SPATIAL AND TEMPORAL VARIATION IN SIZE AND SHAPE OF SEDIMENT PARTICLES IN THE TOBACCO CREEK WATERSHED

BY

Cenwei Liu

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Department of Soil Science
University of Manitoba
Winnipeg

ABSTRACT

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Particle size and shape are important characteristics of the sediment which affects the adsorption of sediment-associate contaminants and nutrients onto the surface of sediment. This thesis characterized the spatial and temporal variation in size and shape of sediment particles in the Tobacco Creek Watershed. A strong correlation between the particle size of suspended sediment and stream discharge was observed. Spatial and temporal variation in size of suspended and channel bed sediment showed that particle size was significantly coarser at the upper reaches and following the rainfall events, but finer at the lower reaches and following the snowmelt events. Image analysis of coarser particles showed that rock fragments are not becoming rounded in short distances, but they reduced in size. The coarser materials from bedrock outcrops can be sources of fine-sized particle during transport. These findings have important implications for understanding suspended sediment dynamics transport in the study watershed.

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1. INTRODUCTION

1.1 Lake Winnipeg Basin

Lake Winnipeg is an important component of Manitoba's hydroelectric system and supports a large commercial fishery (LWSB, 2006). Lake Winnipeg Basin (LWB) drains water approximately 1 million km^2 (Voora and Venema, 2008), passing through 90% of the Canadian Prairies' agricultural land. The south basin receives 80% of its annual water supply from the Winnipeg River, and 20% from the Red River (Evans, 2000). The drainage basin of the Red River supplies approximately 70% of the total phosphorus load to the south basin (Evans, 2000).

Human activities have significantly impacted the health of the lake ecosystem in the Lake Winnipeg Basin. It has experienced a significant decline in water quality over the past several decades. Eutrophication has been identified as one of the greatest threats to the ecosystems (LWSB, 2006). Due to excessive amounts of nutrient loading into the lake, primarily phosphorus and nitrogen, contributes to the growth of algae (Evans, 2000). The nutrient emissions into water bodies includes both many point and non-point sources, such as surface runoff, municipal wastewater effluent, fertilizers applied to agricultural land, livestock waste and industrial discharges. It has been estimated that agriculture in Manitoba contributes approximately 5% and 15% of the total nitrogen and phosphorus loads to Lake Winnipeg, respectively (LWSB, 2006). Therefore, identifying the sources of sediment and understanding the interaction of sediment with nutrients are important to help protect Lake Winnipeg.

1.2 The connection between sediment and contaminants/nutrients

Soil erosion from the upper reaches of a watershed results in the subsequent sedimentation downstream, which has significant impact on the surface water quality. Sediments, in particular, fine particles, are both the carriers and the potential secondary sources of nutrients and contaminants, such as pesticides, heavy metals and pathogens in fluvial systems (Calmano et al., 1990; Walling, 2005). The nutrients and contaminants can be adsorbed by the surface of sediment, bound to organic matter, incorporation into lattice structures and released from the sediment particle surfaces (Nayar et al., 2007). Additionally, the sediment-nutrient interactions via adsorption and/or desorption are affected by the flow rate, grain size and mineralogy (Liang et al., 2013). Studies of nutrient budgets are necessary to take into account the importance of sediment-associated nutrient transport in the watershed (Svendsen et al., 1995). A full understanding of the characteristics of sediment during transport by rivers has become important.

1.3 The use of sediment fingerprinting techniques in assessing sediment sources

Excessive sediment and nutrients in the water bodies and waterways of agricultural watersheds often arise from non-point sources. Without clearly defined entry points, the pollution is hard to attribute to a specific location. To protect and improve water quality requires identification of sediment sources and transport mechanisms of sediment within agricultural watersheds on the Canadian Prairies. The technique of sediment fingerprinting has been used to provide information for determining the origin of the sediment transported by rivers within watersheds. Sediment fingerprinting techniques are based on the idea that materials entering the water have a chemical and physical signature that reflect their source, and therefore can be used diagnostically to identify the origins of the sediment (Collins et al., 1997; Walling et al., 1999; Owens et al., 2000). Spatial and temporal variability in the physical and chemical characteristics of suspended sediment directly reflect those found in the relative contribution of sediment from potential sediment sources (Collins et al., 1998).

Sediment fingerprinting techniques are based on the assumption that the properties of tracers used in fingerprinting technique behave conservatively in fluvial systems and the properties of source materials and sediment samples can be directly compared. It is assumed that the composition of sediment, including biological (e.g., organic matter content), geochemical (e.g., trace metal content), radiometric and physical properties (e.g., colour, particle size and shape), would be consistent with those of the source materials as the sediment moves through the watershed, from uplands to the outlet (Koiter et al., 2013). Under this assumption, a representative volume of the source soil can be used to characterize its source providing the particle size distribution and the organic content of the soil conforms to the corresponding properties of the sediment (Motha et al., 2002). It is acknowledged that tracer properties are dependent on particle size (He and Owens, 1995; Walling and Woodward, 1995) and generally there is an enrichment of fine particles downstream during sediment generation and delivering processes (Walling and Woodward, 1992; Collins et al., 1997). Particle size characteristics of suspended sediment have been found to be different from those of its source (Martinez-Mena et al., 1999;

Motha et al., 2002) due to selective erosion and selective deposition during sediment transport. Comparing the sediment mobilized from steep gradients found in headwater streams with the lower reaches found at the outlet of the watershed, fine particles were enriched in the lower reaches (e.g., Stone and Walling, 1997; Walling, 2013). This resulted in contrasts in particle size distribution between suspended sediment and source material samples (Walling, 2013). In addition, due to high variability in water flow, which affects the sediment concentration and sediment size, it is difficult to use particle size as a sediment tracer in the fingerprinting technique to assess the sources of sediment.

