunity before me and guided me through it. You have blessed me and I am forever grateful. Thank you.

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1 Introduction/Literature Review

1.1 Context

Hydrological events have long been known to be responsible for the mass transport of sediment and other solids. Dickinson and Green (1988) found in eight agricultural streams, in southern Ontario, 90% of annual suspended solid load is delivered in less than 10% of the year which corresponds with the highest time of flood occurrence (Dickinson, 1972). In agricultural cropland areas, Dickinson and Green (1988) and Wall *et al.* (1982) found that the bulk of the sediment load comes from sheet and rill erosion, in response to surface soil conditions. In southern Ontario most of this load is less than 63 μm in diameter (Stone and Saunderson 1992) and thus travels suspended in the flow (wash load). Due to human activities around waterways, high sediment loads can cause depositional problems and even low sediment loads can provide transport for pollutants (Dickinson and Green, 1988). Thus, understanding sediment movement is important.

Sediment yield from a basin is a function of many factors including climate (precipitation amount and intensity), basin morphology, soil characteristics and land use (Dickinson *et al.*, 1975, Walling and Webb, 1987; Stone and Saunderson, 1996; Dickinson and Green, 1998; GRCA, 1993). In the 1970's the Pollution from Land Use Activities Reference Group (PLUARG) examined the relationships between agricultural land use and potential pollutant variables such as sediment yield, in southern Ontario. It was identified that sediment entering the Great Lakes was not in it self an issue but locally the loss of soil from agricultural land was of concern

(Dickinson *et al.*, 1975, Van Vliet *et al.*, 1976, Wall *et al.*, 1982). Although south-western Ontario streams do not exhibit extreme suspended sediment loads (Dickinson *et al.*, 1975), on an agricultural basis it was found that row crops have the potential to cause more than twice as much soil loss than rotational cropping or pasturing (Van Vliet *et al.*, 1976). Dickinson and Scott (1979) noted that agricultural activities adjacent to Ontario streams increased bank recession rates. These studies examined monthly and yearly trends of soil loss from agricultural lands, as well as, suspended sediment loads and transported nutrients such as phosphorus, potassium and nitrates, in southern Ontario rivers. However, little attention was given to the patterns and relationships between storm discharge and suspended solids load. As we are entering a period of an elevated frequency of extreme events (IPCC, 2001) understanding the relationship between stream flow and sediments loads becomes more important.

More recently, in southern Ontario, the Grand River Conservation Authority, in conjunction with other stakeholders, has attempted to understand the characteristics and processes at work in the Laurel Creek watershed. For the past decade the Laurel Creek Watershed Monitoring Program has conducted to monitor basin hydrology, water quality, aquatic habitat and terrestrial features (GRCA, 1993; City of Waterloo, 2001). The influences of land use change and storm events within the watershed on water quality have been more closely examined by Rusmir (2001). However, studies such as this and the monitoring program have only evaluated storm influences on discharge and suspended solids at a broad watershed scale. The goal of this research is to examine the relationships between these elements at a finer scale on Beaver Creek, an agricultural tributary to Laurel Creek. Detailed hydrologic, meteorological and suspended solid field measurements were made from July to November of 2005. The effects of both antecedent and event precipitation influences on discharge and sediment load characteristics were examined.

1.1.1 Temporal Scale and Dynamic Equilibrium

Over the past 30+ years, geomorphologists, hydrologists and earth scientists have debated the possibility of natural systems being in a state of equilibrium. The 9th and 12th Binghamton symposia gathered minds together to discuss the thresholds binding natural system equilibrium and the various states of which this may exist. Natural systems do not exist in a state of static equilibrium, whereby no change is observed (Thornes, 1982). This can only exist when all variables in the system are unchanging. Natural systems are too complex for complete stagnation. Steady state equilibrium is described as having a constant mean over a long time scale but where fluctuations due to interacting variables occur (Thornes, 1982). Thornes (1982, p. 327) defines dynamic equilibrium as having "balanced fluctuations about a constantly changing systems condition which has a trajectory of unrepeated 'average' states through time." This unrepeated average refers to a constant or definable change at a long temporal scale. More simply put dynamic equilibrium describes fluctuations about a changing condition whose long term trends may be linear or non-linear (Orme, 1982). Schumm (1980) also presents a state of dynamic metastable equilibrium. A stable state equilibrium may be interrupted resulting in a change in average or mean. These interruptions are related to exceeding of thresholds within the system, either by internal or external activities. Examination of the long term shows a stepped sequence of steady state equilibrium about one mean followed by changes to steady state equilibrium about another mean which is statistically significantly different from the preceding mean. As a whole this change through time fits the above definitions of dynamic equilibrium. Thus, it is referred to as dynamic metastable equilibrium. For the purposes of this study the terms equilibrium and dynamic equilibrium are references that can only be applied to long term studies. This is not to say that short term studies lack value. Schumm (1980, p. 473) discusses that if "research is to be of value to those who are managing and attempting to control various components of the landscape" understanding the processes and relationships between variables in the natural system, in the short term, is mandatory.

Long term studies 'average out' the finer processes and patterns seen in the short term (Schumm, 1980). Impacts of rapid change and development in a watershed, like that of the Laurel Creek watershed and Beaver Creek basin, can first be identified by significant deviation from observed short term patterns. In regards to equilibrium, the temporal scale of this study is short term. The discharges and suspended loads observed throughout this study also need to be placed in perspective. In southern Ontario agricultural basins, 50% of annual suspended load is delivered in the spring, with relatively little being transported in the summer, autumn and early winter (Dickinson *et al.*, 1975). However, development operations in southern Ontario occur almost exclusively in these months. Therefore, studies of the patterns and geomorphic activity of basins and creeks in this period are important for assessing and mitigating impact of land use operations.

This study examined 65% of the events occurring in this time period and covered a range from the lowest event discharges to event discharges 10% greater than the study period average. In relation to multi-year or decade records of flow this is small. However, since 70% of the events discharges in this period were below the average, the data set for this study is fitting for examination of short term patterns and geomorphic activity.

1.2 Sources of Water and Sediment

1.2.1 Overland Flow

It has been well documented that decreased vegetative cover density can result in increased overland flow (or runoff) and erosion (Garcia-Ruiz *et al.*, 1995; Wainwright, 1996). Overland flow tends to occur more over agricultural and urbanized land than forested or heavily vegetated land. Overland flow, a quick method of moving precipitation to the stream, often has erosive potential and carries fine sediments in suspension (Wall *et al.* 1982). Over time, continually reoccurring runoff events, coupled with rainfall splash (Beuselinck *et al.*, 2002) can result in a significant loss of soil at a site (Wotling and Bouvier; 2002).

"Overland flow occurs when the amount of rain reaching the surface is greater than the ability of that surface to absorb the water." (Briggs *et al.*, 1993, p. 244) The generation of overland flow is governed by two sets of factors: the permeability or infiltration capacity of the surface, as well as the intensity and duration of the storm (Briggs *et al.*, 1993). Two types of overland flow have been identified in the literature: Hortonian overland flow and saturation overland flow (Ritsema *et al.*, 1996).

Hortonian overland flow occurs when the precipitation rate exceeds the infiltration rate (Fetter, 2001). Therefore this type of runoff is produced mainly during very intense storms or over impermeable surfaces, such as pavement (Wong and Li, 1998) or un-vegetated slopes in arid and semi-arid regions (Kirkby and Chorley, 1967). Horton's model and analysis of overland flow is valid for areas in these regions but with the soil and vegetative cover normally found in humid-temperate climates, a saturation model would be more appropriate (Kirkby and Chorley, 1967).

As rain falls on a soil surface, water infiltrates downward through the soil pores. Movement of water laterally through the soil is slow and therefore the pores begin to fill with water. Once the soil is saturated, rain can no longer be absorbed and overland flow results. This is known as saturation overland flow. As can be imagined the antecedent soil moisture conditions play a large role in the quantity and timing of when saturation overland flow occurs (Koivusalo and Karvonen, 1995). Kirkby and Chorley (1967) noted that saturation overland flow is likely to occur much more locally than assumed by Horton and at lower rainfall intensities than are required by the Horton model. However, with almost any soil conditions, even in humid-temperate climates, there may be extremely heavy storms during which rainfall intensities exceed infiltration rate and Hortonian overland flow may occur. Thus, on most slopes both Hortonian and saturation overland flow occur, although with markedly different frequencies (Kirkby and Chorley, 1967).

1.2.1.1 Generation of Overland Flow

The generation of overland flow, in any environment, is governed by topology, surface roughness, soil infiltration characteristics, such as initial soil moisture conditions, pressure head and saturated hydraulic conductivity, as well as distribution, duration and intensity of rainfall (Haque, 2002). The percentage of rainfall volume that becomes runoff depends on these characteristics. Soil infiltration capacity and rates decrease as rainfall intensity and duration increase.

Antecedent Conditions

In environments where a permeable surface exists, the most important condition regulating the production of overland flow is antecedent soil moisture. Generally thick soil cover, like in humid vegetated regions, temporarily stores an appreciable amount of rainfall as soil moisture which plays a significant role in the basin hydrological cycle (Kirkby and Chorley, 1967). Koivusalo and Karvonen (1995) noted that even during the largest storms, generation of runoff was low when soil was dry and well cracked but, after groundwater levels reached the topsoil layers, surface runoff increased. In studies on overland flow and rill development, Govers and Loch (1993) and Bryan (1996) demonstrated the complex and highly significant effect of antecedent moisture conditions at the start of a rain storm on sediment transport rates. Therefore, along with vegetation density and slope, soil water content can be seen as one of the most important factors in the generation of overland flow (Seeger *et al.*, 2004).

1.2.1.2 Rainfall Splash and Soil Detachment

Studies have shown that one of the greatest influences on sediment yield from a slope results from raindrop impact, whereby grains are lifted from the surface by splash and carried down slope by overland flow (Ferro, 1998; Kinnell, 1988; Lasanta *et al.*, 2000). Ferro (1998) found that the maximum raindrop impact effect on a surface occurs for water depths of less than one drop diameter. Kinnell (1988) suggested a limiting flow depth of approximately three drop diameters after which rainfall impact becomes negligible. There is a double trend: On the one hand runoff will increase from the beginning to the end of the event as a consequence of the saturation of the soil. On the other hand, sediment yield will decrease from the beginning of the event because the impact of splash is higher in the first few minutes of the event when the flow depth is low (Lasanta *et al.*, 2000). Thus, there exists a balance between rainfall and overland flow where maximum sediment transport occurs.

1.2.1.3 Sediment Loading/Transport

The degree of suspended sediment loading or sediment concentration in runoff water depends on rainfall characteristics and antecedent soil moisture conditions (Lal, 1997). Ciampalini and Torri (1998) found that soil detachability by overland flow was caused by a combined effect between initial soil moisture conditions, soil surface characteristics, raindrop kinematic energy, and vegetation, or crop, type and cover.

1.2.2 Surficial Fine-Grained Laminae

Suspended solids in rural Ontario streams have been found to originate from croplands with sheet and rill erosion accounting for 70-100% of the annual load and the remaining 0-30% from other sources (Dickinson and Green, 1988). As a result, in the past fine-grained sediments mobilized from the channel bed were considered to be relatively insignificant to the total suspended load (Stichling, 1973; Dickinson and Green, 1988; Einstein 1950; Walling and Moorehead, 1987). However, more recent field observations in south-western Ontario have concluded that discrete surficial fine-grained sediment deposits, found on the river bed, represent a significant in-channel source of sediment (Droppo and Stone, 1994). This fine-grained sediment originates from out-of-channel sources and is small enough to stay in suspension but, Droppo and Stone (1994) noted that due to flocculation these particles settle to the bed during low flow conditions forming surficial fine-grained laminae (SFGL) up to 5 mm thick.

1.2.2.1 Sediment Loading/Transport

Droppo and Stone (1994) observed that SFGL has a highly porous, water saturated structure with low density. This high water content makes the sediment particles easily re-suspended by relatively small changes in bed shear stress. It was found that in a simplified rectangular channel 5m wide and 1 m deep that even cover as low as 30% of 2 mm SFGL can account for approximately 5 tonnes of fine-grained sediment per kilometre of channel. As a result, during high discharge flows SFGL may be a significant source of fine-grained suspended sediment (Droppo and Stone; 1994).

1.2.3 Agricultural Drainage Tiles

Subterranean drainage systems transport water and effluent from the surface and subsurface to channels. For decades, in southern Ontario cropland, it has been common practice to place such a drainage network below the organic horizons of the fields. These drainage tiles increase the lateral movement of water through the soil thus reducing the potential for field flooding. Studies in southern Ontario of tile discharge have found that water from subsurface drains may contribute up to 60% of the annual runoff and 18% of the annual suspended solid load (Culley and Phillips, 1983; Stone and Krishnappan; 2002).

1.3 Discharge and Total Suspended Solids in Streams

In natural systems, that a plot of concentration versus discharge (C-Q graphs) is often poorly correlated. With natural data there may be too much scatter to definitively conclude a rating line. This suggests that concentration is not a simple function of discharge magnitude. Langlois *et al.* (2005) noted that even if the suspended solid concentrations are grouped according to stage, a lack of linear relation can still persist. Rather a C-Q rating for an event should be thought of as a changing relation controlled by season, antecedent conditions, precipitation characteristics and available sediment source characteristics (Walling, 1974; Wood, 1977). These looped relationships are the result of changing sediment supply, whereby concentration at a given discharge on the rising limb of the hydrograph are not the same as those at the same discharge on the falling limb (C/Q ratio) (Arnborg *et al.*, 1967). Hysteresis is the lag of one of concentration or discharge to the other. Hysteresis loops in streams have been reported in many studies (Hall, 1967; Walling and Teed, 1971; Walling, 1974; Wood, 1977; Evans, 1999; Seeger *et al.*, 2004; Langlois *et al.*, 2005).

1.3.1 Quantitative Analysis of Hysteresis

Quantitative analysis of hysteresis in natural rivers has been proposed by recent literature. Langlois *et al.* (2005) have proposed an approach whereby the C-Q graphs are separated into rising limbs, peaks and falling limbs. An index of hysteresis is created through relationships between integrals for the various parts of the C-Q graphs. A restriction, as noted by the authors, is that an index value "could only be calculated when stream discharge increased by more than 30% during a[n]...event." (Langlois *et al.*, 2005) The explanation offered by the authors is that changes in discharge of less than 30% "are too small to move enough 'new' sediment either to create a distinctive hysteresis loops or to increase suspended sediment concentrations above the scattered portion of the calibration curve of the turbidimeter." (Langlois *et al.*, 2005, p. 3577) Another limitation of this analysis involves the correlation thresholds. The authors noted that the calculation of the hysteresis index could only be accurately executed if the regression coefficient of both the rising and falling limb curves could account for greater than 90% of their respective scatter (i.e. $R^2 > 0.90$) (Langlois *et al.*, 2005). Current methods of quantitative hysteretic analysis proposed in the literature have too narrow scopes to be applicable for use on the diverse precipitation events in a natural system.

1.3.2 Qualitative Analysis of Hysteresis

Qualitative analysis of hysteresis is a common technique involving graphical classification. Wood (1977) showed models for two C-Q relations. Williams (1989) identified four classifications of hysteretic loops (Figure 1.1) which have since gained wide acceptance. In creation of the classifications Williams (1998, p. 90) assumed the values of both C and Q in the C/Q ratios to be "within the rise and fall of these variables, rather than before or after the hydrologic event."

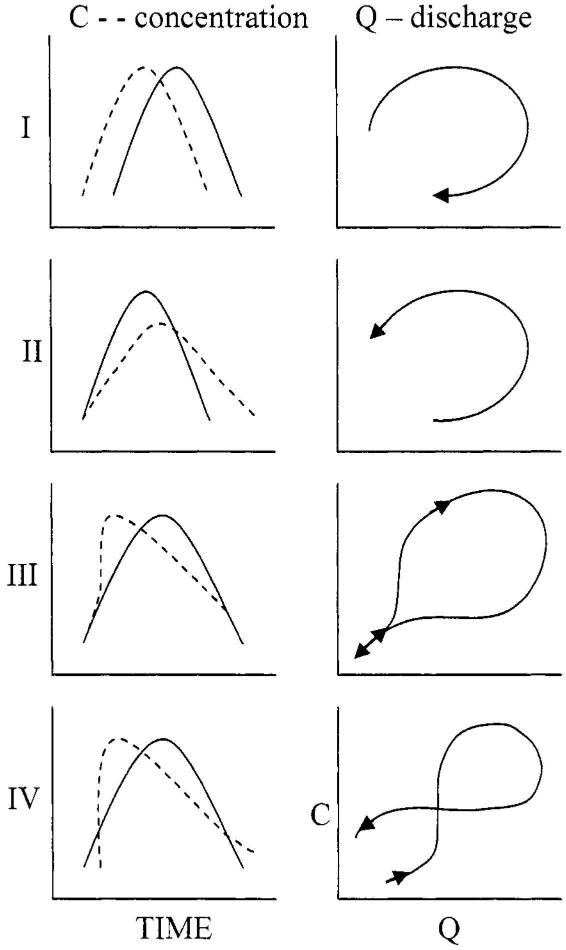


Figure 1.1: Types of hysteretic loops in suspended solids concentration/discharge relationships (based on Williams, 1989; modified from Knighton, 1998)

1.3.2.1 Class I: Clockwise Loop

If the sediment wave precedes the discharge wave a concentration value on the rising limb of the hydrograph will be greater than the concentration at the same discharge on the falling limb. Therefore, the ratio C/Q at any time on the rising limb of the Q-graph is larger than that for the same discharge on the falling limb (Figure 1.1I). If a C-Q graph is plotted sequentially a clockwise loop will form. This relationship is probably the most prevalent, particularly in small basins with small streams (Heidel, 1956; Knighton, 1998). Williams (1989) noted two subclasses that involve the orientation of the long axis of the loop, but this does not affect the overall loop type and therefore, will not be explored in detail here.

1.3.2.2 Class II: Counter-clockwise Loop

If the discharge wave precedes the sediment wave a concentration value on the rising limb of the hydrograph will be smaller than the concentration at the same discharge on the falling limb. Therefore, the C/Q ratio at any time on the rising limb of the Q-graph is smaller than that for the same discharge on the falling limb (Figure 1.1II). If a C-Q graph is plotted sequentially a counter-clockwise loop will form. This type of hysteretic relationship was first noted by Heidel (1956). Suspended load (or wash load) usually moves at the mean velocity of flow and can be overrun by an event 'flood wave' having higher velocity. In large basins the 'flood wave' (or discharge wave) may have time to overrun the suspended sediment wave and thus reaches the cross-section of measurement first (Knighton, 1998). Counter-clockwise loops may also be created by high soil erodibility associated with prolonged flooding or due to seasonal variations in water and sediment sources within a drainage basin.

Although occurring in nature, studies of Class II loops are not highly published in the literature.

1.3.2.3 Class III: Single Line plus Loop

It is possible that at one range of discharge the C-Q relationship conforms to that of a single valued rating line and then in a later range develops a looped relationship (Figure 1.1III). In this, the C/Q ratio on the rising limb of the Q-graph in one range of discharge is equal to that of the same discharge range on the falling limb. As the sequence moves into a higher discharge range the C/Q ratio follows one of the previously discussed relationships. Although conceivable, Williams (1998) was unable to find any published examples of a Class III relationship.