Particle morphology is another physical property that has been used in a couple fingerprinting studies (e.g., Krein et al., 2003; De Boer and Crosby, 1995). The particle morphology is determined by imaging sediment particles quantitatively (e.g., fractal dimension) or describing qualitatively (e.g., circularity; roundness) the morphology of sediment particles. Particle shape of a sample is influenced by abrasion, disaggregation and aggregation that can happen as the sediment moves through the watershed. De Boer and Crosby (1995) demonstrated that the difference in particle morphology can provide a distinct fingerprint for different topsoil (e.g., farmland soil and forest soil). In particular, the particle morphology of clay sized particles had significant differences between the suspended sediment from two sediment sources. Their research showed that fine particles (clay sized) derived from farmland soil were more rounded than those derived from forest soil. Clast morphology has been used to successfully distinguish between till and fluvioglacial material (Gregory and Cullingford, 2003). Although there are few studies characterizing the evolution of particle size and shape in a natural stream, particle shape has been proved to change along the river as particles are transported from sources to the lower reaches (Mikos, 1994; Ueki, 1999; Szabo et al., 2013). Transport of coarser materials (e.g., pebble) in a stream drives them to rub against the stream bed and other materials, which results in abrasion and produces smooth and round shapes. Similarly, particle shape can also be regarded as a form of non-conservative property, which conflicts with the fundamental assumptions of sediment fingerprinting techniques.

Previous studies in the South Tobacco Creek Watershed have focused on nutrient loads and nutrient fluxes (e.g., Tiessen et al., 2010; 2011; Liu et al., 2013) when considering adverse impacts on water quality within the ecosystems. However, the dynamics of sediment transport in stream, and the spatial and temporal variations in particle size and shape of sediment are not well understood. Many sediment studies miss information on particle size and shape of sediment or shorten the analyzing range of particle size. These gaps in the data set can have significant consequences for the study and modeling of sediment transport processes. Full characterization of the dynamics of particle size and shape of sediment will aid in the understanding of sediment fingerprinting studies.

The objectives of this thesis are: 1) to characterize the variation in suspended sediment concentration with varied water discharge; 2) to quantify spatial and temporal variations of suspended sediment in the agricultural watershed during different events; and 3) to develop a better understanding of the basic sedimentation and erosion processes.

1.4 Thesis overview

This thesis is one part of an interdisciplinary, large project titled “Development of environmental fingerprinting techniques for sources of sediment and associated phosphorus within agricultural watersheds of Canada”.

Chapter 2: A hydrology and sediment study that characterized the temporal variations in water discharge, sediment load and particle size distribution of suspended sediment mainly in South Tobacco Creek Watershed, in south-central Manitoba, Canada. This study characterized temporal variations in sediment particle size as influenced by seasons (e.g., snowmelt in winter-spring and rainfall in summer-fall) and flow conditions.

Chapter 3: A field scale study that evaluated the spatial and temporal variation in the particle size of suspended sediment, and directly compared the particle size of suspended sediment and potential source materials (e.g., topsoil; streambank) during sediment transport through the Tobacco Creek Watershed. This study is important for understanding the dynamics of particle size characteristics of suspended sediment, channel bed sediment and its source material.

Chapter 4: A small field scale study that characterized the morphology of rock fragments (> 3 cm) collected from the source outcrops and those deposited in the stream downstream near the selected outcrop. This study mainly took place in the three selected outcrops in the South Tobacco Creek Watershed. Image analysis software was used to characterize the rock fragments. This study is important for the understanding of the dynamics of particle morphology during transport.

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2. TEMPORAL VARIABILITY OF HYDROLOGY AND SEDIMENT CHARACTERISTICS IN THE SOUTH TOBACCO CREEK WATERSHED

2.1 Abstract

Soil erosion is a global ecological problem, threatening agricultural production and water resources. Historical water and sediment dataset for STCW was obtained to examine the water quality and sediment characteristics by Water Survey of Canada. The annual and seasonal variations in water discharge, sediment load and particle size of suspended sediment were evaluated. Suspended sediment was collected at different times of the year so that temporal variation of hydrology was represented. The particle size distribution of suspended sediment collected at the outlet of the watershed (IS1) showed that the lower reaches are dominated by fine particles (< 62 μm). Historical records of water discharge, sediment load and sediment concentration from 1963 to 1977 showed that there was a positive relationship between water discharge and sediment load. The relationship between water discharge and flow rate during snowmelt and rainfall events was identified using event-based suspended sediment data collected from 2002 to 2011. The flow-weighted mean concentration of total suspended sediment at the two stations (IS1 and IS3) was significantly higher in rainfall events than that in snowmelt events. The relationship between the particle size distribution of suspended sediment and water discharge was examined using sediment data collected in 2013. The results shows that the proportion of sand increased, and the proportion of silt decreased when responding to the increased stream discharge.

2.2 Introduction

Significant effort has been focuses on concentrations and fates of nutrients and contaminants in dissolved form (Bowes and House, 2001), with much less attention given to sediment-associated contaminants and nutrients. However, sediment plays an important role in nutrients and contaminants production and release and water quality in rivers has been recognised by a number of studies (e.g., Dorich et al., 1984; Walling et al., 2001; Foster et al., 1996; Walling et al., 1997). Sediment functions as a carrier of nutrients and contaminants, which have significant impacts on the downstream waterways and water bodies. The sediment-nutrient interaction via adsorption and desorption is affected by the flow and particle size of sediment. Combinations of these controls determine the hydrologic and sedimentary regimes of steam channels and, therefore, the spatial and temporal variations for erosion, sediment transport, and deposition.

Sediment transport processes in a watershed are complicated due to the impact of recent land use and land cover changes on the fluvial spatial and temporal dynamics (Heitmuller and Hudson, 2009; Young et al., 1996). The processes of erosion and deposition in rivers are not significantly affected by the main climatic parameters such as mean annual temperature and annual precipitation (Vandenberghe, 2003), but hydrologic factors such as the intensity of precipitation and its seasonal distribution affect water quality and sediment runoff significantly. Surficial geology exerts considerable influence the overall valley slope and associated hydraulics that control erosion, sediment transport and deposition (Heitmuller and Hudson, 2009). For example, dramatically changes in valley slope (e.g., escarpment) can result in abrupt changes in predominant fluvial processes (Schumm, 2005). The mineralogy of the surficial geology influences resistance to weathering and erosion, and thus affects the type of sediment delivered to stream channels (Heitmuller and Hudson, 2009).

The traditional assumption is that increased shear velocities associated with increased discharge empower the transport of larger particles, and that a positive relationship exists between discharge and the magnitude of the coarse fraction (Horowitz, 1985). However, there is a different relationship between the particle size distribution of sediment and flow during snowmelt or storm events (Walling and Moorehead, 1989). Differential mechanisms and rates of weathering not only affect the initial size of sediment, but also the rate of particle size reduction downstream (Morris and William, 1999), thereby, indirectly influencing the spatial and temporal distribution of sediment. Understanding time series trends of water discharge, sediment load and the particle size of sediment can be a key solution to understanding the correlation of sediment with local landscapes when developing practices to reduce and control sediment export. In addition, to determine how hydrological systems are affected by climate change and human activity disturbance also requires the knowledge of hydrology and sediment dynamics.