1.3.2.4 Class IV: Figure Eight

The figure eight may occur where one temporal graph begins to rise before the other, as seen in the other classes, but due to the rate of increase and/or timing, the initially lagging variable peaks first. Williams (1989, p. 102) noted in this situation "C/Q ratios are larger for one range of Q on the rising limb of the Q-graph and smaller for another range of Q on that limb, compared to the same values of Q on the falling limb." For example, in the temporal graph of Figure 1.1IV, the C/Q ratios in the lower discharge range of the rising limb are smaller than those at the same discharge on the falling limb. This results in a counter-clockwise loop. However, in the upper portion of the Q-graph the C/Q ratios on the rising limb are larger than those for the same discharge on the falling limb. This results in a clockwise loop. Therefore, the two sub-loops of a figure eight sequentially plot in different directions

(Williams, 1989). Although occurring in nature, studies of Class IV loops are not highly published in the literature.

1.4 Objectives

The overall goal of the research is to examine the effect of precipitation events and creek response to both discharge and total suspended solids. This will be done by making small scale measurements and observations on a second order, agricultural basin in southern Ontario. Relationships between total suspended solids concentration and discharge, as well as the influence of antecedent conditions on the event hydrograph, will be closely examined.

1.4.1 Specific Objectives

1. To determine the influence of antecedent conditions on hydrologic basin response to rain events in summer, autumn and early winter.
2. To determine if suspended solids patterns on Beaver Creek show hysteresis and if warranted, assess the appropriate hysteretic classification.
3. To determine the geomorphic state/activity of Beaver Creek during the study period.

2 Study Site

Beaver Creek is a perennial tributary to Laurel Creek which flows into the Grand River. The basin is located north west of the City of Waterloo, Ontario. The study site was located on Beaver Creek just south of Conservation Rd. (see Figure 2.1). At the study site Beaver Creek is a second order stream. The entire basin is 740.5 ha and the study site drains an area of 697.4 ha (GRCA, 1993). The land use of the basin is completely rural, comprised of approximately 50% mixed systems (crop cultivation and livestock rearing), 40% row crop and 10% early successional/idle agriculture, woodlot and wetland GRCA, 1993; Rusmir, 2001). During the study period, agricultural land next to the site consisted of approximately 20 rows of corn (*Zea mays*) around the outside and fallow in the centre of the fields. In the winter months the centre of the fields are cropped with winter wheat (*Triticum*). The riparian zones adjacent to the study site are between 4.5-23.5 m wide. Directly upstream of the study site the land use adjacent to the stream consists of fallow fields with similar width riparian zones. Farther up the basin Beaver Creek flows through agricultural land dominated by corn (*Zea mays*) and soybean (*Glycine max*) crops (Rusmir, 2001). The site receives groundwater from the north east and from recharge areas in the north west of the basin (GRCA, 1993). It is reported that the surrounding soil is classified as medium, mixed, moderately to strong calcareous loam and silt loam, of Luvisolic order, Travistock Series (Rusimr, 2001). Surface soils in this area were identified as containing 22% clay and 10.3% organic matter (Presant and Wicklund, 1971; Rusmir, 2001). The head waters of Beaver Creek are located at Paradise Lake. There are small weirs located at the mouth of Paradise Lake and the

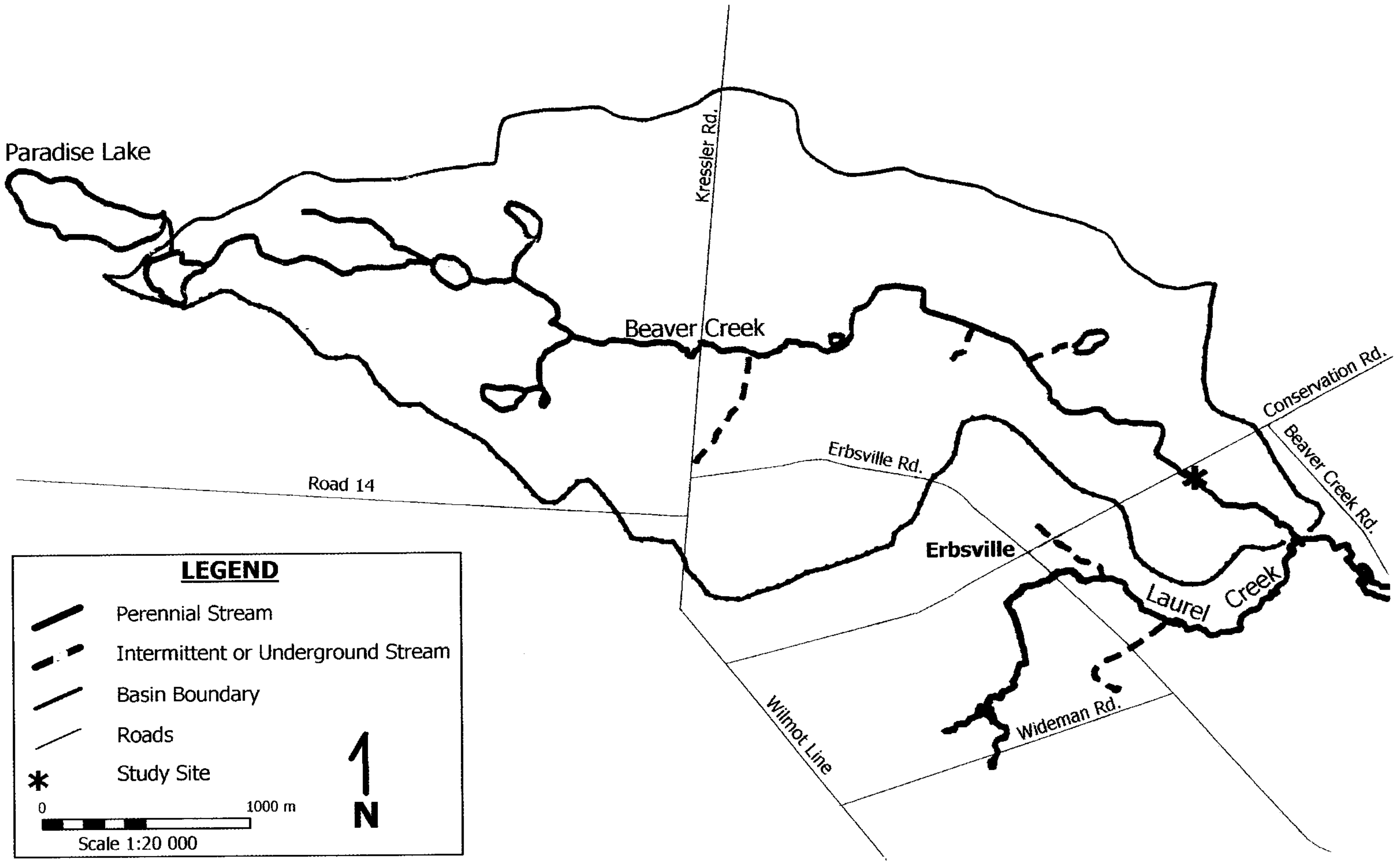


Figure 2.1: Beaver Creek basin (modified from GRCA, 1993)

reservoir down stream. Both these structures are stagnant and not altered or controlled. The degree of influence of reservoirs and such structures on suspended solids load depends on many factors including the location within the basin, trap efficiency of the reservoirs, and size and weight of the suspended load (Dickinson *et al.*, 1975). Due to the complexity of influence, lack of data regarding these reservoirs and their location near the upper most, head water, parts of the basin, no attempt was made to estimate their relative influence (Dickinson *et al.*, 1975).

The study reach this study began at the basin study cross section and extended approximately 120 m downstream (see Figure 2.2). The bank-full width of Beaver Creek, along this reach, ranged between 1.15-3.69 m (mean = 2.54 m). The mean discharge over the period of this study was 0.030 m^3/s. Ten cross sections were placed along this reach. Six cross sections within this reach were sampled (4, 5, 6, 7, 8, and 9). The locations of these cross sections are seen in Figure 2.2. Due to time constraints measurements were not conducted on the other four cross sections (1, 2, 3, and 10). These four specific cross sections were selected for exclusion due to their similarity in morphological characteristics (i.e. straight channel with a flat bed profile). The six sampled cross sections were chosen for measurements because of their varying morphological characteristics (i.e. meander, cut bank, point bar, pool, riffle, etc.):

1. Cross section 4 had thick riparian vegetation completely blanketing both banks. The right bank was fairly flat compared to the steep and tufted left bank. The overall profile of the bed was a gentle bowl with the greatest depth

Figure 2.2: Air photo of study reach showing locations of sampling sites and cross sections (base image from GRCA, 2005).

slightly off center, towards the left bank (see Figure 2.3). The bed material, uniform across, was soft with a top layer of very fine sediment.

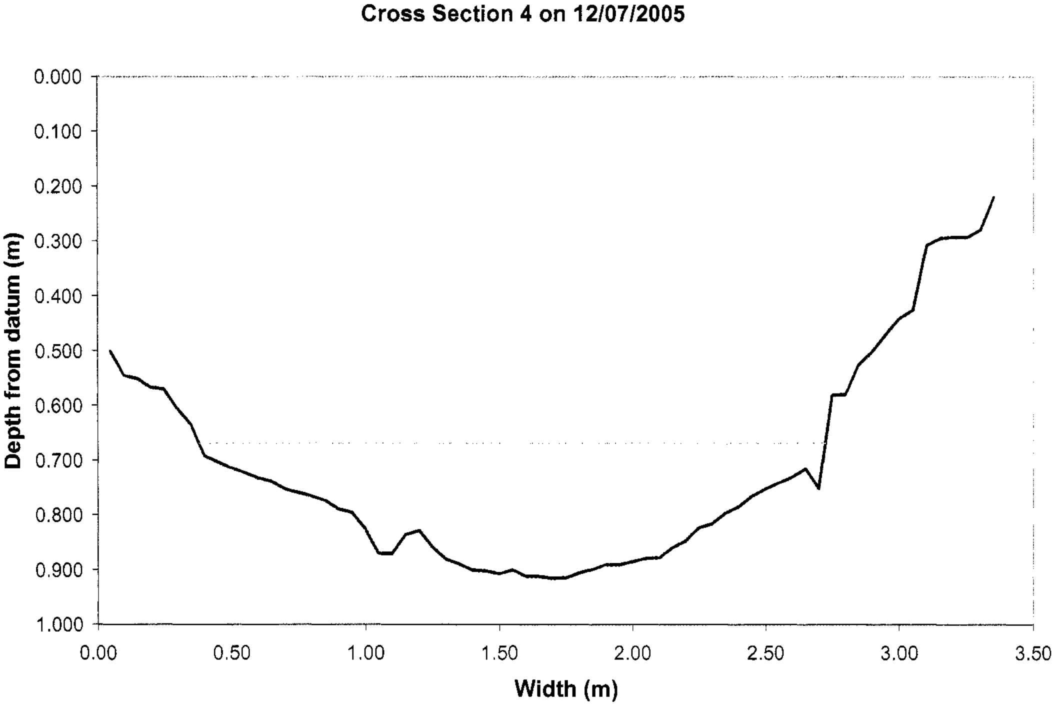


Figure 2.3: Cross section 4

2. Cross section 5 was situated downstream of cross section 4, directly over a tile drain (T1). The tile drain emerged from the left bank and constantly had a low flow of water emptying into the creek. During base flow the tile was approximately 0.15 m above the water surface. This resulted in a small scour hole beneath the tile opening. Around and in the scour hole was coarser grained sand, compared to the soft fine material that made up the rest of the cross sectional bed. On the bank, next to the tile a small gully had formed from the adjacent agricultural field from years of overland flow. The left bank was vegetated with mostly tall bushes and grasses. The right bank was more heavily vegetated with low shrubs and grasses. The right bank was steeper

than the left bank and slightly undercut by the flow. Woody debris secured to steel T-bar had been placed slightly up stream of the cross section, in the flow, years prior. The woody debris was approximately 0.50 m from the right bank and directed flow away from the bank, limiting the amount of undercutting. The overall bed profile was that of a meander with the main flow path being right of center. The greatest depth was not located directly next to the right bank due to slight diversion of flow by the woody debris (see Figure 2.4).

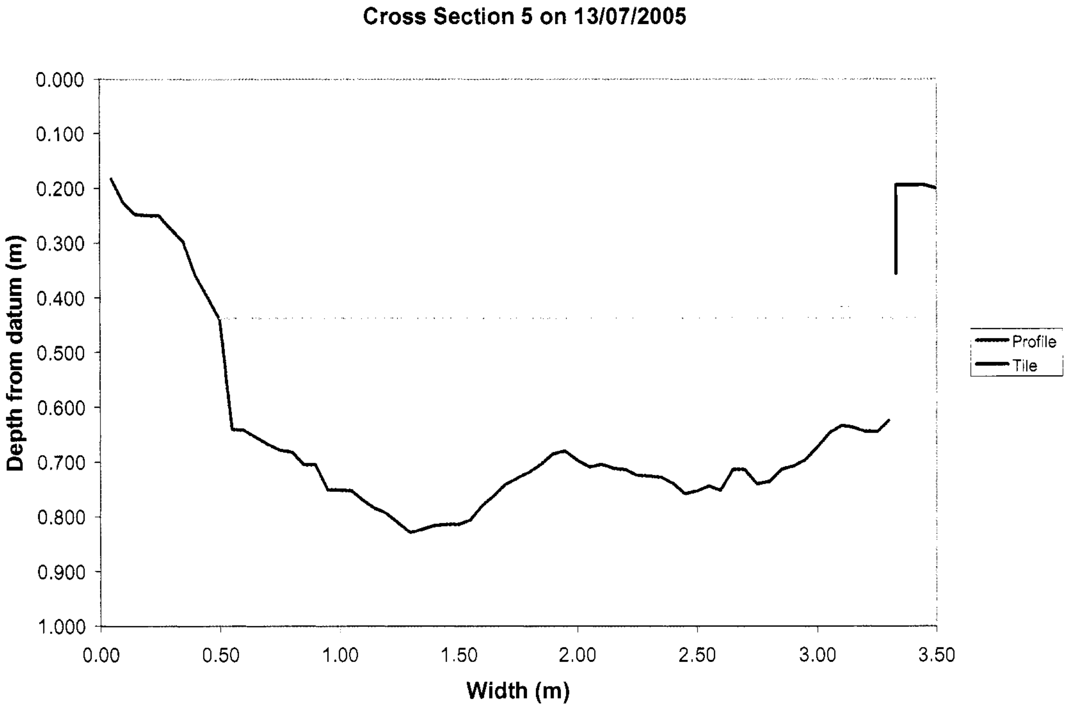


Figure 2.4: Cross section 5

3. Cross section 6 was about 4 m downstream of cross section 5. The left bank was vegetated with bushes and grasses. The right bank was vegetated with only grasses. The bed material was similar to that of cross section 4. This cross section was on a meander. The bed profile had the classic features, consisting of a deep pool adjacent to an undercut bank (right bank), with a

point bar on the opposing (left bank) (see Figure 2.5). Woody debris, like that seen at cross section 5, was stuck into some bushes just downstream of cross section 6. This debris was not permanently fixed and moved up and down with changes in water level. The debris was present at this site until the end of August, when a large storm dislodged it and carried it farther down stream.

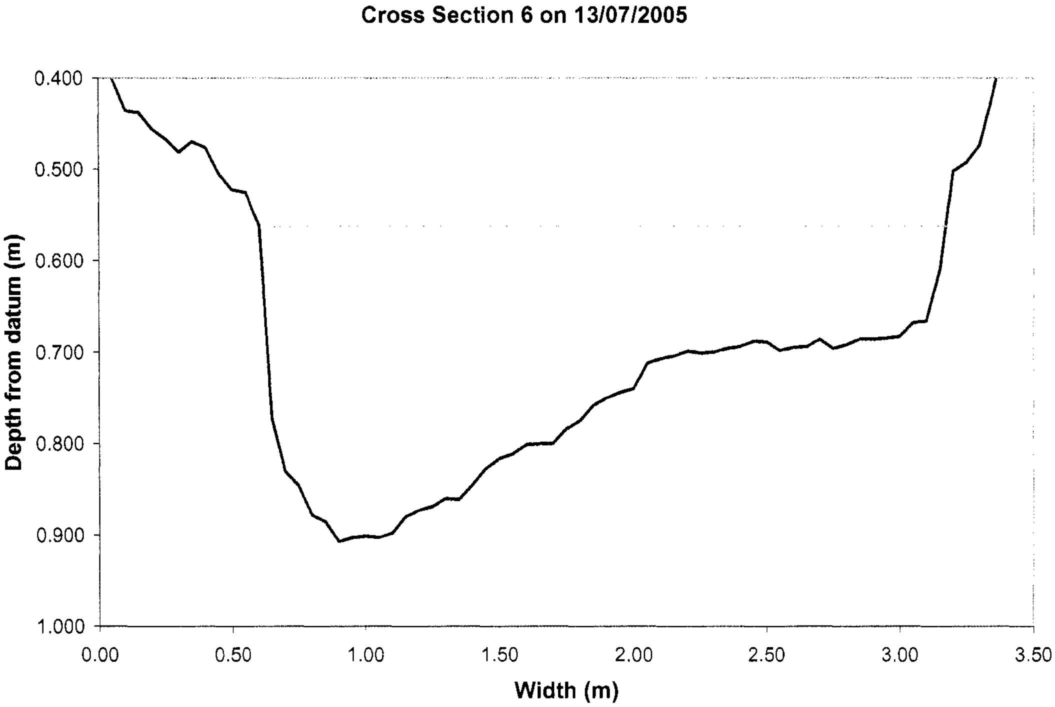


Figure 2.5: Cross section 6

4. Cross section 7 was downstream of cross section 6, located at the end of a riffle. The right bank was low with a gradual slope. The left bank was quite steep; almost vertical between the first and second bank. Both banks were vegetated by only grasses at the cross section but had bushes upstream and downstream. The main flow and greatest depth was located left of center (see Figure 2.6). The bed material in this area was sand, pebbles and small

cobbles. The bed material was finer towards the right bank becoming soft with a top layer of very fine sediment.

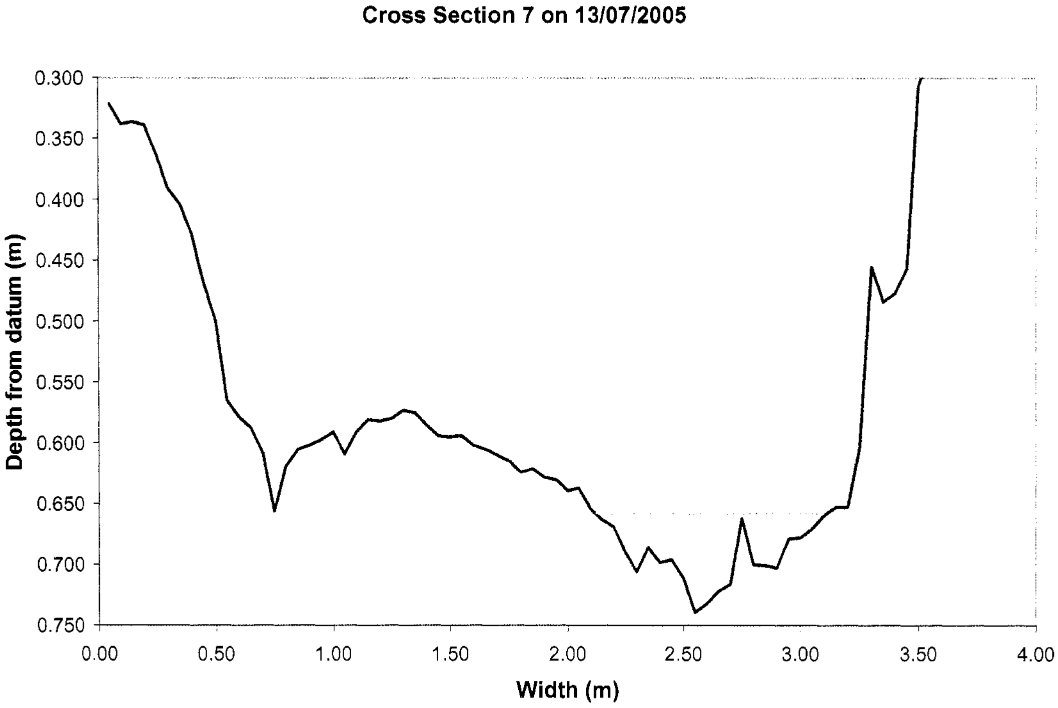


Figure 2.6: Cross section 7

5. Cross section 8 was downstream of cross section 7. The left bank had a gradual slope up from the creek to the agricultural field. The right bank was slightly steeper. Like cross section 7, both banks were vegetated by only grasses at the cross section but had bushes upstream and downstream. The riparian bushes upstream had grown into the creek and were above and below the water surface approximately 0.30-0.80 m from the right bank. The overall profile of the bed was a gentle bowl with the greatest depth at the center of the channel (see Figure 2.7). The bed material was uniform across and was soft with a top layer of very fine sediment. About 1 m up stream, set back

approximately 1.5 m from the water, was an old, collapsed ceramic tile drain that did not produce any water during base flow.

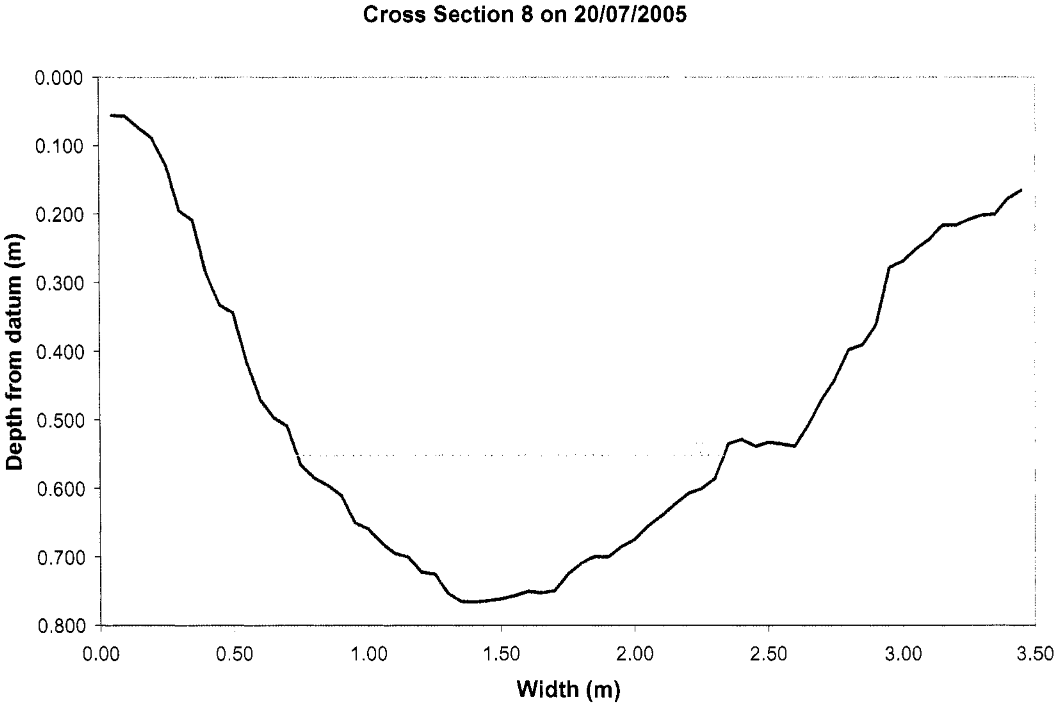


Figure 2.7: Cross section 8

6. Cross section 9 was downstream of cross section 8. It was the widest cross section. The right bank had a gradual slope and was vegetated by grasses and small trees. The left bank was vertical from the bed to the second bank; thus there was no first bank on the left side of the creek. On top of the second (upper) left bank was an apple tree and raspberry bushes. The flow was split into two channels. The main channel was located next to the steeper left cut-bank (see Figure 2.8). The bed material in the main channel consisted of sand, pebbles and small cobbles. The secondary channel was less deep and less wide, cutting into softer, partially vegetated bed material. The secondary

channel was the result of low flow incising into the point bar formed during storm flow.

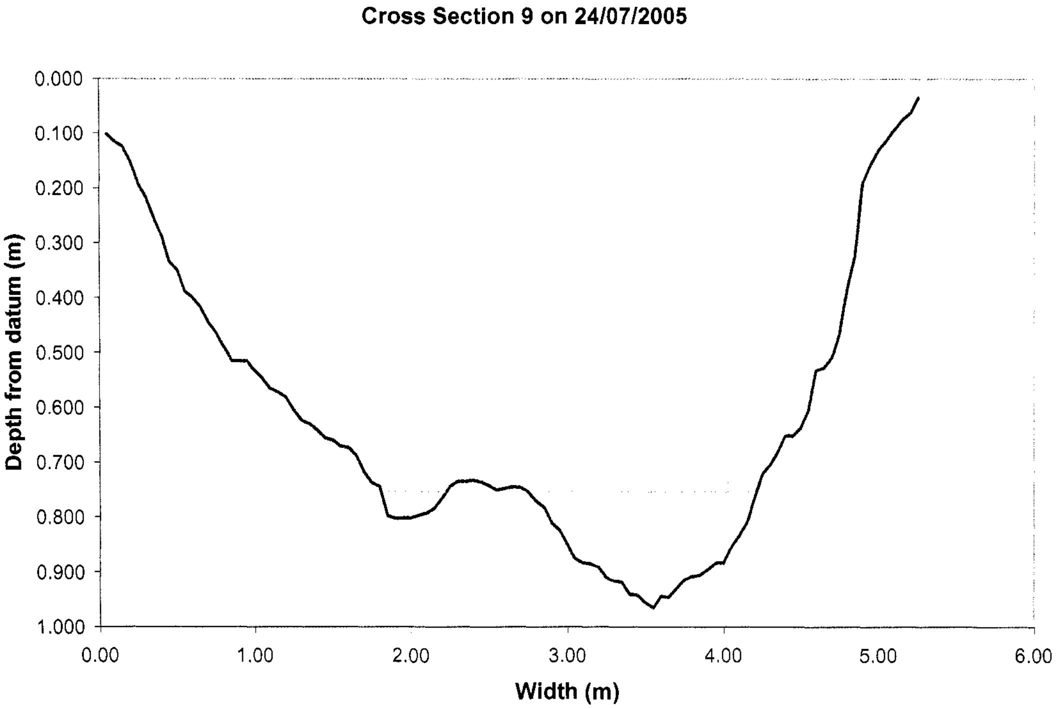


Figure 2.8: Cross section 9

3 Methodology

3.1 *Sampling*

3.1.1 Installation of Field Equipment

Installation of field equipment occurred between 26/06/2005 and 06/07/2005. TruTrack stage recorders were placed at the up-stream and down-stream ends of the study reach. To protect the stage recorder from debris, a 2 meter long, 0.038 m, PVC pipe was used as a guard. The lower 1 m of pipe was perforated using an electric drill. A 1.82 m steel T-bar was hammered into the creek bed in the center of the channel so that approximately 1.2 m remained above ground. The guard pipe was then inserted into the bed next to the T-bar so that approximately 1.85 m remained above ground. Using zipper ties the guard pipe was secured to the T-bar. Two holes were then drilled near the top of the guard pipe and a bolt was placed through them as a hanger for the stage recorder (see Figure 3.1). The actual depth of flow was measured by hand using an aluminium ruler for calibration of the stage recorder. The stage recorder was then lowered into the guard pipe, suspended from the hanger and programmed to take instantaneous water height measurements at ten minute intervals (accuracy: ±0.01 m; resolution: ±0.001 m). Stage recorders were installed at the up-stream and down-stream ends of the study reach and labelled SR1 and SR2, respectively.

A Teledyne ISCO automatic water sampler was placed at the up-stream end and down-stream ends of the study reach. A 1.828 m steel T-bar was hammered into the ground on top of the second bank. Approximately 1 m of T-bar was above ground. The ISCO was placed on the same bank and secured to the T-bar with braided cable wire and a weather resistant pad lock. The end of the ISCO hose was placed in the center of the main flow path. The end was positioned with the opening pointing up stream and was secured in place using zipper ties fastened to the stage recorder support T-bar (see Figure 3.1). The length of hose and the head of draw was measured and programmed into the ISCO. ISCO samplers were installed at the up-stream and down-stream ends of the study reach and labelled ISCO1 and ISCO2, respectively.

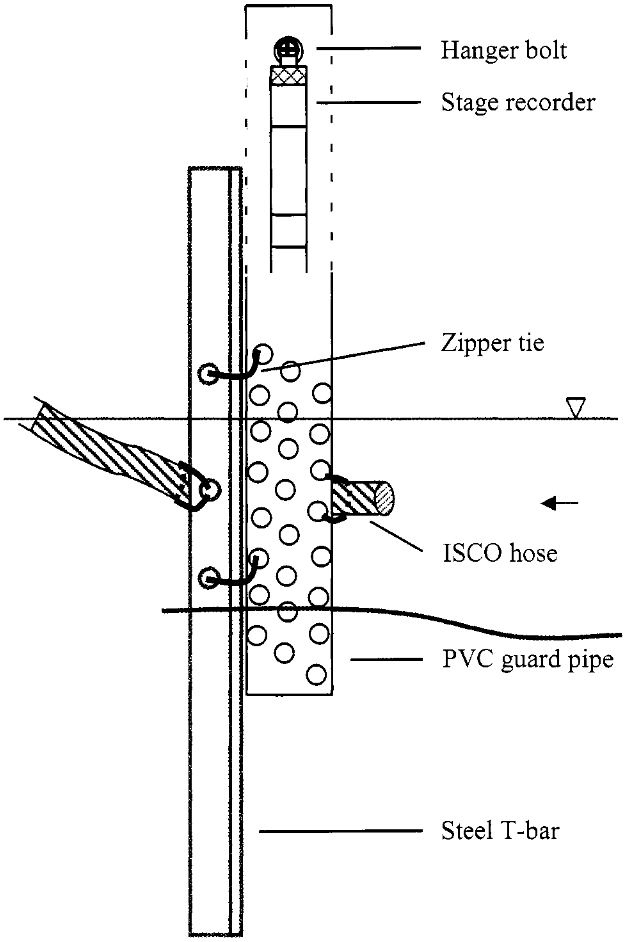


Figure 3.1: Stage recorder and ISCO hose set up (not to scale).

There were 10 cross sections in total. A 1.82 m steel T-bar was cut in half using an air powered cutting wheel. A hole was drilled near the top of each bar using an electric drill. The 0.91 m long bars were hammered vertically into the top of the first bank on opposite sides of the creek, so that a line drawn between them would be perpendicular to water flow. At each cross section wire was strung between the two bars using the drilled holes as attachment points. The wire was pulled tight and levelled using a laser level and adjusting the anchor depth into the ground. The wire was levelled a second time on a fine scale using a hanging bubble level. Using an aluminium ruler the wire was measured from the right bank and marked every 5 cm with indelible ink. Every meter and half meter was labelled using coloured electrical tape, white and blue, respectively.

A rain gauge was installed at the study site. The gauge consisted of a clear plastic cylinder, diameter of 0.126 m, fastened to a wooden stake using a wood screw. The gauge was hammered vertically into the top of the second left bank so that the top of the cylinder was approximately 1 m from the ground.

3.1.2 Suspended Solids Sampling

The ISCOs were used to sample the mass movement of suspended solids into and out of the study reach. When possible the ISCOs were set to take a few samples prior to a precipitation event. When this was not possible they were set to start shortly after precipitation had begun, which was usually before any rise in stage. The ISCOs were set for 40 minute intervals, except on dates 07/07/2005, 14/07/2005, 13/08/2005, 29/09/2005 and 05/11/2005 where the interval was 20, 10, 180, 60 and 90 minutes, respectively due to estimated duration of the event. Sample volumes ranged from 400-1000 mL. Twenty four samples per event were taken, with the exception of 29/09/2005 (fourteen samples) due to loss of power to the samplers.

3.1.3 Bed Measurements

Before and after each precipitation event creek bed profiles at cross sections 4 through 9 were measured. This was done by first checking the tension of the cross wires to insure there was no slack. If adjustment was required the left bank end was re-fastened to its original position on the anchor. An aluminium extension ladder with a rope tied to one end was lowered across the creek from the left bank. This was used as a bridge so that the bed was not disturbed. Using the suspended wire as a datum the bed profile was measured every 0.05 m, to the millimetre, with an aluminium meter stick. The depth from the datum was recorded into a field book and later transposed into Microsoft Excel for further data analysis. This was done at each of the 6 selected cross sections.

During base flow the creek bed was considered to be in a state of rest because there was minimal suspended sediment and bed flow of sediment was visually minimal. Therefore, often one set of cross sectional measurements was used as both post- and pre-measurement for the next precipitation event.

3.1.4 Lab Analysis

Prior to any sampling dry weights of bottles were measured and recorded. All suspended solids samples were analysed in the same way following standard procedure (Environment Canada's Analytical Methods Manual, 1979). Whatman GF/C glass-fibre filters of 4.25 cm diameter were placed in numbered aluminium trays and baked at 100 °C for 24 hours. The unused filters were then weighed to the microgram on a Mettler Toledo MX5 analytical balance. The balance directly output values to a Microsoft Excel spread sheet. All samples were weighed to the hundredth of a gram (±0.01 g) on a Mettler Toledo PB4002-S analytical balance. Each sample was then filtered using Millipore vacuum filtration equipment and an electric aspirator through one (or more as needed) of the prepped filters. Each bottle was rinsed using deionised water, double filtered through a Millipore filtration system, to ensure no sediment was left on the bottle walls. Sediment on the glass funnel was also rinsed using deionised water onto the filter. The used filters were placed back in their numbered trays and baked again at 100 °C for 24 hours. The used filters (with solids) were then weighed on the Mettler Toledo MX5 analytical balance.

3.1.5 Velocity Profiles

Cross sectional velocity profiles were measured at stages ranging from base flow to high storm flow. These were done at SR1 and SR2 using a Marsh-McBirney Electromagnetic Current Meter. The Marsh-McBirney was set to display the velocity for a given point, in m/s, as an average over 6 seconds. Using a field tape the total width of the flow was measured and recorded. Starting at the right bank the creek was divided into 20 cm panels. Using an aluminium meter stick, water depth was measured every 10 cm and recorded. At the center of each panel (i.e. 10, 30, 50, 70 cm, etc.) velocity was measured at 0.6 of the water depth and recorded. The above was done a total of six times; at different stages of flow at each stage recorder. Discussions of errors in sampling and analysis are presented in Appendix A.

3.2 Data Analysis

3.2.1 Precipitation

Precipitation data were obtained from the University of Waterloo Weather Station. The station coordinates are 43 28' 25.6" N and 80 33' 27.5"W and its elevation is 334.4 m. The station is approximately 3.30 Km south east of the study site. The weather station records data every 15 minutes. Precipitation measurements from a Texas Electronics (Model TE525) Tipping Bucket were downloaded from the weather station archives for the months of July through November. The date/time for each data point was reformatted to match that used by this study (dd/mm/yyyy hh:mm:ss). Five data points were missing between July through November 2005; 25/09/2005 21:00:00, 29/09/2005 21:15:00, 21/10/2005 22:00:00 and 01/11/2005 22:00:00. A total of 3139 cells were corrected from -9999 to 0 (zero); 1786 in August and 1353 in September. The total precipitation over each event was summed. The UW weather station recorded 0 mm of precipitation for events on dates 12/08/2005, 27/08/2005 and 14/09/2005. However, precipitation did occur on these dates in the study site basin. The noted differences in precipitation are likely due to the high spatial variability over short distances common with convective rain storms. The total amount of precipitation had been recorded from Environment Canada's daily internet weather broadcast for 14/09/2005 and was substituted in place of the weather station record. To fill in the data for the other two dates, precipitation values were extrapolated from the gauge at the study site. The recorded depths of water in the backup gauge were plotted against the weather station total precipitation, for six dates. A linear regression showed a high correlation; $R^2 = 0.96$. The regression equation was then applied to the data, from the gauge at the study site, for 12/08/2005 and 27/08/2005. The resulting precipitation values were then substituted in place of the weather station records.

On 14/07/2005 the weather station recorded 14.2 mm for one sampling interval. Observations did not comply with this record. As previously described, this noted difference in precipitation was likely due to the high spatial variability over short distances common with convective rain storms. Whereby, the precipitation recorded at the weather station, 3.30 Km south east of the basin, was not the same as that recorded at Beaver Creek basin. Therefore, the precipitation volume was extrapolated using a linear regression between event hydrograph amplitude and precipitation for the other sampled events in July.

Intensity of precipitation was calculated in two forms; maximum rainfall intensity and average rainfall intensity. Maximum rainfall intensity (mm/h), for each event, was calculated by dividing the maximum amount of precipitation recorded in a sampling period by the sampling interval (0.25 hours). Average rainfall intensity (mm/h), for a given event, was calculated by dividing the total precipitation recorded at the weather station by the duration of precipitation. Although the event duration was known, maximum rainfall intensity could not be calculated for the event on 14/07/2005 because only the total precipitation could be extrapolated, as described above. Also, no rainfall intensity could be calculated for the events on 12/08/2005, 27/08/2005 and 14/09/2005 because only 24 hour total precipitation values were available. Actual rainfall duration and individual sample values were not obtainable, as described above.

3.2.2 Discharge

Applying the velocity-area method, the recorded depths and velocities at SR1 and SR2 were used to determine discharge at a given time. Where the total width of flow did not equally divide by 20, the panel width, the width of the first and last were determined as follows:

$$EndPanelWidth = (TW - ((n-3)\cdot 0.1)) \div 2 . \qquad [1]$$

Where TW is the total width of flow and n is the number of depth measurements, including the two banks. The calculated discharge values were date and time correlated with stage. Six calculated discharge values and the time correlated stage values were plotted to produce Figure 3.2. A second order polynomial was found to give the best fit, $R^2 = 0.98$ and $R^2 = 0.99$, for SR1 and SR2 respectively. The regression equations were then applied to the stage values recorded by the stage recorders to produce a near continuous discharge record over the study period, at 10 minute intervals.