In the South Tobacco Creek Watershed (STCW), agricultural practices affect the quality and quantity of water in the rivers, lakes and streams. Nutrients, especially nitrogen and phosphorus, enter water systems from agricultural lands mainly through runoff. Runoff during both snowmelt and rainfall events are common sources of sediment and nutrient loads to surface water from agricultural landscapes in Manitoba (Tiessen et al., 2011).

The objectives of this study were: 1) to examine the temporal variation in particle size distribution of suspended sediment; and 2) to examine the seasonal patterns of water discharge and sediment load. The purpose of this chapter is to provide context for studies into particle size and morphology of the sediment and to characterize the water quality data collected between three different periods.

2.3 Study Area

The study area South Tobacco Creek Watershed (STCW) is located in south-central Manitoba, Canada. Briefly, the STCW drains 74.6 km^2, of which 71% is under cultivation and 29% is comprised of non-cultivated grasslands, trees, water bodies, yard sites and roads (Deerwood Soil and Water Management Association). The creek originates above the Manitoba Escarpment and flows eastward over the escarpment to the Red River and Lake Winnipeg (Tiessen et al., 2011). The elevation drops dramatically (nearly 60 m) in less than 3 km at the escarpment (Tiessen et al., 2011). The majority of sampling sites are located below the Manitoba Escarpment. Soils are classified as Gleyed Dark Gray Chernozem, which is dominated by a mixed till of shale, limestone and granite in the lower slope positions. The native vegetation includes oak and poplar woodlands, while grasslands have largely been cleared and covered by cultivated land since 1870 (Hope et al., 2002). The regional climate is sub-humid with a mean annual precipitation of 550 mm, of which approximately 25% of precipitation occurs as snowfall. The average temperature is approximately 3.3 ^{o}C with short, cool summers and long, cold winters (Environment Canada, 2012). Flooding and soil erosion during snowmelt and heavy rainfall impact the agricultural land, causing significant damage to roads, bridges and crops (Tiessen et al, 2011). To address the escarpment's flooding problems, a network of 26 small dams and reservoirs was built up in the headwaters of the STCW (Yarotski, 1996). These dams and reservoirs significantly reduced rapid runoff and flooding from the Manitoba Escarpment, and also reduced annual sediment loads, annual concentrations of sediment and total nitrogen (Tiessen et al., 2011). Agriculture activities included continual cropping and livestock production.

Regular runoff monitoring and water quality sampling occurred at two gauging stations. These two gauging stations have been monitored by the Water Survey of Canada (WSC) since 1963. The first station is below the escarpment (IS3, WSC station 05OF023), and it drains the upper 34 km^2 of the watershed (Hope et al., 2002). The second one is at the outlet of the watershed (IS1, WSC station 05OF017) (Fig. 2.1).

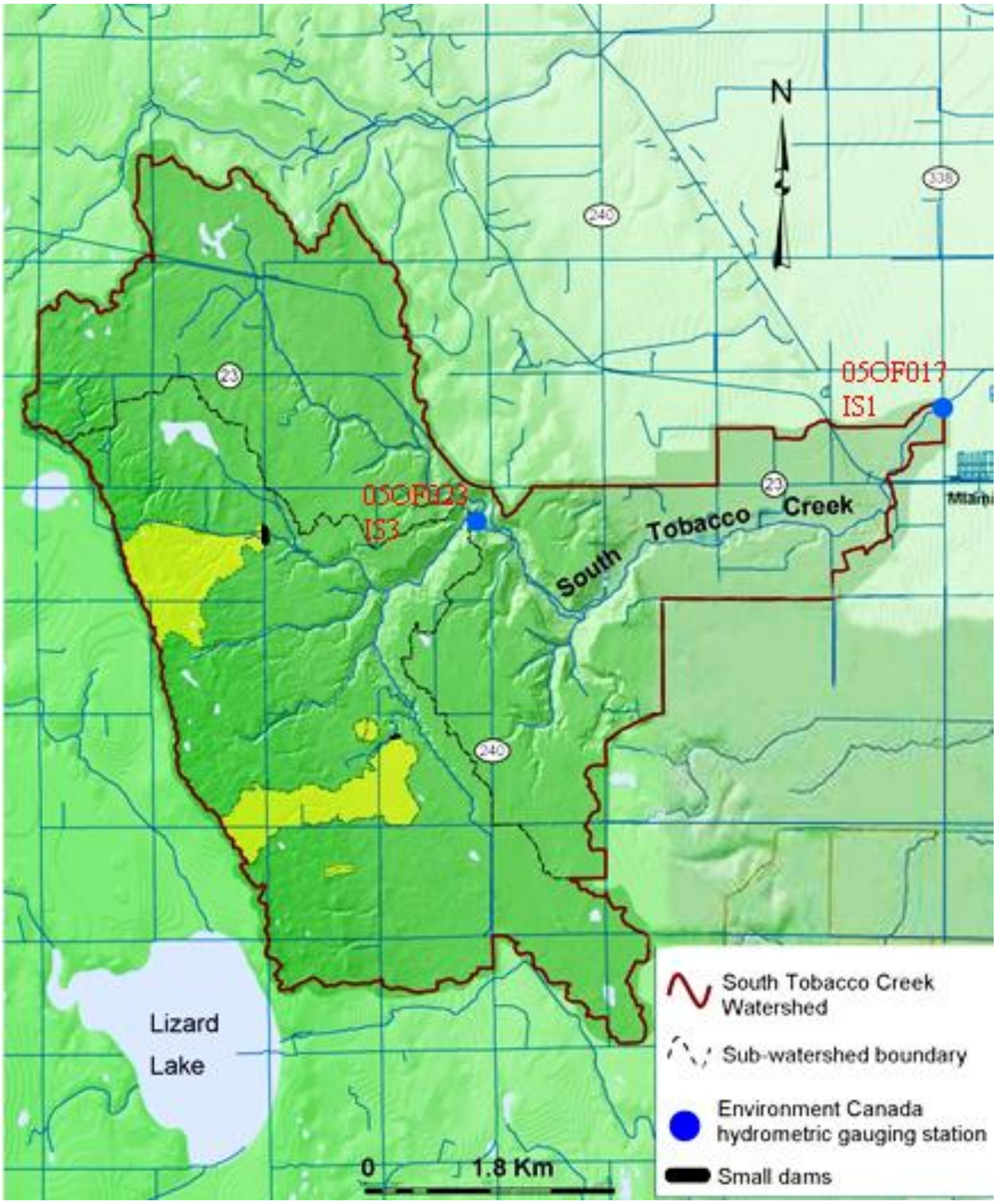

Figure 2.1 Location of two gauging stations in the South Tobacco Creek Watershed.