3.2.3 Total Suspended Solids

The lab analysis of suspended solids yielded gross weight (mg) and filter weight (mg). The filter weight was subtracted from the gross weight to determine the net weight of solids (mg) from a sample. Some samples required more than one filter. Where this occurred the net weights of all filters for a given sample were summed. Sample bottle IDs and dry bottle weights (g) were then input. The gross weight of the sample (g), solids plus bottle plus water, recorded prior to filtering, was entered into the spreadsheet with their appropriate bottle label. The net weight of the

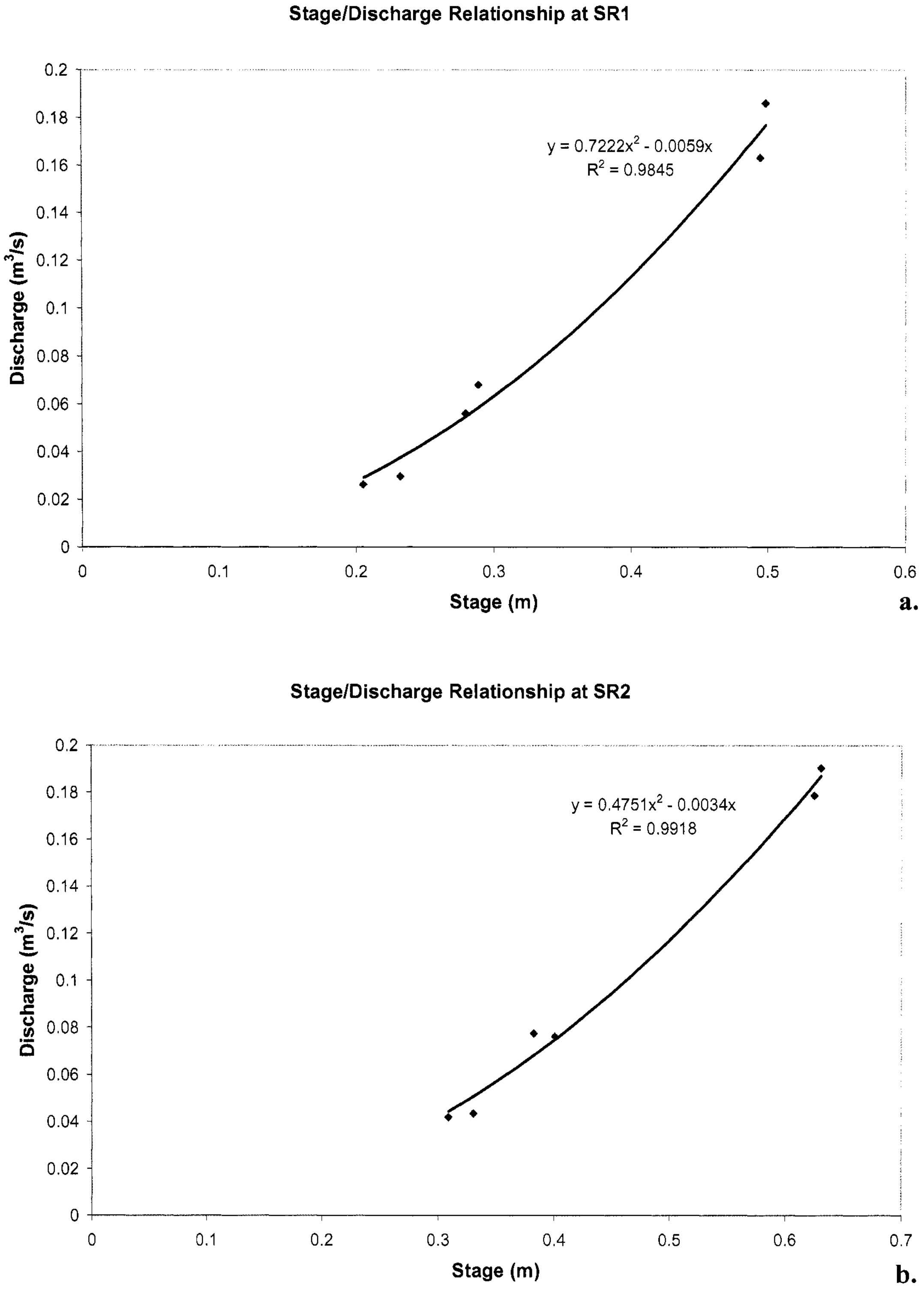


Figure 3.2: Stage/Discharge relationship for a. SR1, b. SR2.

sample (g) was determined by subtracting the dry bottle weight from the gross weight. The volume of water (L) in a sample was calculated using Equation 2:

$$V = (Mw - (Ms \div 1000)) \div 1000\,. \qquad [2]$$

Where V is the volume of water (L), Mw is the net weight of the water (g) and Ms is the net weight of the solids (mg). Since 1 mg is approximately equal to 1 mL the second division by 1000 is to convert mg to L. The concentration of total suspended solids [TSS] in a sample (mg/L) was then calculated by dividing the net weight of solids by the result of Equation 2. Each [TSS] value was given a sample ID by date/time reference (dd/mm/yyyy hh:mm:ss). The date/time ID was determined using the recorded ISCO start time and sampling interval. All total suspended solids analysis was done using Microsoft Excel.

3.2.4 A/P ratios and Antecedent Conditions (r)

Basin and creek response to each sampled event was examined using the event hydrograph. The hydrograph was used to calculate evaluative variables such as amplitude (A) of the event and antecedent conditions (r). To properly evaluate these variables seasonal base flow for each event was also determined. The lowest discharges for each of the five months of study were plotted against time and were overlain with an exponential regression (Figure 3.3). Using the regression equation and inputting the time of maximum event discharge, the seasonal base flow for each event was calculated. Amplitude (A) of the event was then calculated by subtracting the event seasonal base flow from event maximum discharge. Using the amplitude and precipitation (P) from the weather station, A/P ratios for each event were found. The A/P ratio solves for what the amplitude would be, under the given conditions, if 1

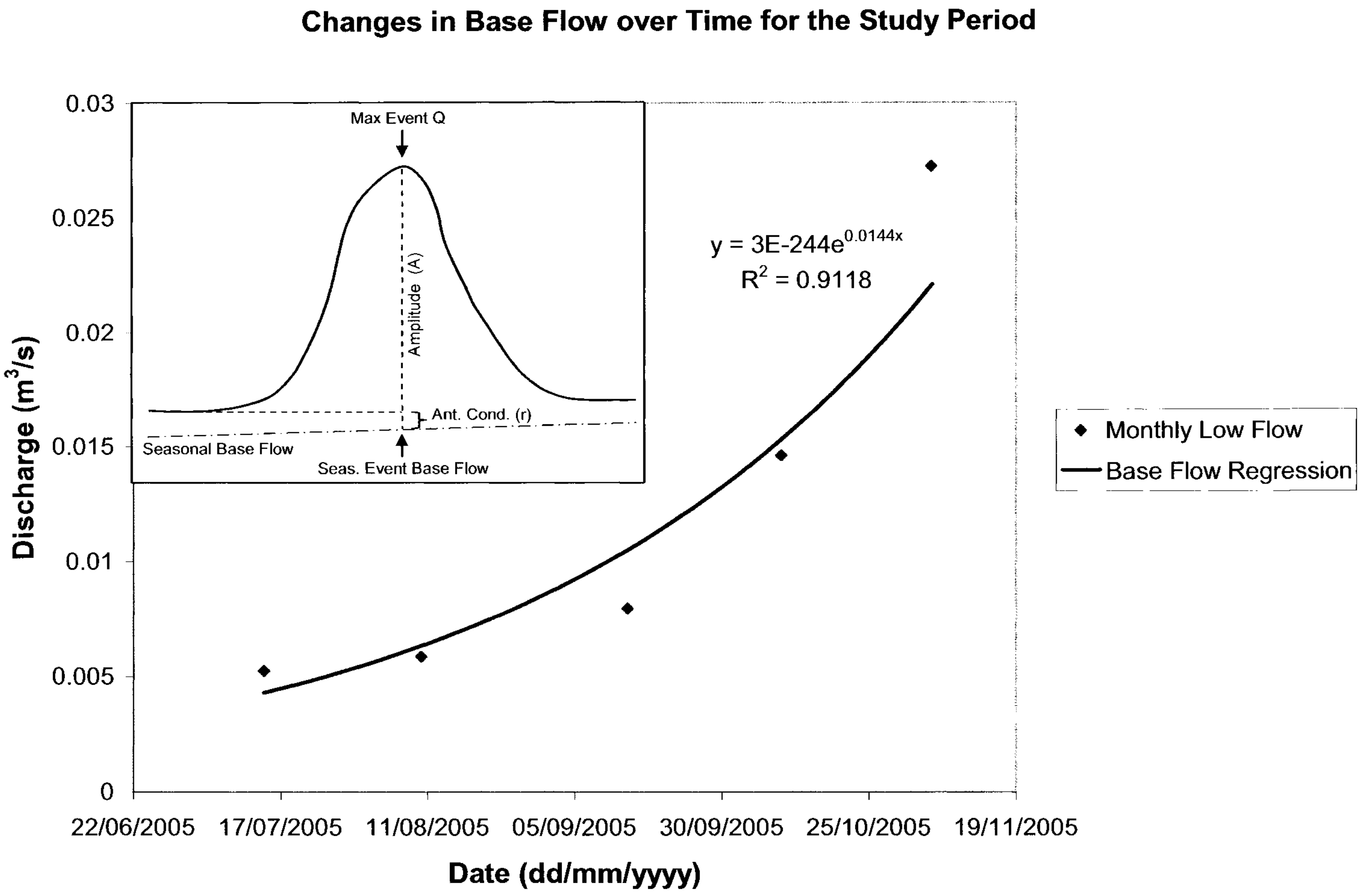


Figure 3.3: Calculated changes in base flow over time; Inset: diagram of hydrograph components used to calculate evaluative variables.

mm of precipitation was received by the basin. Quantification of antecedent conditions (r) was calculated by subtracting the base flow at the time of the hydrograph peak from the low flow prior to each storm hydrograph rising limb. Discussion and explanation of why these variables were evaluated in this way is presented in Chapter 4: Results and Discussion; Section 4.1.2: Antecedent Conditions and Event Hydrograph.

3.2.5 Hysteresis

The thirteen sampled storm events were qualitatively analysed for hysteresis following similar methodology to that of Williams (1989). Temporal graphs of discharge and suspended solids concentration were created on the same plot. The y-axes ranges were set so that the minimums or the start of both graphs align and the maximums or peaks of both graphs align.

Concentration versus discharge graphs were plotted for each of the sampled events. These were created setting both the x-axis and y-axis (discharge and total suspended solids concentration, respectively) to zero and the maximum to two major units greater than the largest data point, on a square (1:1) plot area.

3.2.6 Mass Flux of Total Suspended Solids

Using the sample IDs (dd/mm/yyyy hh:mm:ss) the total suspended solids concentrations were correlated with the continuous discharge record. Total mass of suspended solids was determined by dividing the sampling time into equally divided periods based on the sampling interval. The discharge between samples was averaged. The two concentration values, which determine the ends of each period, were also averaged. The mass of solids moving past the cross section for the time period was calculated as follows:

$$Mi = Qave \cdot [TSS]ave \cdot t \qquad [3]$$

Where Mi is the mass of suspended solids moving past the stage recorder at time interval i, Qave is the average discharge over time interval i, [TSS]ave is the average concentration over time interval i and t is the time interval in seconds. This was done for each sample time periods. These were summed to give the total mass of suspended solids moving past the stage recorded for the sampled period of an event. An example graph and calculation are shown in Figure 3.4. Discussions of errors in sampling and analysis are presented in Appendix A.

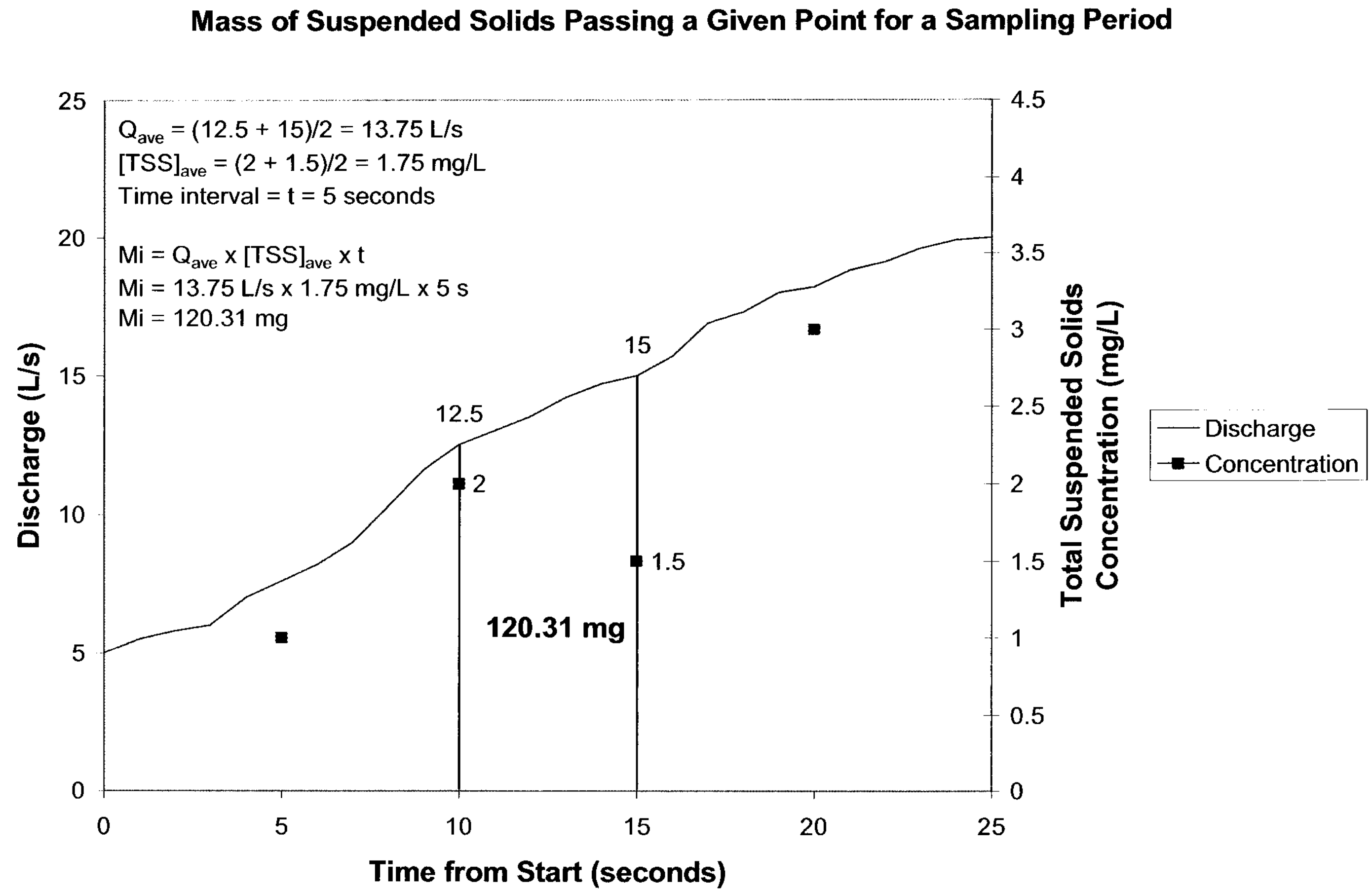


Figure 3.4: Example graph and calculation of mass suspended solids moving past a given point for a sampling interval. Note: data shown are fabricated and do not represent data used in this study.

4 Results and Discussion

4.1 Basin Study

4.1.1 Base Flow

Seasonal changes in base flow are important because they give insight to the hydrologic state of the basin and the nature or magnitude of the basin response to a given event. Data from this study demonstrate the influence of seasonal changes in base flow. Table 4.1 shows the numerical evaluative parameters for sampled events. The events on 24/07/2005 and 17/10/2005 have similar antecedent conditions ($r = 0.006$ and 0.006, respectively) and equal precipitation (5.8 mm). Knowing this it would be expected that the event hydrographs would show similar amplitudes. However, the October event has a higher base flow compared to the July event (0.020 and 0.010 m^3/s, respectively). As a result the amplitude of the October event (0.026 m^3/s) is nearly double the summer event (0.014 m^3/s). This demonstrates that seasonal changes in base flow can give insight to the hydrologic state of the basin and its response to precipitation.

The hydrograph of the 19 week study period shows an overall rise in base flow. Figure 4.1 shows three rises in base flow corresponding with changes in season; the beginning of September, the beginning of October and the beginning of November. From a hydrologic perspective, this study includes data from the seasons of summer, autumn and early winter. As can be seen in Figure 4.1 the autumn rise increases in rate mid-September. A quick increase in base flow was

Date	07/07/2005	14/07/2005	24/07/2005	26/07/2005	04/08/2005	10/08/2005	12/08/2005	27/08/2005	14/09/2005	22/09/2005	29/09/2005	17/10/2005	05/11/2005
Base Level (m^3/s)	0.007	0.006	0.010	0.011	0.008	0.007	0.009	0.011	0.009	0.011	0.020	0.020	0.035
Seas Evnt Base (m^3/s)	0.003	0.004	0.004	0.004	0.005	0.005	0.005	0.007	0.009	0.010	0.011	0.014	0.019
Max Q (m^3/s)	0.011	0.009	0.018	0.061	0.012	0.014	0.021	0.078	0.011	0.037	0.076	0.040	0.101
Amplitude (m^3/s)	0.008	0.005	0.014	0.057	0.007	0.009	0.016	0.071	0.002	0.027	0.065	0.026	0.082
Precipitation (mm)	1.2	2.3	5.8	10.8	3	7	9.5	17.2	7	11.8	14.2	5.8	11
A/P Ratio ($m^3/s/mm$)	0.007	0.002	0.002	0.005	0.002	0.001	0.002	0.004	0.000	0.002	0.005	0.005	0.007
Ante. Condi. (r)	0.004	0.002	0.006	0.006	0.003	0.001	0.003	0.005	0.000	0.002	0.009	0.006	0.016
Tot RainTime (h)	0.50	2.75	4.50	6.00	7.75	1.00	*	*	*	11.25	8.25	19.50	24.75
Ave Rain Int (mm/h)	2.4	0.8	1.3	1.8	0.4	7.0	*	*	*	1.0	1.7	0.3	0.4
Max Rain Int (mm/h)	2.4	*	6.4	24.0	4.8	20.8	*	*	*	5.6	13.6	6.4	8.0

Table 4.1: Numerical evaluative parameters for sampled events, * indicates unavailable data.