2.4 Sediment and water data sets

In this study, data on water discharge, particle size of sediment and sediment load were collected from 1963 to 1977, from 2002 to 2011 and in 2013 during snowmelt and rainfall events are summarized in Table 2.1.

2.4.1 Sediment and water discharge data set (1963-1977)

Water discharge and sediment load delivered in the Tobacco Creek Watershed (TCW) were recorded in various timescales since 1963. The monthly water discharge and daily sediment load were supplied from WSC. A depth-integrating suspended sediment sampler, USDH-59 was used to collect suspended sediment, and a bed material sampler, USBMH-53 was used to collected channel bed sediment (WSC, 1963). Particle size of suspended sediment (< 1 mm) and channel bed sediment (< 16 mm) was analyzed using a bottom withdrawal tube (WSC, 1963).

Yearly water quality data were split into two seasons (snowmelt and rainfall). The seasonal time periods are not the same in length (snowmelt season from March to May, and rainfall season from June to November), but represent seasons that are considered to be hydrological distinct (Tiessen et al., 2011).

2.4.2 Sediment and water discharge data set (2002-2011)

The monthly water discharge and sediment load at the two stations were recorded and analyzed from 2002 to 2011. Runoff was monitored at the outlet of the watershed using a compound angle v-notched weir and an ultrasonic depth instrument (SR50, Campbell Scientific) connected with a data logger (CR10X0, Campbell Scientific)

(Tiessen et al., 2010). It monitored the depth of flow over the weir and the flow rate was calculated. Volume of runoff (VolR) was calculated for each interval and was summed during the entire runoff event and expressed as runoff yield. Average flow rate (AvFR) was calculated as the flow volume per unit of flow time. Peak flow rate (PkFR) was maximum flow rate in a given flow event (Liu et al., 2013). Flow-weighted mean concentrations (FWMCs) were calculated by dividing the total load for each individual runoff event by that event's total flow volume (Tiessen et al., 2011).

An auto-sampler (800SL; Sigma, Medina, NY) was triggered using a float system which was programmed based on changes in water level (i.e., flow) at the v-notched weir. The sampler was located at the top of the weir and then took water samples during low and high flows (Tiessen et al., 2010). Water samples (2 L) were collected each day from the sampler, and the concentrations of total nitrogen, total dissolved nitrogen, total phosphorus, and total dissolved phosphorus were determined using standard analytical techniques (Eaton et al., 2005). Total suspended sediment (TSS) was determined as the mass of material remaining on a 0.45-μm filter paper after filtration (Tiessen et al., 2010).

2.4.3 Water discharge data and particle size of sediment (2013)

Frequent sediment samples were taken at the end of a snowmelt event and during the rainfall events at IS1, Roland, La Salle River using a centrifuge (model M512, US Centrifuge) in 2013. The sediment from the river was continuously collected by the centrifuge and stored in the solid holding bucket until the bucket becomes full. The centrifuge was placed in the middle of the stream, in order to collect the suspended sediment in stream. Two grams of suspended sediment was mixed with 40 ml distilled water, and then poured through a 600-μm sieve before particle size analysis using a laser diffraction instrument (Mastersizer 2000S, Malvern, UK).

Table 2.1 Summary of sampling sites, sampling periods and data types in the South Tobacco Creek Watershed

Sampling site	Collecting years	Data types†
IS1	1963-1977	PS+DWD+SL
IS1	2002-2011	DWD+SL
IS3	2002-2011	DWD+SL
IS1	2013	PS+DWD+PS

†PS = particle size of sediment and channel bed sediment; DWD = daily water discharge; SL = sediment load

2.5 Statistical analysis

The pattern of sediment particle size was investigated separately for three sediment-size classes: (a) clay-size (< 2 μm); (b) silt-size (2-62 μm for the data set from 1963 to 1977 and 2-63 μm for the data from 2013); and (c) sand-size (62 μm-1 mm for the data set from 1963 to 1977 and 63 μm-600 μm for the data from 2013). A Mann-Whitney U test (95% level of confidence) is a nonparametric method, which was used to compare the median particle size of sediment collected between March-May (snowmelt events) and June-November (rainfall events). Flow-weighted mean concentration of total suspended sediment (FWMCTSS) was not normally distributed and therefore a non-parametric statistical technique was applied. When comparing the variation in water quality at different spatial scales (more than three groups of data were analysed), a Kruskal-Wallis one-way analysis of variance was used.

2.6 Results and Discussion

2.6.1 Sediment and water quality analysis (data set from 1964-1977)

2.6.1.1 Downstream variation in particle size distribution of suspended sediment

Yearly particle size composition patterns at IS1 from 1963 to 1977 are presented in Fig. 2.2. Particle size of suspended sediment was only measured once in 1973 and 1974, and was not included in the figure. Significant downstream variation in particle size distribution of suspended sediment was evident across the temporal scales within the study period. The particle size distribution varied between years, which can be explained by the difference in rainfall patterns, flood characteristics, and land use during the study period. The percentage of particle size < 2 μm fraction (clay-sized material) was relatively large and ranged from 6 to 76% (Fig. 2.2a), and the average percentage of the particle size smaller than 2 μm was approximately 36%. The percentage of the particle ranges from 2-62 μm ranged from 24 to 93% (Fig. 2.2b), and the average percentage was approximately 61%. The percentage of coarser particles (62 μm-1 mm) was relatively small and ranged from 0 to 15% (Fig. 2.2c), and the average percentage only accounted for 3%.

Most natural rivers become finer grained in sediment size, higher in discharge, gentler in slope, and more meandering when going downstream (Paola et al., 2014). As IS1 is located at the outlet of the watershed, it provides the evidence of a downstream fining process of suspended sediment, since the particle size was dominated by finer grains in most of the study years. In general, size selectivity is probably an important fining process observed in a number of studies (e.g., Stone and Walling, 1997; Asadi et al., 2007*a,b*; Malam Issa et al., 2006; Miller and Baharuddin, 1987).

Particle size selectivity of sediment processes result in a permanent downstream fining trend when the longitudinal bed profile is upward concave. This concave bed profile can cause the decrease in flow strength and transport capacity downstream, which leads to coarse particles deposition. In contrast, when the bed profile is linear, particle size selective transport processes may result in a higher transport rate for fine materials than coarse particles, which does not lead to permanent downstream fining (Frings et al., 2011). The STCW is characterised by meandering reaches, which is dominated by finer-grained sediment, especially at the outlet of the watershed (e.g., IS1).

Sampling at the outlet of the watershed may not provide sufficient information to support a meaningful conclusion on the sediment dynamics in the watershed. Further information of particle size distribution of all the sites from headwater to the outlet is presented in Chapter 3.

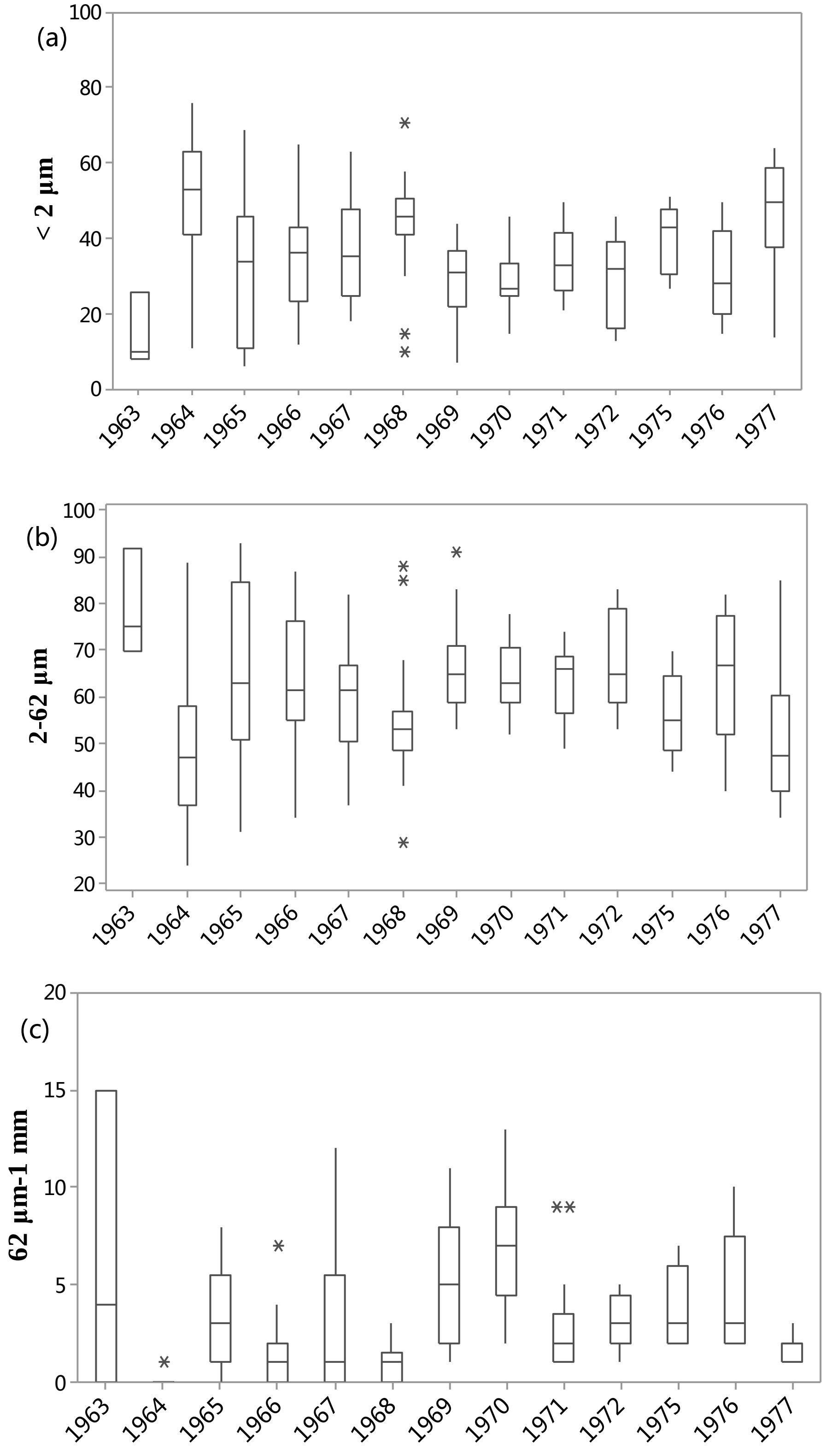

Figure 2.2 Particle size distribution of the suspended sediment collected at IS1 from 1963 to 1977.

2.6.1.2 Seasonal variations in particle size distribution of suspended sediment

A comparison of the particle size distribution of suspended sediment between snowmelt events (March-May) and rainfall events (June-November) is presented in Table 2.3. The temporal change of sediment particle size distribution showed that the particle size distribution of suspended sediment varied among runoff events. The high temporal variation could be due to the differences in flow rate. The annual average (1963-1977) percentage of particle size < 2 μm of suspended sediment was slightly smaller in snowmelt events (mean % < 2 μm = 33.3%) than that in rainfall events (mean % < 2 μm = 37.6%). However, the average percentage of particle size ranges from 2-62 μm of suspended sediment in snowmelt events (mean % 2-62 μm = 63.1%) was slightly larger than that in rainfall events (mean % 2-62 μm = 58.0%). The percentages of particle size 62 μm-1 mm in snowmelt event and rainfall event were both small (3.5% and 4.4%, respectively) (Table 2.2). In general, particle size of suspended sediment collected in snowmelt events was coarser than in rainfall events.