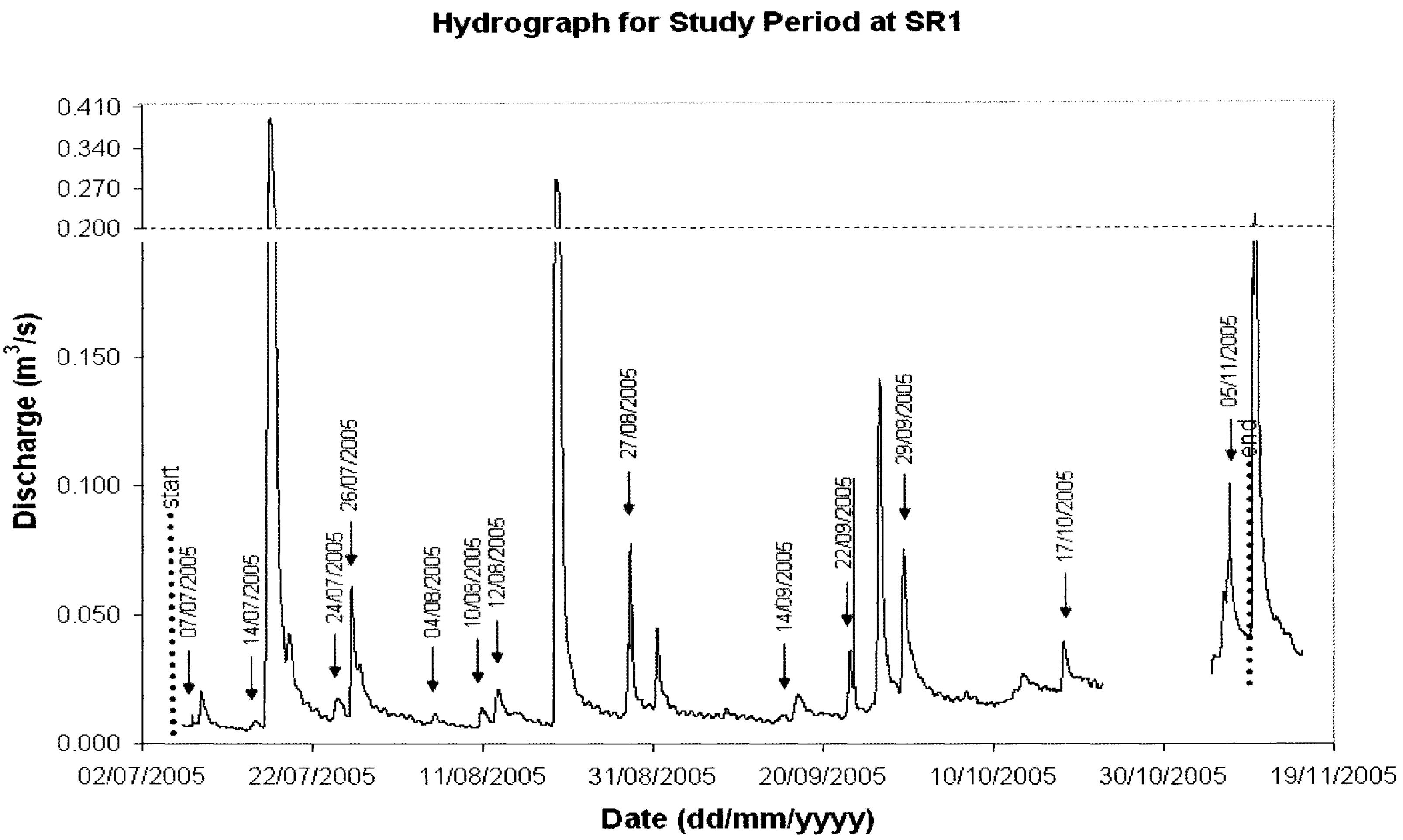


Figure 4.1: Hydrograph for study period at SR1. Arrows indicate sampled events

observed in the beginning of October. The rate of base flow rise also increases at this point. This is likely due to decreased storage potential as a result of decreased evapotranspiration by vegetation. The decreased evapotranspiration in the basin can be accounted for by the seasonal reduction in foliage and the harvest of crops. The beginning of November, the winter season, showed a similar increase in both base flow and the rate of rise (see Figure 4.1). This increase in base flow and rate of rise in the early winter is also likely related increased amounts of stored water and precipitation water reaching the creek; due to the minimal amount of evapotranspiration associated with few to no crops and plant hibernation.

4.1.2 Antecedent Conditions and Event Hydrograph

The amount of water held within the basin as soil moisture has a direct bearing on the basin response to a storm. For example, under wetter basin conditions, a storm of a given magnitude would be expected to produce a greater change in creek discharge, than under dryer conditions. This is because the basin has lower potential storage. Therefore, more precipitation would be moved to surface water causing a greater measurable change in creek flow. Examination of the response of Beaver Creek basin to precipitation events must include analysis of the influence antecedent conditions hold on basin and subsequently creek response.

Analysis of the influence of antecedent conditions requires more than simple comparison of maximum discharge. Also, seasonal influences must first be removed. As previously shown, base flow on Beaver Creek increased with changes in season, throughout the study period. Rises in base flow condition are assumed to equate to rises in basin water table. Rises in the water table decrease potential basin storage.

Since seasonal rises in water table decrease potential storage, for any given storm, amplitude cannot simply be the difference between maximum event discharge and minimum discharge prior to the start of the rising limb. Doing so would give bias to those events occurring in the autumn and winter seasons, as discussed in the previous section. Therefore, to examine the influence of antecedent conditions on the event hydrograph the amplitude must include these influences (r) but not those of seasonal base flow rise. For example, comparing the events on 10/08/2005 and 27/08/2005 it would not be correct to just compare maximum discharge values because they start at different base flows. By subtracting the seasonal base flow, which includes antecedent influences, from the maximum discharge for each event amplitude (A) is obtained (see Figure 3.3; Inset). However, it is not sufficient to simply examine amplitude when comparing event hydrographs because storms with greater precipitation volume will naturally be expected to produce greater change in stream flow. Therefore, the A/P ratio must be used. The A/P ratio solves for what the amplitude would be, under the given conditions, if 1 mm of precipitation was received by the basin.

Antecedent conditions influence basin and creek response to precipitation events. Figure 4.2 shows the relationship between antecedent conditions and A/P ratios for the thirteen sampled events. As can be seen A/P increases exponentially, at a decreasing rate, as r increases. The decreasing rate indicates a limit to which the A/P ratio will be affected by r. Increasing soil moisture will eventually lead to saturation (Knighton, 1998). At the point of complete soil saturation there can not be any further increase in soil moisture. At that limit, there is little to no storage effect

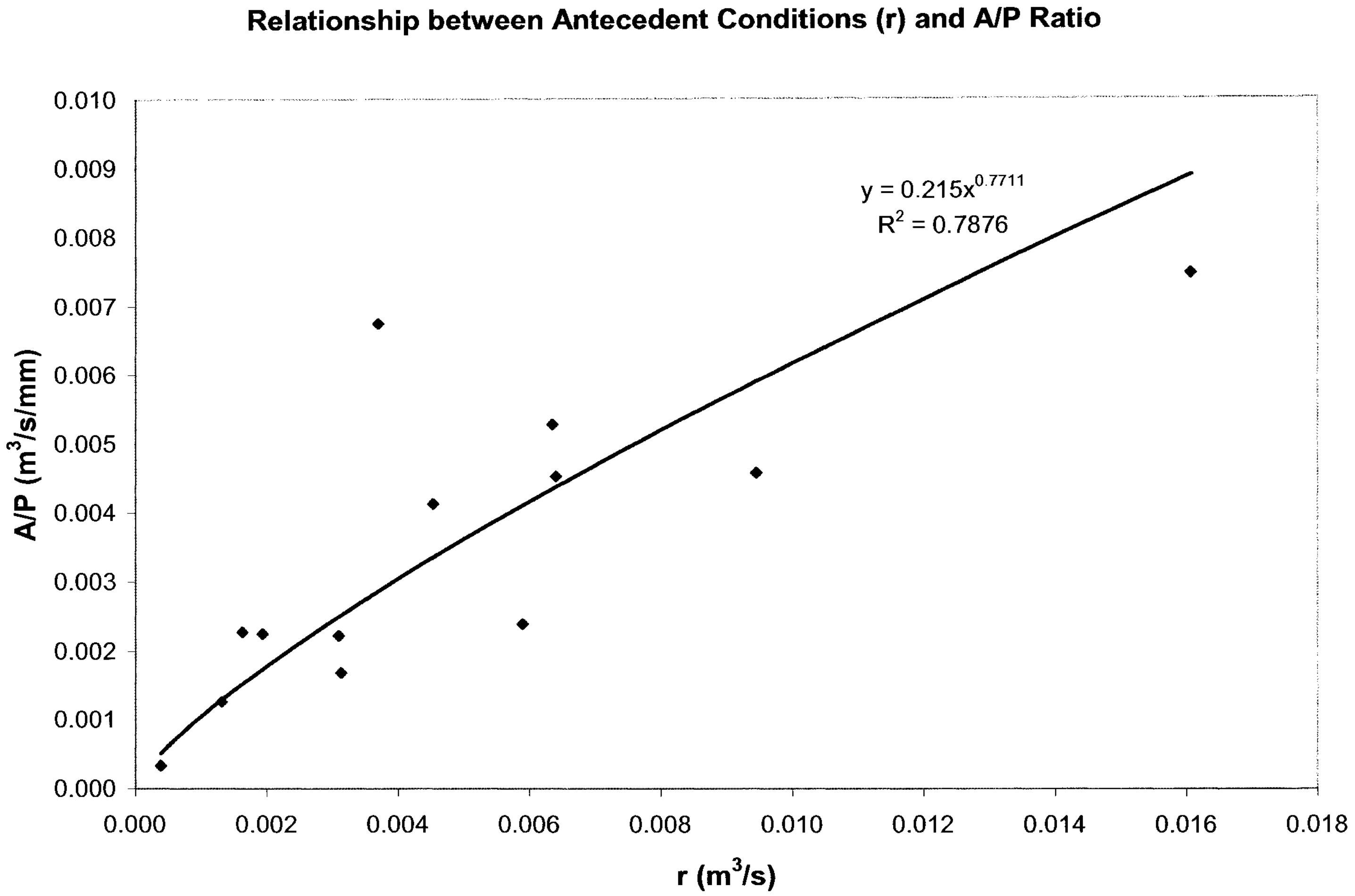


Figure 4.2: Relationship between antecedent conditions and A/P ratio.

and response will be more directly related to the volume and intensity of precipitation. However, during the summer, autumn and early winter, conditions are not near this complete basin saturation limit and therefore, antecedent conditions (r) potentially hold greater influence on basin response to storms. The positive trend seen in Figure 4.2 can be supported by comparison of sampled events on Beaver Creek. For example, the events on 26/07/2005 and 05/11/05 received similar precipitation amounts (10.8 mm and 11 mm, respectively). However, 05/11/2005 had a higher A/P. Recall that this greater A/P could not be due to higher seasonal flow since seasonal flows were removed from A. The higher A/P seen on 05/11/2005 could be due to precipitation characteristics. By examining r and both the maximum and average rainfall intensities for both events (26/07/2005: r = 0.006, Max Rain Int. = 24.0, Ave Rain Int. = 1.8; 05/11/2005: r = 0.016, Max Rain Int. = 8.0, Ave Rain Int. = 0.4), we see that antecedent conditions are more important than rainfall intensity.

A second comparison of results between events on 24/07/2005 and 10/08/2005 add further support to the positive trend seen in Figure 4.2. The event on 10/08/2005 had higher precipitation volume (7 mm) yet smaller event hydrograph amplitude (0.009 m^3/s) and therefore, smaller A/P ratio (0.001 $m^3/s/mm$) than that of 24/07/2005 (5.8 mm, 0.014 m^3/s, 0.002 $m^3/s/mm$, respectively). This is either due to event characteristics or antecedent conditions. Examining rainfall intensities we see that for the event on 10/08/2005 average and maximum rainfall intensities are greater than 5 times and greater than 3 times, respectively, those for the event on 24/07/2005 (see Table 4.1). Table 4.1 also displays that r is greater for 24/07/2005 than 10/08/2005 (0.006 m^3/s and 0.001 m^3/s, respectively). Therefore, antecedent conditions must hold a greater influence on creek response than that of rainfall intensity. This is supported by the findings of Meyles *et al.* (2003) which indicated that under dry soil moisture conditions storm discharge was relatively small compared to even moderate precipitation under wet soil conditions. Other studies have also found that basin response to storm events is directly related to antecedent soil moisture conditions, whereby wetter conditions produce greater flow (Koivusalo and Karvonen, 1995; Seeger *et al.*, 2004). Comparisons of other sampled events yield similar results, adding further support to the findings that antecedent conditions influence response to rain events in the Beaver Creek basin in summer, autumn and early winter.

The event on 07/07/2005 is a unique occurrence in the data set. Given the precipitation volume recorded at the weather station the amplitude is relatively high compared to the other events. As a result the A/P ratio is high. Even with the given r, A/P is high and appears far from the regression as an outlier on Figure 4.2 at the upper left of the plot area (r = 0.004 m^3/s, A/P = 0.007 $m^3/s/mm$).

4.1.3 Total Suspended Solids

The relationship between discharge and total suspended solids concentration was first analysed using a standard log-log ratings curve. It was found that discharge only accounted for 14% of the total variance of the concentration data (see Figure 4.3). The data were then separated by season. Although separation by season did show higher correlation coefficients than for the overall plot, they only accounted for 18%, 44% and 9% of the total variance of the concentration data from summer,

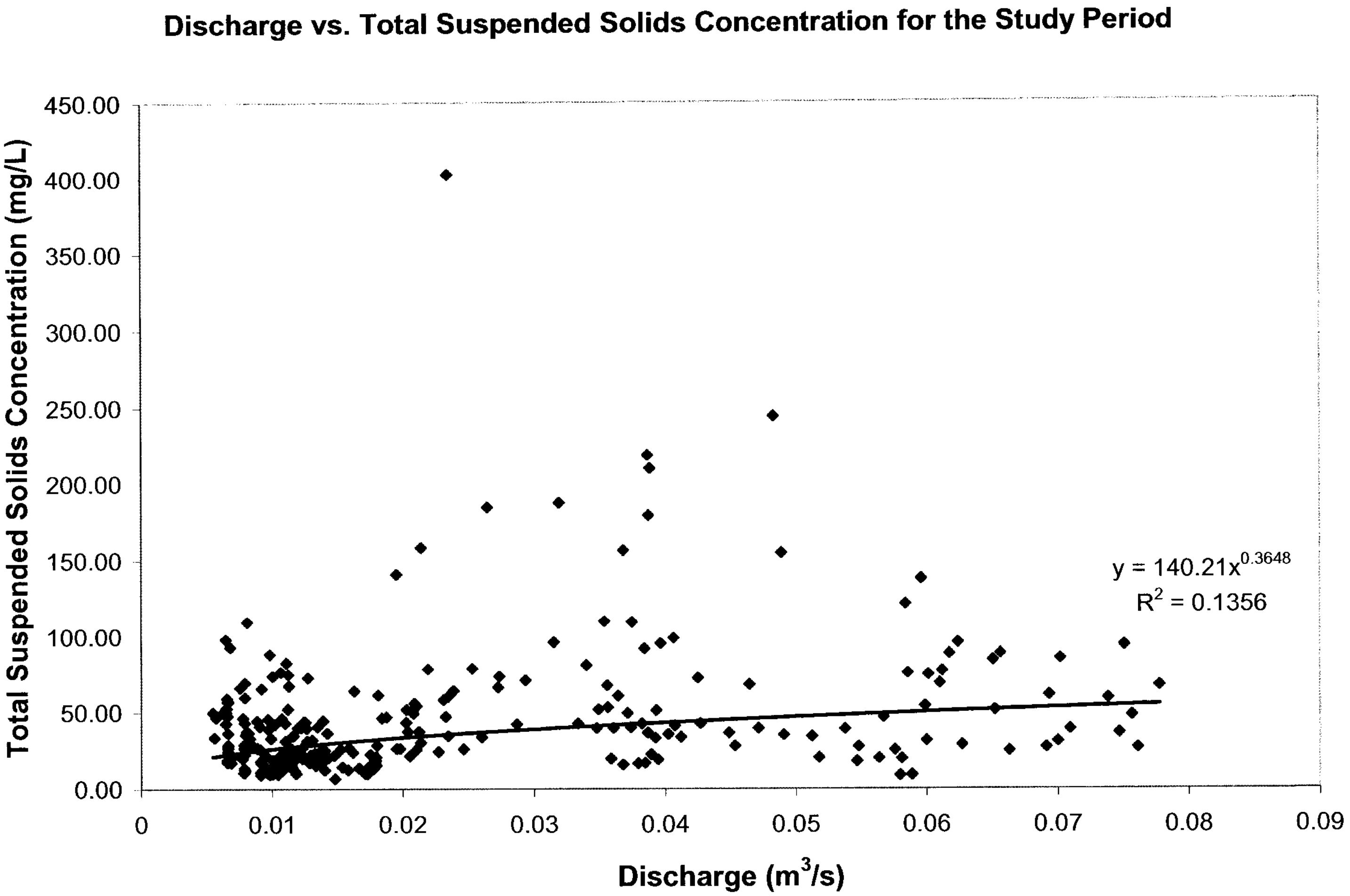


Figure 4.3: Discharge-total suspended solids concentration rating curve for the study period.

autumn and early winter, respectively (see Figure 4.4). Walling (1974) also did not find strong correlation using ratings curves separated by season.

Almost all events showed a rapid increase in total suspended solids concentration at the start of the rising limb of the hydrograph; after a relatively small rise in discharge. Concentration then began to drop prior to the peak in discharge. This suggests a lagged relationship between discharge and suspended solids concentration.

The individual events on Beaver Creek were examined for hysteretic relationships between total suspended solids concentration and discharge. Quantitative hysteretic evaluation, following the methods of Langlois *et al.* (2005), proved to be not possible for the events sampled on Beaver Creek. The correlation values between total suspended solids concentration and discharge were below the $R^2 = 0.90$ threshold on both the rising and falling limbs of the event C-Q graphs. The highest correlation found on a rising limb was $R^2 = 0.66$ and on a falling limb was $R^2 = 0.82$ (see Figure 4.5). This is due to natural scatter. The inability to quantitatively evaluate the hysteresis of the events could more generally be due to the lack of samples on both the rising and falling limbs. Simply put, for quantitative hysteretic evaluation of a natural system, a greater number of total suspended solids samples (lower frequency between samples) are required over the entire event hydrograph. As a result hysteresis was evaluated qualitatively, for the events sampled in this study.