The seasonal variations in particle size of suspended sediment could be explained by seasonal variations in stream flow with the increasing proportion of large particles transported during large discharges (Stone and Walling, 1997). At the beginning of snowmelt runoff (i.e., early spring), most runoff occurred on the frozen soil and resulted in finest particle sizes. As the snowmelt proceeded, snowmelt water and soil contact provided a chance for water erosion to occur. With the high flow rate during the middle of snowmelt runoff, large particle sediments which originated from river bank and fields can be washed into the streams resulting in coarse soil particle (i.e., snowmelt event). The coarser soil particles observed in rainfall events can be attributed to storm events. Similar results conducted by Stone and Walling (1997) showed that a greater amount of primary and aggregate particles in the silt- (20-63 μm) and sand- (63 μm-2 mm) sized classes were easy to mobilize in snowmelt events while greater amounts of fine silt were mobilized in rainfall events.

Table 2.2 Statistical summary of particle size distribution of suspended sediment during snowmelt events (March-May) and rainfall events (June-November) at IS1

Events		**Particle size fraction (% total)**		
		< 2 μm	**2-62 μm**	**62 μm-1 mm**
Snowmelt events	Mean	33.3	63.1	3.6
	Median	32.9	63.3	3.5
	Skewness	-0.2	0.5	-0.05
	Min	48.3	79	7
	Max	14.7	51.7	0
Rainfall events	Mean	37.6	58	4.4
	Median	37.9	55.7	2.2
	Skewness	-0.04	0.3	2.7
	Min	51	70	22.5
	Max	23	48.5	0.5

Table 2.3 Comparison of particle size distribution of suspended sediment during snowmelt event (March-May) and rainfall event (June-November) at IS1

Event	Year	Particle size fraction (% total)			Event	Year	Particle size fraction (% total)		
		< 2 µm	2-62 µm	62 µm-1 mm			< 2 µm	2-62 µm	62 µm-1 mm
Snowmelt	1963	14.7	79.0	6.3	**Rainfall**	1963	ND	ND	ND
	1964	48.3	51.7	0.0		1964	51.0	48.5	0.5
	1965	26.8	69.8	3.3		1965	42.3	55.0	2.7
	1966	35.9	62.4	1.7		1966	31.3	66.4	2.3
	1967	32.7	62.9	4.4		1967	48.5	51.0	0.5
	1968	44.8	54.1	1.1		1968	42.8	56.4	0.8
	1969	33.0	63.8	3.3		1969	23.0	69.6	7.4
	1970	28.1	64.9	7.0		1970	ND	ND	ND
	1971	34.0	61.3	4.7		1971	33.4	64.4	2.1
	1972	28.6	68.2	3.2		1972	ND	ND	ND
	1973	ND	ND	ND		1973	28.5	49.0	22.5
	1974	29.0	66.0	5.0		1974	ND	ND	ND
	1975	40.7	55.7	3.7		1975	27.0	70.0	3.0
	1976	30.4	65.2	4.4		1976	ND	ND	ND
	1977	39.8	58.6	1.6		1977	48.0	50.0	2.0

ND, no data

2.6.1.3 Annual variation in water discharge, sediment load and sediment concentration

Analysing the water discharge data recorded at IS1 station, gave a long-term (1963-1977) mean value for annual flow rate of 44.1 m^3 s^{-1} (annual total discharge $=1.3*10^9$ m^3 yr^{-1}; annual sediment load = 13,349 t yr^{-1}; sediment yield = 18.7 m^3 m^{-2}) while the maximum and minimum value of water discharge was 135.7 m^3 s^{-1} and 1.24 m^3 s^{-1}, respectively (Fig.2.3). Annual suspended sediment loads for 1963-1977 were calculated from the daily observations of sediment concentrations and are shown in Fig. 2.4. Increasing trends in the water discharge and sediment load between 1963 and 1970 are statistically significant ($p < 0.001$ and $p = 0.003$, respectively). A positive linear regression indicated that the trends of water discharge and sediment load increased over this period. These results suggest that the increase in sediment load is likely due to increased precipitation and water discharge. Between 1971 and 1977, there was a decrease in water discharge and sediment load. Because the sediment load is usually correlated with water discharge, the decrease sediment load was also attributed to the decreasing trends in water discharge.

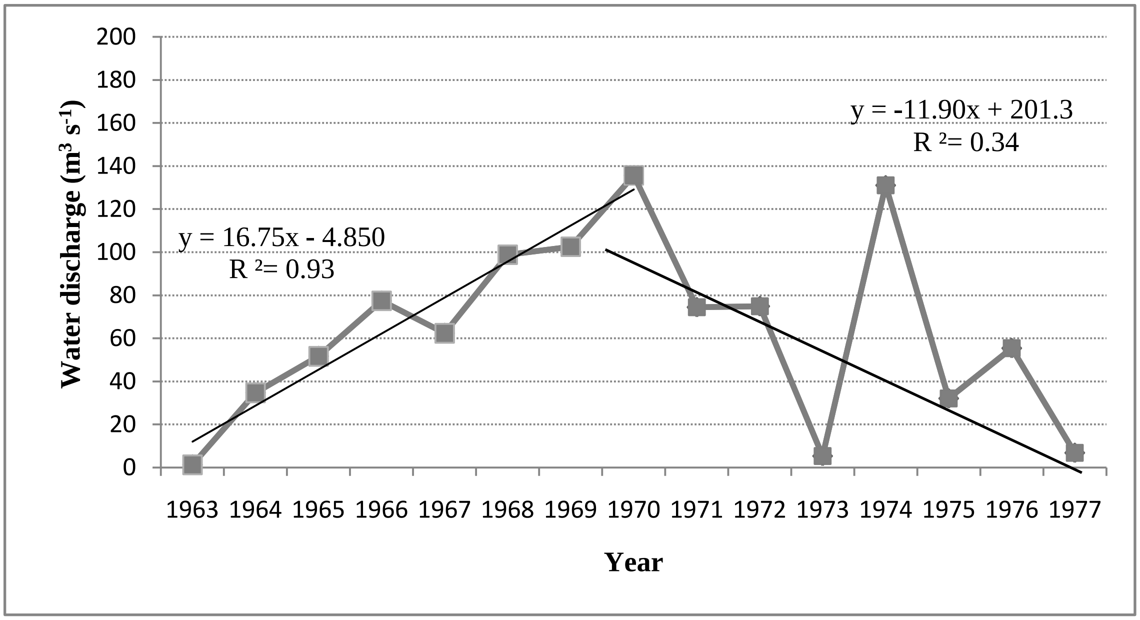

Figure 2.3 Temporal variations in annual water discharge during 1963-1977 at IS1.