The classification of Williams (1989) is widely used in the literature for qualitative hysteretic analysis and thus was used here. In the graphical analysis procedure Williams (1989) made no mention of axis formatting. Are both C- and Q-

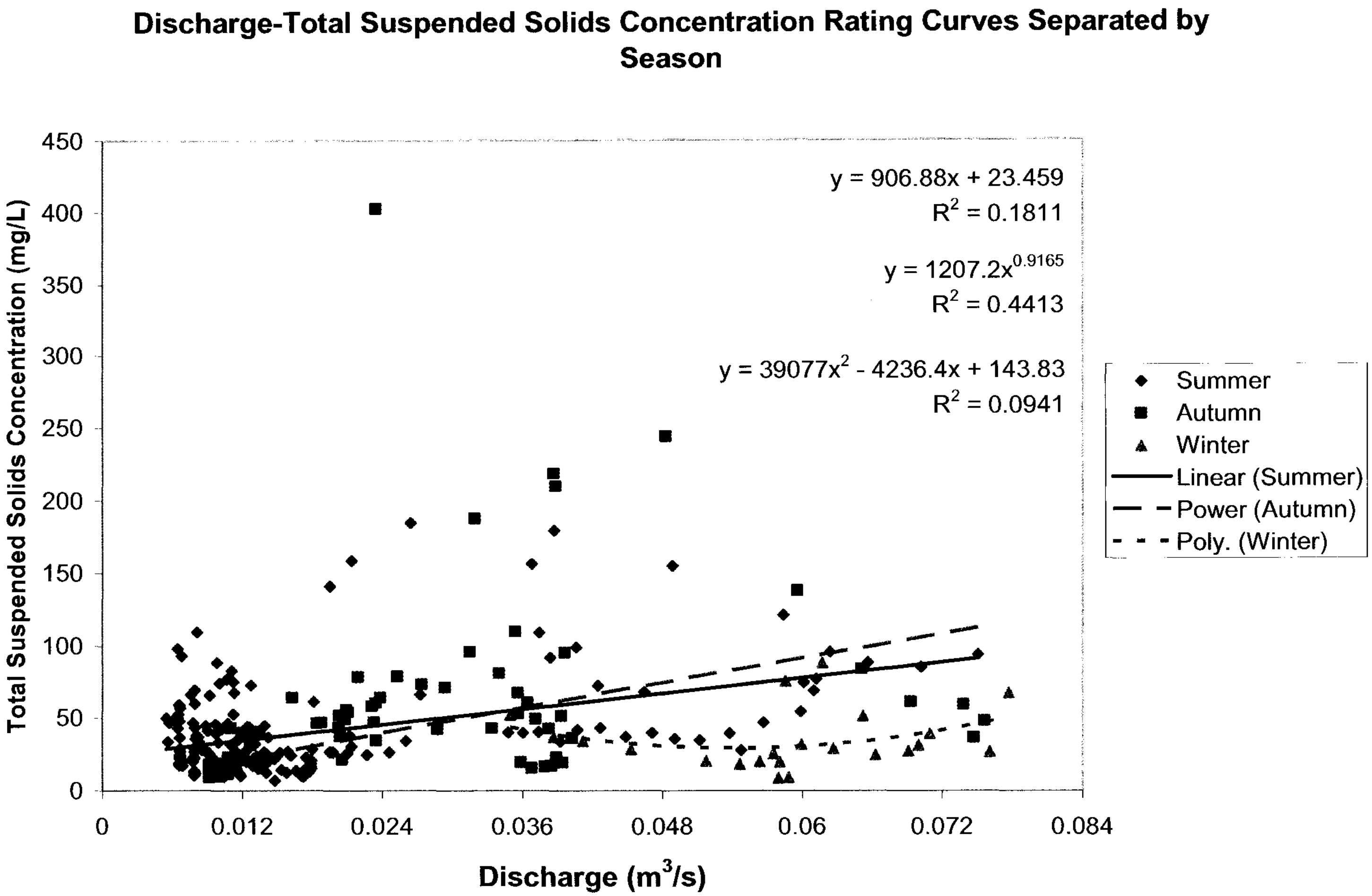


Figure 4.4: Discharge-total suspended solids concentration rating curves separated by season.

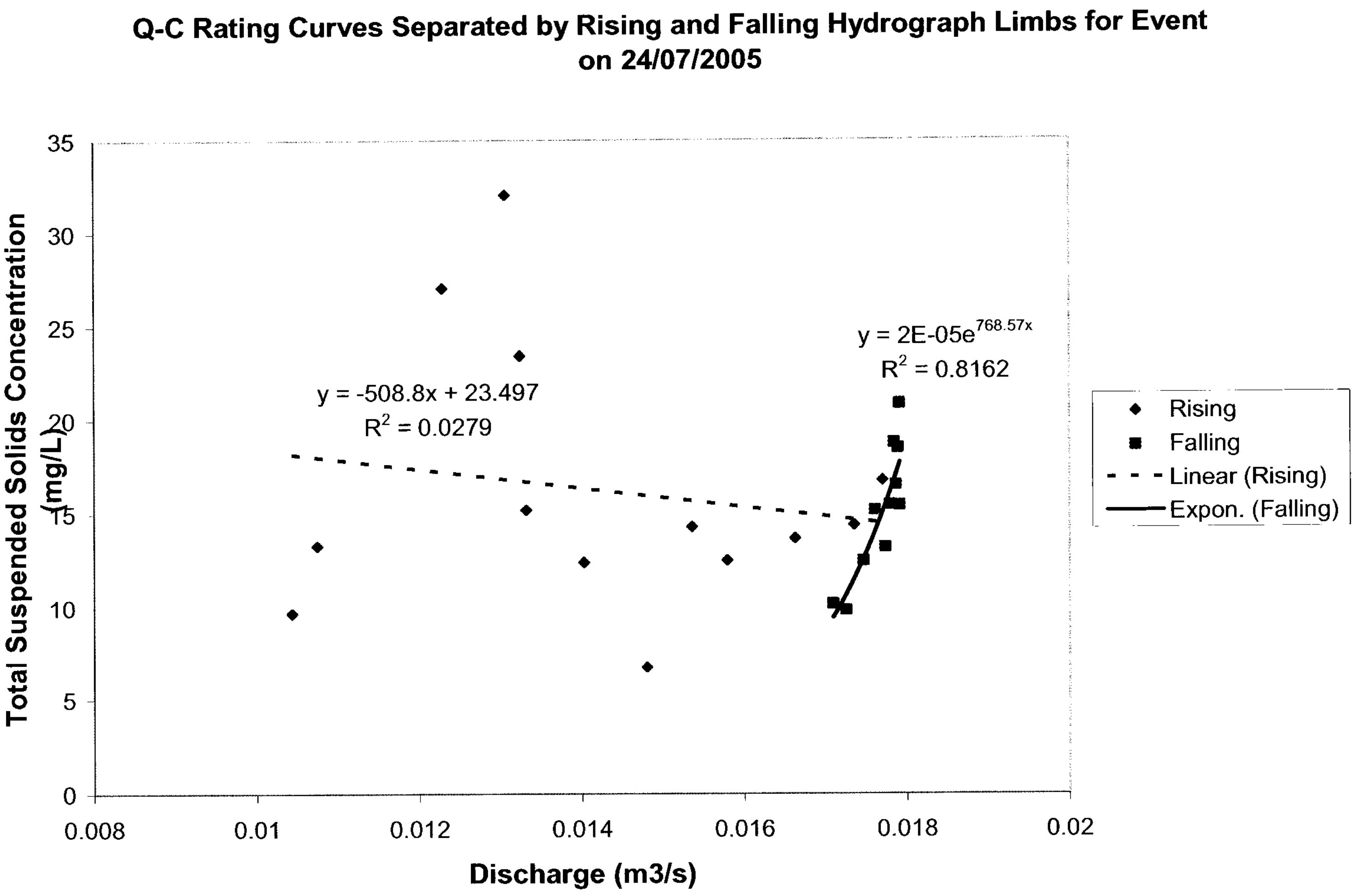


Figure 4.5: An example of Q-C rating curves separated by rising and falling hydrograph limbs for quantitative analysis of hysteresis.

graphs supposed to have a minimum of zero on the y-axis? If this is the case then the C-graph and Q-graph often are not in the same part of the plot area. The same is true when the y-axis is logged, according to Williams' (1989) methods. Alignment of the two temporal graphs is important for visual observation, even though the magnitude of the peaks hold little bearing on the analysis. Spread, the width of the temporal graph curve and skewness, the asymmetry of the curves, are identified by Williams (1989) as being more important to the classification of hysteretic events. This is because these factors influence the C/Q ratios and the graphical observation of differences in the C/Q ratio over the period of an event, as can be seen in Figure 1.1. Therefore, for the events examined in this study, the y-axes ranges were set so that the minimums or the start of both graphs appear approximately together and the maximums or peaks of both graphs appear approximately together.

In order to use a log graph for the C-Q graph both sets of data must cover at least two orders of magnitude. If they do not the plot is highly compacted and visual observation is not possible. By setting both the x-axis and y-axis (discharge and total suspended solids concentration, respectively) to zero and the maximum to one major unit higher than the closest in the data, on a square plot area, the desired effect, as shown by Williams (1989), is achieved. It is important to have a 1:1 plot area to eliminate visual obscurity. The hysteretic analyses of the events sampled in this study are summarized in Table 4.2. Four of the events are presented in detail as examples of the analysis and results.

The C-Q graph for the event on 07/07/2005 show a strong Class I hysteretic loop (see Figure 4.6a.ii.). The two temporal graphs have similar spread but the C-

Event Date	**Classification**	**Strength**	**Notes**
07/07/2005	Class I	Very good	
14/07/2005	-	Very poor	• No sediment samples past Max Q • Sediment data offers no trend for extension
24/07/2005	Class I	Good	• Extension of C_f trend would extend Class I loop
26/07/2005	Class I	Good	
04/08/2005	-	Poor	• No sediment samples past Max Q • Initial C-graph spike is completed prior to Q_r
10/08/2005	Class I	Good	• Only one data point for C_r • High amount of scatter on C-graph after Max Q
12/08/2005	Class I	Very Good	• Scatter on C_f but overall strong Class I relationship
27/08/2005	-	Very poor	• No sediment samples past Max Q • Sediment data offers no trend for extension
14/09/2005	-	Very poor	• No sediment samples past Max Q • Sediment data offers no trend for extension • C-graph appears to still be rising
22/09/2005	Class I	Poor	• One sediment sample past Max Q • Sediment data offers little trend for extension • Begins to loop but not enough to be definitive
29/09/2005	Class I	Moderate	• One sediment sample past Max Q • Sediment data could be extended to yield a stronger result
17/10/2005	Class I	Poor	• No sediment past Max Q • Trend suggest Class I
05/11/2005	Class I	Moderate	• C-graph decreases initially with increase in Q • C-graph still peaks prior Q-graph • High amount of scatter

Table 4.2: Summary of hysteretic analysis for sampled storms

graph peaks before the Q-graph (event hydrograph) (Figure 4.6a.i.). The lag, or space between the peaks, adds and manipulates the loop shape. Williams (1989) discussed that when the two temporal graphs have the same graphical characteristics the loop will be oriented at 45° to the horizontal. When the lag is large the width of the loop

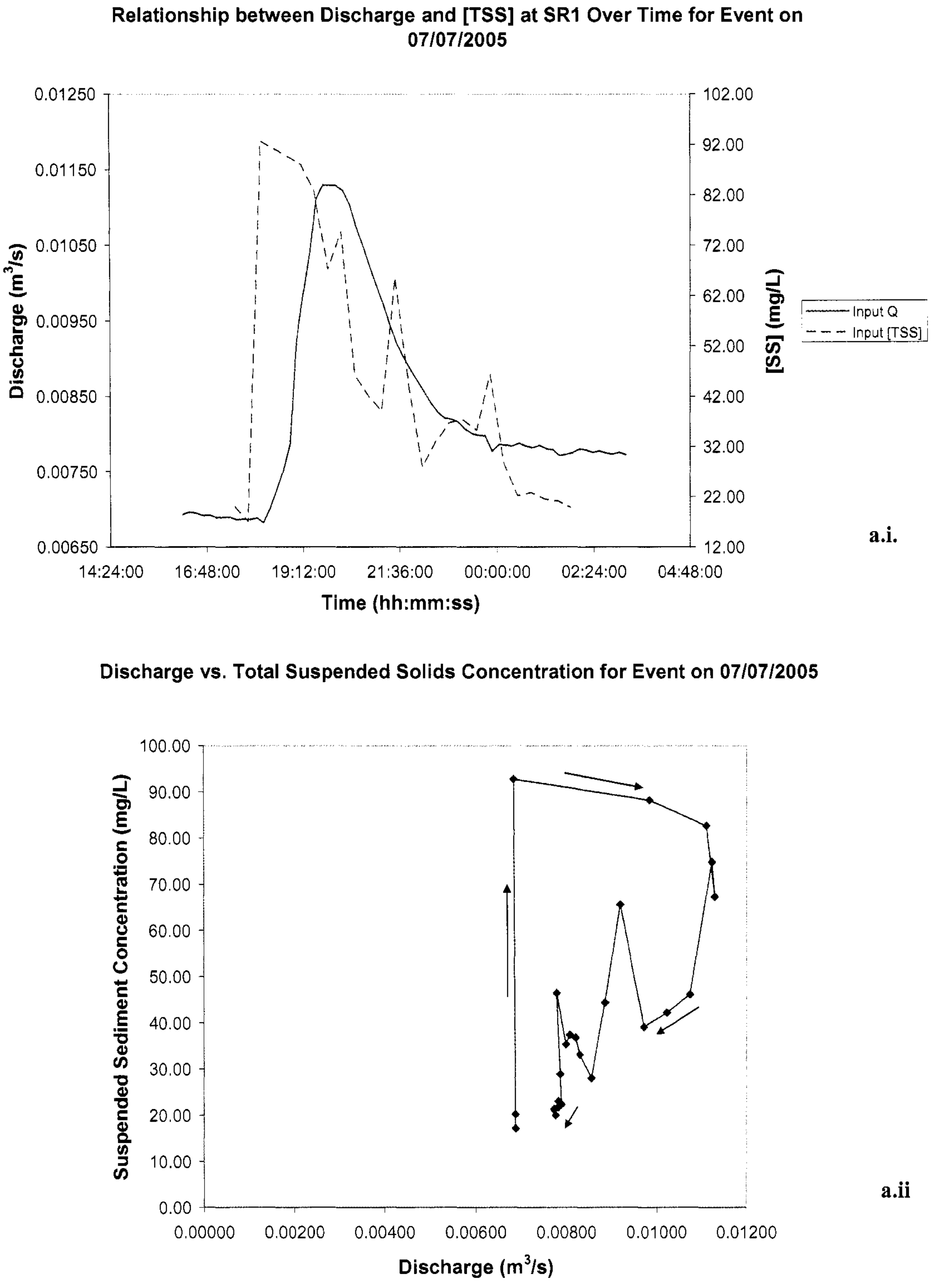
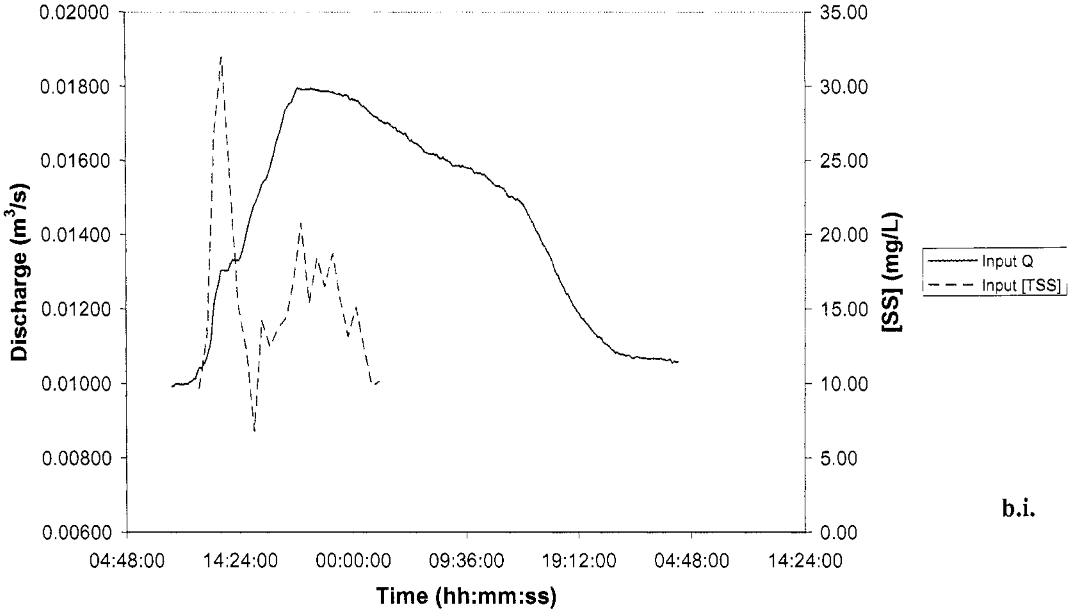


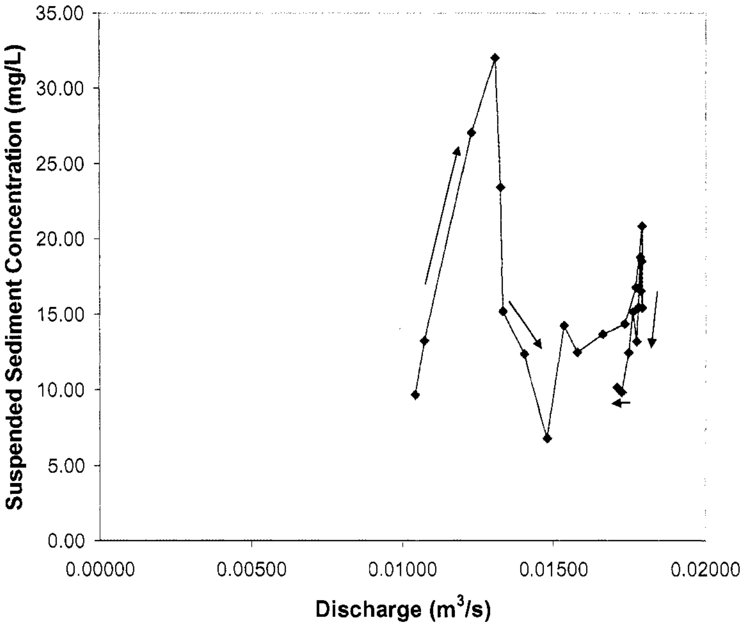
Figure 4.6: Hysteresis graphs; i. Total Suspended solids concentration and discharge temporal graphs, ii. C-Q graphs; a. 07/07/2005, b. 20/07/2005, c. 26/07/2005, d. 12/08/2005

Relationship between Discharge and [TSS] at SR1 Over Time for Event on 24/07/2005

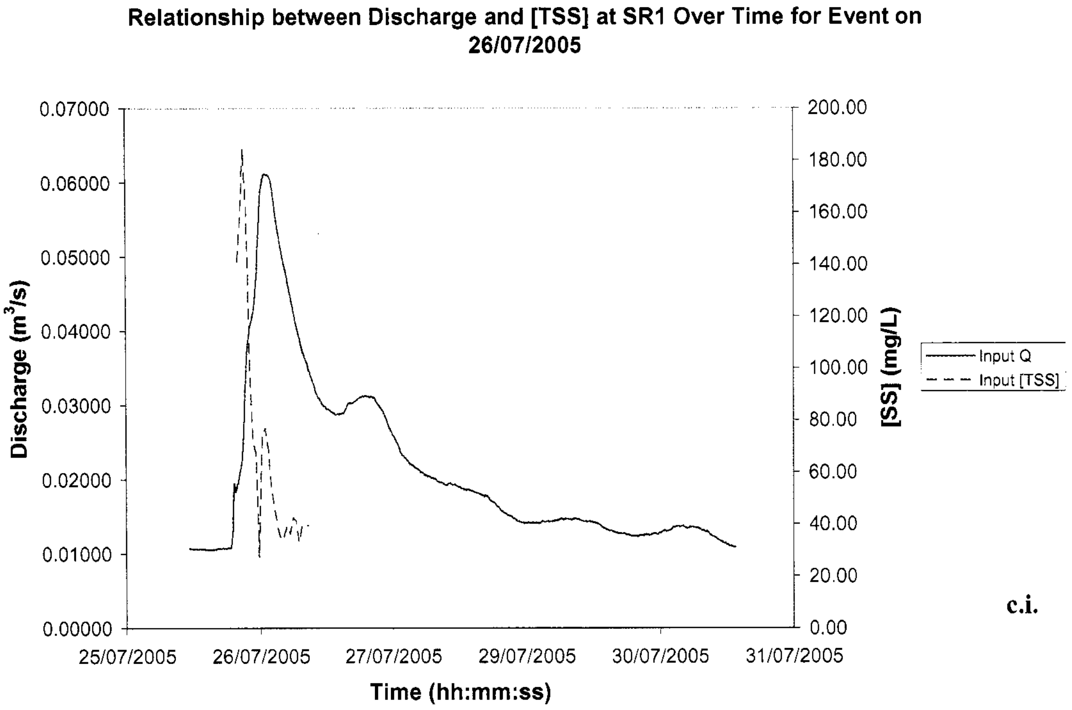


b.i.