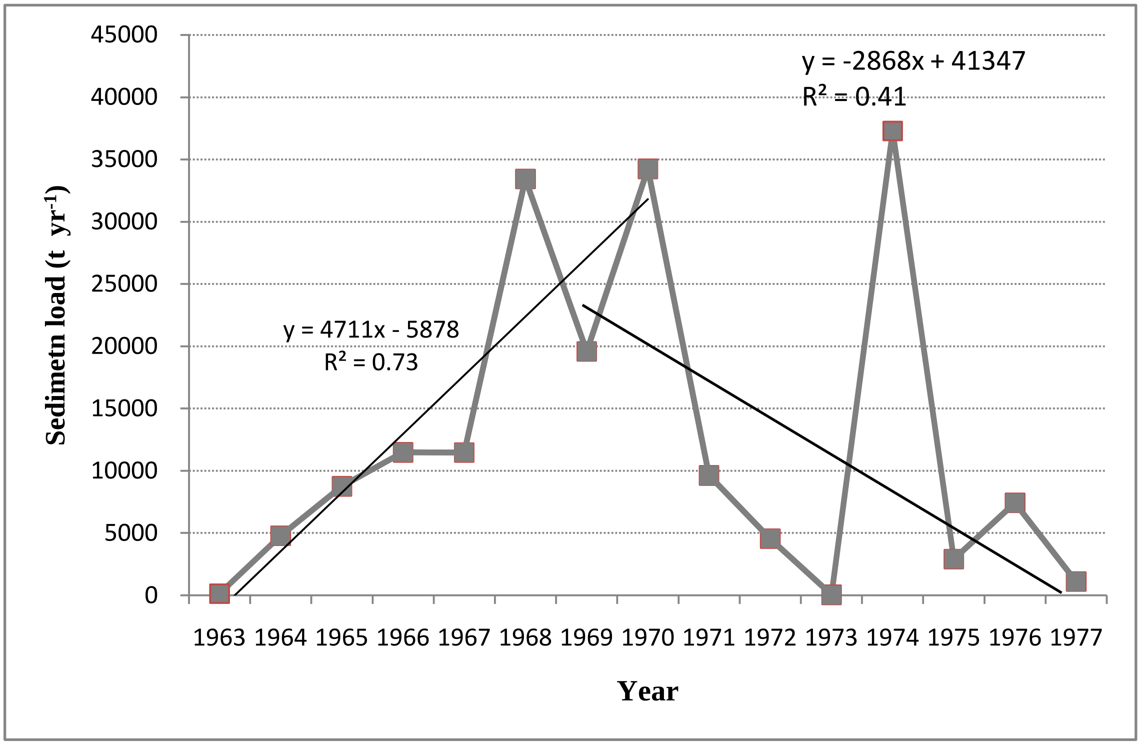

Figure 2.4 Temporal variations in annual sediment load during 1963-1977 at IS1.

2.6.1.4 Seasonal changes in water discharge, sediment load and sediment concentration

A statistical summary of water discharge, sediment load and sediment concentration in two seasons is presented in Table 2.4. A statistically significant difference (Mann-Whitney U test 95% level of confidence) was identified for water discharge, sediment load and sediment concentration between March-May (snowmelt event) and June-November (rainfall event), with *p* values of 0.004, 0.007 and 0.02, respectively. Yearly water discharge patterns typically displayed a snowmelt peak (usually in March and April in spring) and multiple rainfall event peaks (various time between June and September). The three months of March through May represent snowmelt events and carry most of the flow which was caused by the snow melt. The five months of June through November represent rainfall events and carry far less of the flow. The annual average of sediment concentration during March-May was 36,283 mg L^{-1}, where during June-November was 150 mg L^{-1}. In snowmelt event, it had the highest maximum discharge (131.3 m^3 s^{-1}). In rainfall events, on the other hand, had the lowest maximum and minimum discharges (80.4 m^3 s^{-1} and 0.1 m^3 s^{-1}, respectively). The water discharge in the snowmelt season accounted for approximately 78% of the annual water discharge during 1964 to 1977. In rainfall events, the water discharge was attributed to relatively more intensive rainfalls, but only accounted for 21% of the annual water discharge during that period. Among the two periods, the rainfall events had the most variable discharges (CV=167.5%), while water discharges in snowmelt events had smaller degree of variation (CV = 54.2%). Statistically, water discharges in snowmelt events were relatively high and those in summer were relatively low.

Suspended sediment concentration followed the seasonal patterns of discharges, and showed a significant difference between the two seasons. Although mean sediment concentration (36,283 mg L^{-1}) was higher in snowmelt events than that in rainfall events (20,532 mg L^{-1}), rainfall events had higher maximum sediment concentration (83,765 mg L^{-1}) than that in snowmelt events (71,823 mg L^{-1}) (Table 2.4). This was consistent with higher suspended sediment concentration in rainfall events than that in snowmelt events (CV = 107.8%, and 53.1%, respectively). Generally, the stream transported more sediment in snowmelt events than that in rainfall events, whereas, sediment transport in summer had higher variability (Table 2.4). The high suspended sediment concentration in snowmelt events may be due to sediment stored on hillslopes and in stream during winter snowmelt events and flushed by early spring floods. The greater sediment variations in rainfall events were caused by high variations of summer rainfall events, which agreed with the high variations of summer-fall water discharges. The general pattern also coincides with the seasonal changes of land cover: during the snowmelt events, the degree of grass covers decreases and there are relatively large areas of exposed bare soils. This coincidence suggests that suspended sediment transport is not only related to stream discharges, but also affected by seasonal changes in land use and land cover, which control sediment supply from upland hillslopes to stream network (Gao and Josefson, 2012).