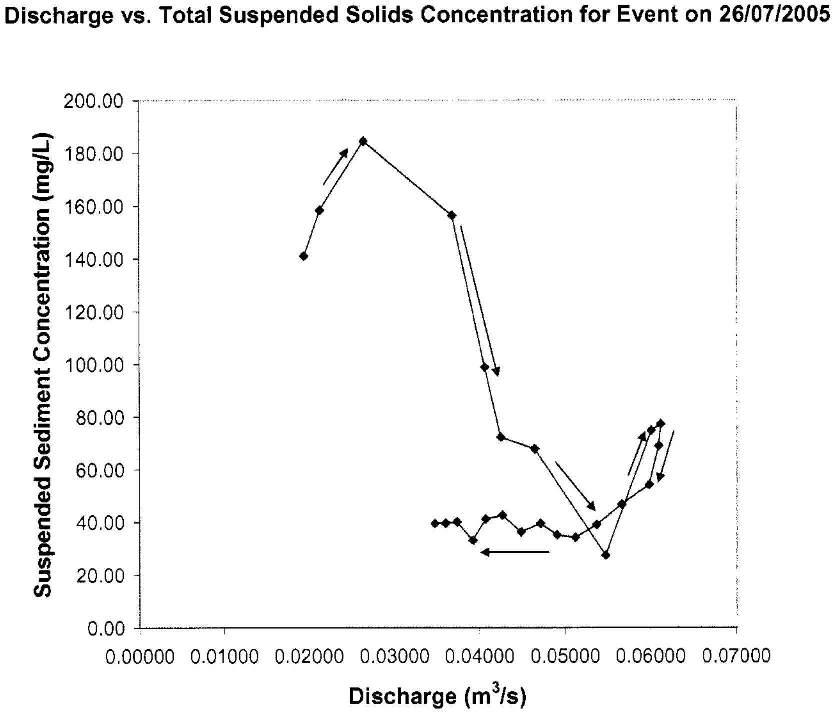
Discharge vs. Total Suspended Solids Concentration for Event on 24/07/2005



b.ii.

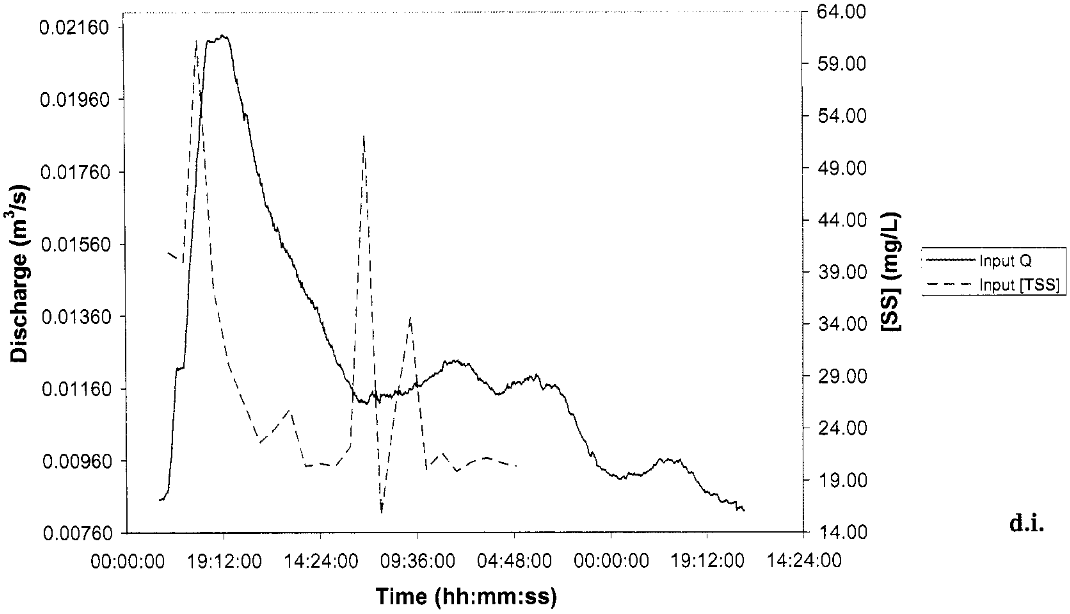

Relationship between Discharge and [TSS] at SR1 Over Time for Event on 26/07/2005

c.i.


Discharge vs. Total Suspended Solids Concentration for Event on 26/07/2005

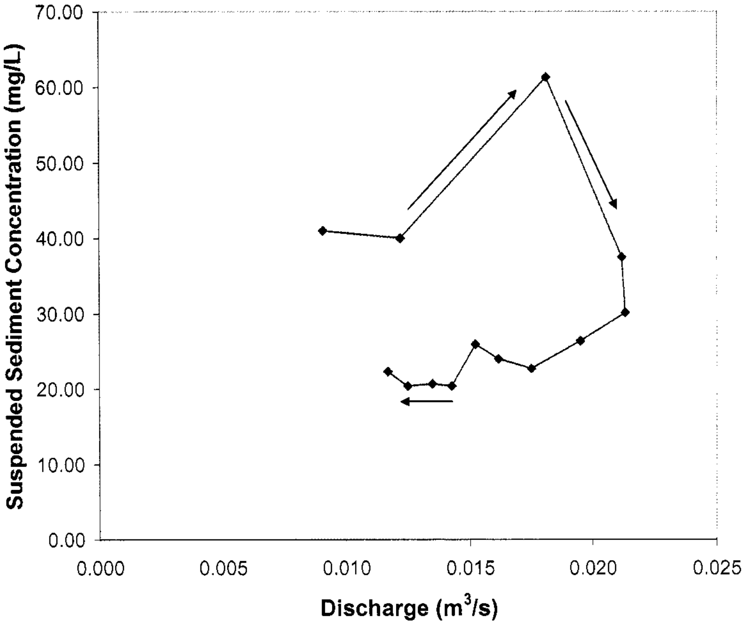
c.ii.

Relationship between Discharge and [TSS] at SR1 Over Time for Event on 12/08/2005



d.i.

Discharge vs. Total Suspended Solids Concentration for Event on 12/08/2005



d.ii.

will be large. As the time lag gets smaller so does the width of the loop. As can be seen in Figure 4.6a.ii. the overall width of the loop, is narrow. It is important to take careful note of the scale of the axes when observing the loop on the C-Q graph. The C-Q graph for this event is an order of magnitude lower than the others shown. Therefore, by comparison, it is narrower than the others. This event is a very good example of the defining C/Q ratio characteristics that make up a Class I hysteretic loop. The C/Q ratio at a given discharge on the rising limb (Q_r) will be larger than the ratio at the same discharge on the falling limb (Q_f). Scatter on C_f (C-graph falling limb) causes deviation from Williams' (1989) model, but the Class I trend is evident (see Figure 1.1).

The event on 24/07/05 also shows a definite Class I hysteresis. The C-graph for this event shows a rapid spike of high concentration. This is likely due to the release of sediment from one or more significant sources. This first peak is followed by a second, less high rise in concentration as other sources contributed to the sediment supply in the flow (see Figure 4.6b.i.). The C-graph has a spread less than that of the Q-graph and C_r (C-graph rising limb) crosses Q_r at approximately 11:30:00. Therefore, Williams' (1989) classification would assign a sub class describing the shape and location of the loop on the plot. However, the crossing of the two rising limbs can be adjusted using the y-axis scaling. Adjustments of the y-axes scale can even be done using the semi-log graph proposed by Williams (1989). This is not to say that the sub-classification has no merit. In examples of events which show total suspended solids concentrations and discharges that range over at least two orders of magnitude, as presented with the original model, the sub-classes are valid because the data are more adequately plotted using logarithmic axes. In the case of the events seen on Beaver Creek the magnitude of change of both total suspended solids concentration and discharge are not great enough to apply a subclass. Figure 4.6b.ii. has a weak looped appearance due to the lack of total suspended solids concentration values with the falling limb of the hydrograph. The loop is still present with what is shown and extension of the observed C_f trend would yield a more complete clockwise loop (Class I).

The third event examined occurs two days later on 26/07/2005. Once again it was found that this event held the characteristics of Class I hysteresis. The C-graph (Figure 4.6c.i.) has similar features as that of 24/07/2005; whereby a second smaller rise in concentration occurred following an initial large peak in total suspended solids concentration prior to the peak of the event hydrograph. However, the C-Q graph (Figure 4.6c.ii.) has the appearance of secondary loops not previously seen in the other events. These are, in fact, not secondary loops and not a Class V: Figure 8. They are simply due to the very low drop in concentration of the first C_f. The path of the loop continues in a clockwise direction and does not have the characteristic reversal of a Class V figure 8. More data on the rising limb of the C-graph would be preferential and required to show a more complete loop. However, the C/Q ratios that are produced from Figure 4.6c.i. clearly support a clockwise, Class I loop. Extrapolation, using shown trends, of the C-graph in both directions also certainly exemplify this. Detailed analysis of this event and the event two days prior were included to also show that Class I hysteresis is not isolated to select events but occurs sequentially from storm to storm, even consecutive storms, on Beaver Creek.

Figure 4.6d.i. displays the temporal graphs for the event on 12/08/2005. The plot has the peak in total suspended solids concentration prior to that of the discharge followed by a second smaller increase in concentration, typical of Beaver Creek. As previously explained, this is likely due to the release of sediment from one or more significant sources at the onset of precipitation before the precipitation has accumulated enough to raise the water level in the creek. These sources are likely to include fields and slopes with little vegetative cover, which are more susceptible to erosion by rain. The smaller secondary increase in concentration is the result of the input from other less significant sources of sediment. These smaller sources could include SFGL, bank erosion, lagged overland flow and input from agricultural tile drainage networks. In this event a second rather large peak is observed. This second peak corresponds with a second rise in discharge at the start of 13/08/2005 (see Figure 4.6d.i.). However, no precipitation was recorded at the weather station. Therefore, it can be concluded that this rise is due to precipitation occurring in the upper basin that was not seen in the area of the weather station. Also, following this second large peak is a smaller rise in concentration. This second set of peaks on the C-graph and the related rise in discharge are the result of a storm in the upper part of the basin. Therefore, it is a separate event and should not be included in the hysteresis of the event on 12/08/2005. Figure 4.6d.ii. shows the C-Q graph for only the event on 12/08/2005. This is the strongest Class I event sampled and exemplifies the classification model put forth by Williams (1989).

The results show that the patterns between discharge and total suspended solids concentration observed on Beaver Creek show hysteresis. The hysteretic analyses of the events sampled in this study are summarized in Table 4.2. It has been shown that precipitation events in Beaver Creek basin result in discharge/total suspended solids concentration relationships that can best be described by Class I (clockwise) hysteresis. Table 4.2 also shows that a hysteretic loop may become less common later in the seasons. This is likely related to the removal of easily transported fine sediments from the major sediment sources, as well as cover by leaf litter and harvested crop litter protecting the slopes and fields from the impact of rain fall. This seasonal decrease in hysteresis is confirmed by the work of Sidle and Campbell (1985).

The initial spike in total suspended solids concentration is attributed to input from a large source or sources. Where the initial spike in concentration had a steep falling slope, like many of the events sampled in this study, such as 24/07/2005, 04/08/2005, 29/09/2005 and 17/10/2005, the rapid decrease in concentration has been attributed to exhaustion of the sediment source (Walling, 1974; Wood, 1977). However, the results of this study show that spikes in total suspended solids concentration at the onset of precipitation occur in consecutive events that are temporally close together (events on 24/07/2005 and 26/07/2005). If the primary sediment sources were exhausted on 24/07/2005, then it would be unlikely that the event occurring one day later would show a similar initial spike. Therefore, the conclusion of source exhaustion does not seem to hold here.

Dilution has also been suggested as a cause of the decrease in total suspended solids concentration (Loughran, 1974; Wood, 1977). Although the inputs from groundwater, through-flow and increased overland flow are likely to dilute the concentration of suspended solids in the creek, the effects of such input would occur slowly. The C_f in many of the storms, such as 24/07/2005, 04/08/2005, 29/09/2005 and 17/10/2005, is too steep to be the result of dilution.

Since the basin is almost completely agricultural, these sources are likely the tilled and cropped fields with overland flow as the primary transport mechanism. As noted by Gregory and Walling (1973) and later shown by Lasanta *et al.* (2000), as precipitation and thus overland flow continues, the ability for detachment by rainfall splash diminishes and these sources contribute less. Therefore, the results show that the quick drop in the initial total suspended solids concentration spike is more likely due to decreased detachability than exhaustion of supply.

As seen in Figure 4.6i., the initial spike in total suspended solids concentration often declines prior to the input of sediment from other sources. However, in all sampled events, concentrations did increase a second or multiple times following the initial spike. This is attributed to the input from sources that require either increased discharge and flow characteristics (i.e. velocity and shear stress) or require longer periods of time to reach the channel. Up stream of the study cross section, the top layer of the bed is a light, low density network of fine grains, typical of surficial fine-grained laminae (SFGL). As found by Droppo and Stone (1994) during high discharge flows SFGL may be a significant source of fine-grained suspended sediment. Sources that require longer periods of time to contribute sediment include agricultural drainage tiles. It takes longer for water to infiltrate down to a tile drain network than for overland flow to reach the channel. Therefore, the input from tiles will likely be delayed. The conclusion that some of the delayed sediment sources could be tile drains is supported by the findings of Culley and Phillips (1983), as well as Stone and Krishnappan (2002).

4.2 Segment Study

The cross sectional profiles along the study reach and out flow measurements at SR2 (see Figure 2.2), served as a means to evaluate the state of Beaver Creek over the study period. Erosion and deposition of sediment along a creek is natural. However, excessive dominance of either of these processes is cause for concern to the natural state of the creek and the basin. Therefore, in conjunction with the patterns of sediment movement and the influence of basin conditions on response to storms, it is also valuable to examine the level of geomorphic activity of the system. At this point it is important to reiterate the use of the word 'equilibrium'. Natural systems are almost never in a state of steady state equilibrium. Natural systems such as that of the Beaver Creek basin are constantly changing. In fact, to observe no change at all would be an indication of drastic deviance from a natural state. Therefore, here the term 'equilibrium' refers to a natural balance between erosion and deposition. Either process may be dominant at a given point in time or over a given period, but the long term changes over the entire basin and creek are balanced; a dynamic equilibrium. However, as previously discussed dynamic equilibrium is a term only appropriate for long term studies. As such this study will examine the geomorphic state/activity for the relatively short study period.

4.2.1 Cross Sectional Change and Mass Movement of Solids

The state of the reach was examined using cross sectional bed profiles (Figure 4.7) and event mass movement of total suspended solids. The maximum concentrations of total suspended solids for each of the 13 sampled events are shown in Table 4.3. In 9 of the 13 events maximum concentration was greater at the outflow of the reach than at the inflow. The average maximum concentration down stream, for the sampled periods, was 25% greater than that up stream, for the sampled periods (162.12 mg/L and 129.48 mg/L, respectively). Also, the discharge out of the reach, for the sampled periods, was on average greater than the inflow, for the sampled periods (Average Q_{IN} = 0.026 m^3/s, Average Q_{OUT} = 0.036 m^3/s). These results indicate that there was a greater amount of solids moving out of the study reach than coming in. This is confirmed by the calculated mass of total suspended solids into and out of the study reach. The masses of total suspended solids for the sampled period of each event are shown in Table 4.3. Mass movement of solids out of the reach was greater than that moving in for 11 of the 13 sampled events. The mass moving out was on average 34% greater than the mass moving into the reach (Average Mass TSS_{IN} = 85.04 Kg, Average Mass TSS_{OUT} = 114.17 Kg). These results indicate that over the study period the reach showed an overall loss of solids. However, these numbers need to be put into perspective related to the system. The greater discharge at the downstream end of the reach is likely due to the input from the two tile drains, groundwater and overland flow during high events, particularly at the area noted near cross section 5 (see Figure 2.2). The difference in average discharge is only 0.010 m^3/s (or 10 L/s). This is not a large difference. Also,

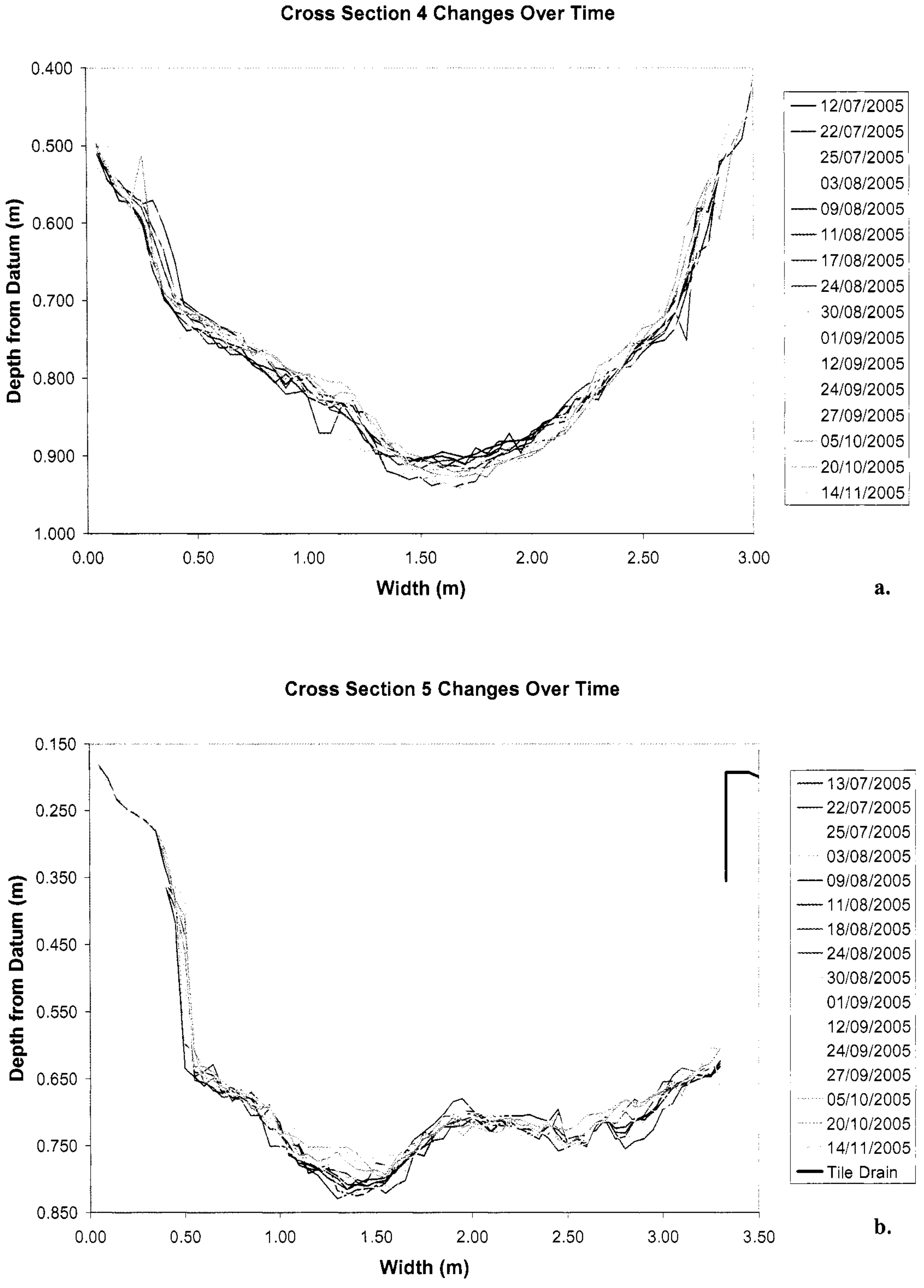
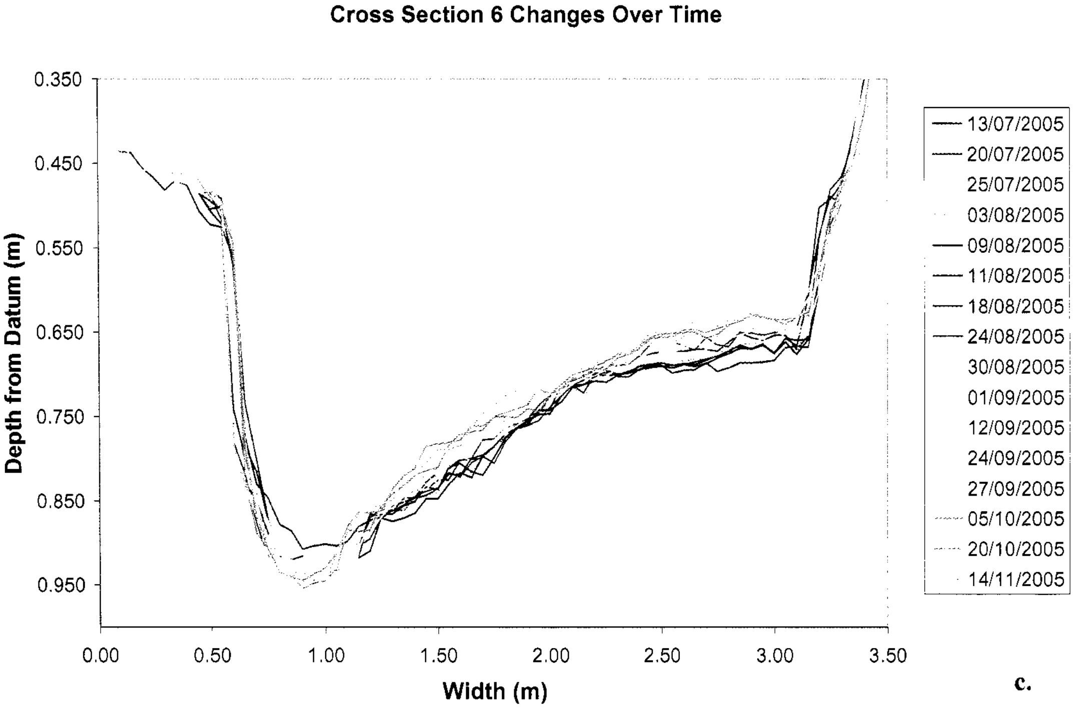
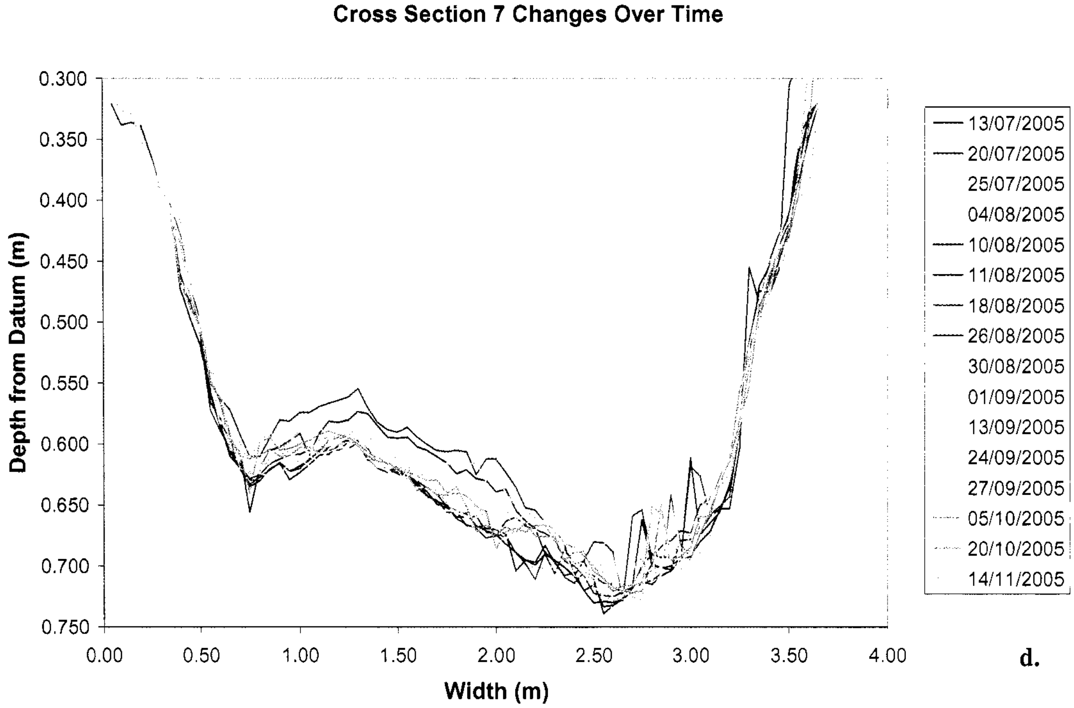


Figure 4.7: Cross sectional changes over the study period for six profiles along the study reach; a. Cross section 4, b. - 5, c. - 6, d. - 7, e. - 8, f. - 9.


Cross Section 6 Changes Over Time
0.350
0.450
0.550
0.650
0.750
0.850
0.950
Depth from Datum (m)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Width (m)
13/07/2005
20/07/2005
25/07/2005
03/08/2005
09/08/2005
11/08/2005
18/08/2005
24/08/2005
30/08/2005
01/09/2005
12/09/2005
24/09/2005
27/09/2005
05/10/2005
20/10/2005
14/11/2005

c.


Cross Section 7 Changes Over Time
0.300
0.350
0.400
0.450
0.500
0.550
0.600
0.650
0.700
0.750
Depth from Datum (m)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Width (m)
13/07/2005
20/07/2005
25/07/2005
04/08/2005
10/08/2005
11/08/2005
18/08/2005
26/08/2005
30/08/2005
01/09/2005
13/09/2005
24/09/2005
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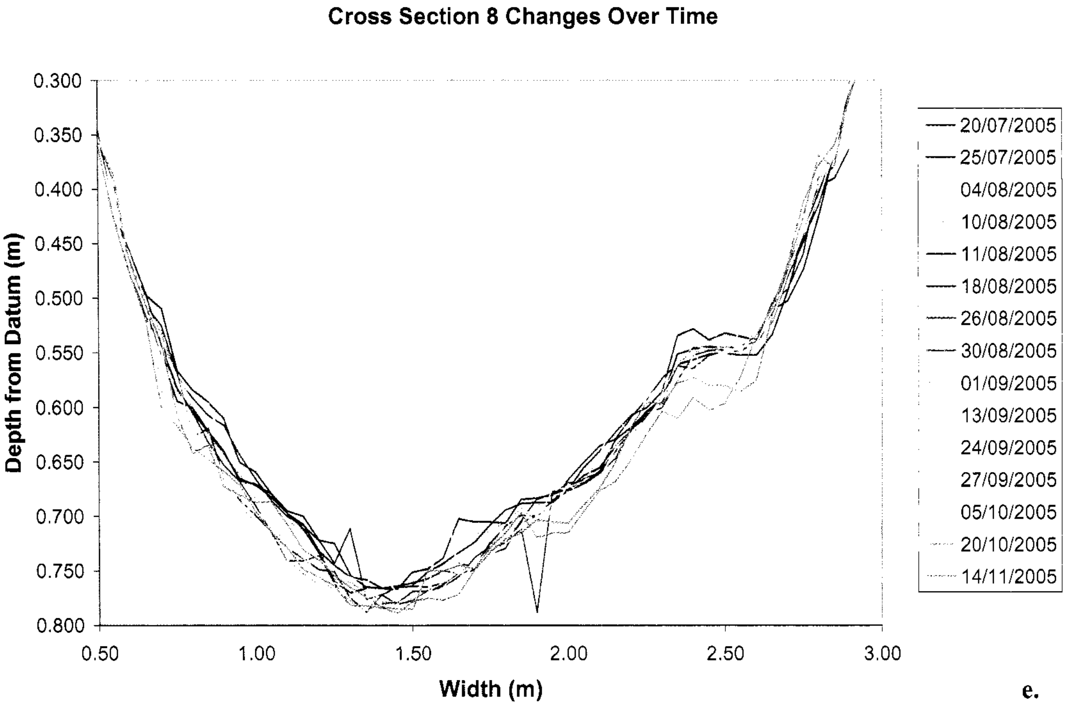
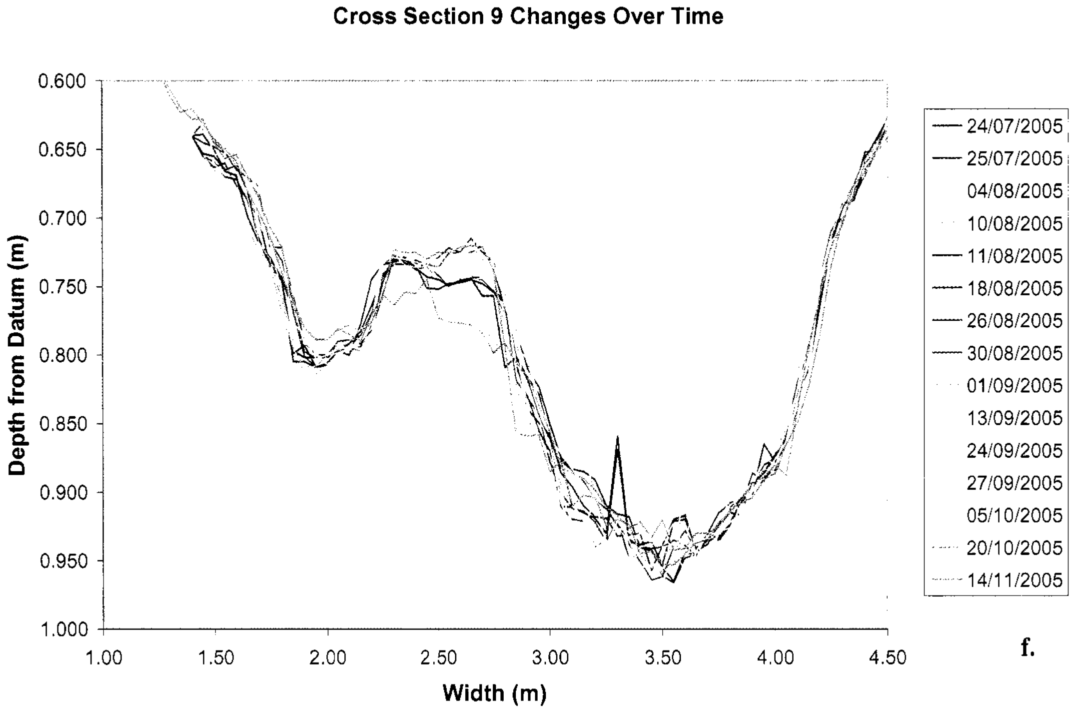
05/10/2005
20/10/2005
14/11/2005

d.


Cross Section 8 Changes Over Time

e.


Cross Section 9 Changes Over Time

f.

although the average mass movement of suspended solids exiting the reach was greater than that entering the difference is only an average of 29.13 Kg. This is negligible in relation to the amount of sediment stored in the reach bed and banks. This is the average difference; sometimes there is a greater outflow of solids and sometimes there is a greater inflow. Although a wide range of events were sampled (see Figure 4.1), this analysis does not include all precipitation events. Events resulting in greater deposition in the reach may not have been sampled. These results indicate that, over the study period, the study reach shows minimal differences in mass suspended solids flux.

	ISCO1	**ISCO2**	**ISCO1**	**ISCO2**
Event Date	**Max [TSS]**	**Max [TSS]**	**TSS Mass (Kg)**	**TSS Mass (Kg)**
07/07/2005	92.82	126.26	11.87	23.55
14/07/2005	98.06	59.84	3.78	8.59
24/07/2005	32.02	27.29	3.23	5.39
26/07/2005	184.61	174.85	153.80	200.54
04/08/2005	109.51	241.37	13.60	37.94
10/08/2005	76.54	80.52	20.27	19.02
12/08/2005	61.34	44.73	98.45	149.18
27/08/2005	179.21	219.26	141.40	159.50
14/09/2005	18.11	114.51	6.30	19.72
22/09/2005	96.01	116.30	63.62	108.12
29/09/2005	244.22	295.08	217.96	341.06
17/10/2005	402.45	515.45	106.10	174.58
05/11/2005	88.32	92.07	265.13	237.06
Average	*129.48*	*162.12*	*85.04*	*114.17*

Table 4.3: Total suspended solids mass and maximum concentration into and out of the study reach.

Changes in the reach can also be examined using cross sectional profiles. Cross sectional changes over the study period for the six profiles along the reach are shown in Figure 4.7. If the reach were in a state of loss then an overall continued lowering of the bed would be seen in the profiles over time. In contrast, if the reach were in a state of gain then the deposition would be seen as a continued rise in the creek bed over time. As can be seen in Figure 4.7 none of profiles show a continued or overall rise or lowering of the bed. The changing profiles shown in Figure 4.7 are not limited to those 13 sampled for total suspended solids. The changing profiles include measurements before and after nearly all events. Changes are clearly evident at all cross sections but the profiles merely fluctuate showing no great continued gain or loss.

The results show that over the study period, the study segment of Beaver Creek is in a state of low morphological activity. This study reach is typical of almost any reach in the basin. The surrounding land use is row crop agriculture with a riparian zone directly adjacent to the creek. This is typical of the entire basin. Therefore, it is acceptable to assume that the trends in the results would be noted throughout the basin. Thus, Beaver Creek is in a state of low morphological activity.

5 Conclusions and Recommendations

5.1 Conclusions

This thesis was conducted to explore relationships between suspended solids concentration and discharge, the influence of antecedent conditions on event hydrographs and the geomorphic state or activity of Beaver Creek. Results of this study were compared to the findings reported in the literature. Numerical representation of basin parameters were used to assess the correlation between antecedent conditions and changes in discharge resulting from a storm. Patterns in suspended solids flux were examined for hysteresis to discharge. It was determined that patterns for sampled events could be classified using the model of Williams (1989). Based on the current findings of this study specific conclusions can be made about each of the areas of examination.

Antecedent conditions influence response to rain events in Beaver Creek basin in summer, autumn and early winter. The results show a positive relationship between antecedent conditions and stream flow, in response to precipitation. This study has shown that wetter conditions in the basin prior to a storm result in greater changes in discharge on Beaver Creek.

Suspended solids patterns on Beaver Creek can best be described using hysteresis models. The Class I: Clockwise hysteresis seen on Beaver Creek is attributed to an initial, rapid increase in total suspended solids concentration flowing down stream prior to significant rises in discharge. This concentration increase is presumed to be associated with one or more sources of easily erodable material which decrease their yield with prolonged precipitation. Delayed sources keep concentrations elevated but decrease with time as storm flow subsides. Knighton (1998) noted that in small basins, like Beaver Creek, storm suspended sediment spikes are more likely to precede discharge spikes because sediment sources are closer to the measuring cross section.

The study segment examined showed fluctuations between erosion and deposition over time. The characteristics of the study segment are typical of the entire basin. Therefore, in the summer, autumn and early winter, Beaver Creek is assumed to be in an overall low morphological state, whereby over time, the amount of solids (or sediment) being transported out is balanced by the amount of solids (or sediment) carried into the flow and deposited along the creek.

Knowledge of the storm sediment patterns, basin response given antecedent conditions and relative sediment flux in the creek, is fundamental in monitoring and assessing changes in the system. The patterns observed in this study can act as guidelines for such monitoring. Continual deviation from these patterns could be an indication of adverse affects from changes within the basin and should be mitigated to preserve the natural dynamics.

5.2 Recommendations and Further Study

This thesis gave light to some data collection and analysis procedures that could further the potential of such a study. Seasonal base flow discharges were determined through extrapolation of monthly lows. Through the use of piezometers in and adjacent to the channel, in addition to well monitoring throughout the basin, seasonal base flow discharges could more accurately be calculated. Regular or continuous water table measurements would allow for even greater confidence in quantifying antecedent conditions.

Hysteretic relationships between suspended solids and discharge were evaluated qualitatively using a graphical model. A quantitative analytical method has yet to be agreed upon in the literature. However, some have been presented. The current quantitative methods of hysteresis analysis require greater correlation between discharge and suspended solids concentration. The limits proposed in the literature may not be obtainable for suspended solids in a dynamic, natural system. However, frequency of sediment sampling greater than that employed in this study could produce higher correlation values. As a result quantitative analysis could be possible.

The sampling method used to determine mass total suspended solids flux was time consuming and hampered by the limited frequency and number of samples that could be acquired for each event. Use of a turbidimeter could also be employed to obtain a more continual, higher frequency, set of suspended solids data. This would allow for more complete determination of the mass flux of suspended solids in the creek.

The analyses of this study do not exhaust the potential of the data sets. The areas examined here could act as the foundation for continued investigation into such things as the relationship between antecedent conditions to total suspended solids concentration. Also, land adjacent the study site is scheduled for residential development in the near future. The information compiled in this study could act as the starting scenario for the influences of land use change on any of the components discussed here. This study adds a unique, small scale examination of the processes existing in a small, agricultural sub-basin of a watershed that has been under more large scale surface water monitoring.

6 References

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Appendix A – Error

When making empirical measurements, there will always be associated errors. Errors result from equipment, sampling technique, mathematical and the researchers themselves, or human errors. While this study made every effort to minimize the amount of error in measurements and analysis, it is recognized that these are an inherent part of field research and analysis. Errors associated with automated field equipment (as provided by the given manufacture) are presented in the text. Less obvious errors include but are not limited to, for example, measurements of discharge.

The simplification of the wetted perimeter and area associated with the velocity-area method of discharge calculation holds some errors. Each of the cross sections taken for discharge had depths measured every 10 cm (two panel edges and a velocity depth in the center of the panel). This means that any bed form in between the depths would be generalized and not included in the calculations. However, bed forms of such small size are unlikely to cause a great enough influence on velocity that their generalization would be of concern.

Velocity was measured using and electromagnetic current metre. This probe was set to average instantaneous velocity measurements over a six second time period. In turbulent flow, velocity is constantly changing. Taking an average or instantaneous velocity measurements are thus not entirely accurate when extrapolated to other times. Also, this instrument measured to ± 0.01 m^3/s. The depths for velocity profiles were recorded using an aluminium ruler to the millimetre. The computation of discharge from these instruments compounds the errors in accuracy.

Further, these velocity profiles were correlated with measurements of water height by the stage recorders (accuracy: ±0.01 m; resolution: ±0.001 m). Using a best fit regression, discharge values were extrapolated for all stage recorder values over the entire study period. Although these regressions had very high correlation values ($R^2 = 98$, $R^2 = 99$, for SR1 and SR2 respectively) they are not perfect and some discharge values will not be exact.

The above discussion of discharge measurement serves as an example of possible errors associated with field work and data analysis. Every effort was made in this study to minimize the amount of error associated with measurements and analysis. The approach to satisfying the objectives of this study was an examination of patterns. Although errors in the data are acknowledged, they are not believed to be great enough to alter the patterns and findings of this study.