Table 2.4 Statistical summary of water discharge, sediment load and sediment concentration during snowmelt and rainfall events

Events		Water discharge ($m^3 s^{-1}$)	Sediment load (ty r^{-1})	Sediment concentration (mg L^{-1})
Snowmelt	Min	3	29	9,317
	Max	131.3	37,276	71,823
	Mean	54.2	10,131	36,283
	CV (%)	73.8	115.4	53.1
Rainfall	Min	0.1	1.3	973
	Max	80.4	29,648	83,765
	Mean	12.3	3,002	20,532
	CV (%)	167.5	250.5	107.8

2.6.1.5 The relationship between water discharge and sediment load

Sediment loads are estimated from sediment-rating curves created by performing a linear least-square regression on log-transformed sediment load versus log discharge data. Fig. 2.5 shows a positive relationship between log discharge and log sediment load in snowmelt and rainfall events with high R^2 values (R^2 = 0.87 and 0.88, respectively). The seasonal variation in discharge and sediment load indicates that sediment transport during high and low flows is controlled by different processes. During the rainfall runoff events, the rainfall storm can trigger substantial water erosion from fields and riverbank. The higher flow rate causes more sediment. This explained the positive linear relationship between the concentration of sediment and flow rate for rainfall runoff. During the snowmelt runoff events, the surface soil was partially frozen. When it is warm, the contribution of the snowmelt period to the sediment load was very significant.

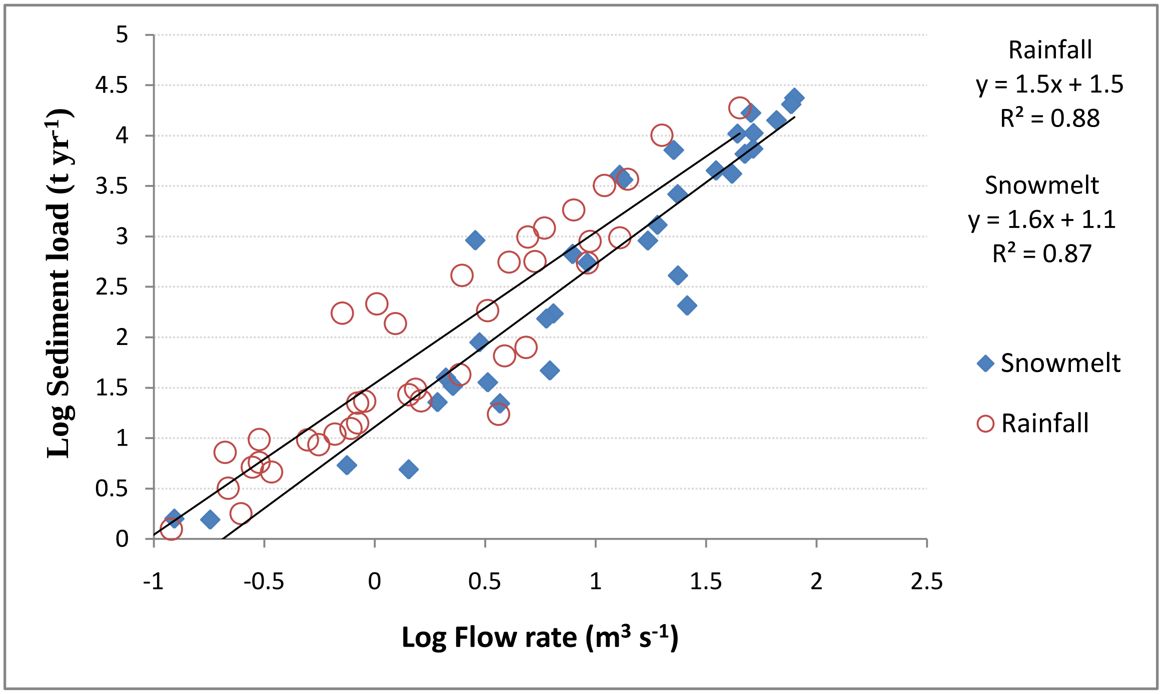

Figure 2.5 Seasonal variation in log flow rate and log sediment load from 1967-1977.

2.6.2 Sediment and hydrologic variables (data set from 2002-2011)

The year-to-year variability in precipitation, including rainfall and snowfall were high in the study watershed. During the entire study period, 10 rainfall and 9 snowmelt events were monitored at IS1 and IS3 (Table 2.5). The hydrologic variables partially reflected the variation of weather parameters among years (Liu et al., 2013). For example, in the yearly snowmelt runoff events, the peak flow rate ranged from 0.3 to 22.5 $m^3 s^{-1}$ (CV = 96%) at IS1, and from 0.3 to 10.0 $m^3 s^{-1}$ (CV = 85%) at IS3. The VolR ranged from 49.7 to 1,028 $m^3 ha^{-1}$ (CV = 87%) at IS1, and from 53.74 to 1,204 $m^3 ha^{-1}$ (CV = 82%) at IS3. In the yearly rainfall runoff events, peak flow rate ranged from 0.3 to 30.2 $m^3 s^{-1}$ (CV = 104%) and the VolR ranged from 40.8 to 1,027 $m^3 ha^{-1}$ (CV = 84%) at IS1, while the corresponding hydrologic variables were relatively lower at IS3 with peak flow rate ranging from 0.03 to 18.3 m^3 s^{-1} (CV = 111%) and VolR ranged from 27.1 to 1,020 m^3 ha^{-1} (CV = 88%). PkFR was greater in the rainfall runoff than in the snowmelt runoff at both sites. In contrast, average flow rate was greater in the snowmelt runoff than in the rainfall runoff.

At both sites, there was considerable inter-year variability for FWMC of TSS (Table 2.5). On average, concentrations of TSS were greater during rainfall events than in snowmelt events. This is consistent with recent studies in two paired agricultural watersheds in Canada (e.g., Tiessen et al., 2010). The long-term data collected at IS1 indicated that sediment concentration was positively related to flow rate for rainfall runoff events, but no significant relationship was observed for snowmelt runoff events.

Table 2.5 Summary of seasonal volume of runoff, average flow rate, peak flow rate and flow-weight mean concentrations of total suspended sediment in snowmelt and rainfall runoff events during the study period from 2002 to 2011

IS1										
Variables[a]	Rainfall events					Snowmelt events				
	Mean	Max.	Min.	CV (%)	n	Mean	Max.	Min.	CV (%)	n[b]
VolR ($m^3\ ha^{-1}$)	406.2	1,027	40.8	84	10	384.7	1,028	11.0	87	10
AvFR ($m^3\ s^{-1}$)	0.3	0.5	0.0	61	10	0.8	11.0	0.1	94	10
PkFR ($m^3\ s^{-1}$)	9.8	30.2	0.3	104	10	8.5	22.6	0.3	96	10
FWMCTSS ($mg\ L^{-1}$)	1,450	3,158	22.9	66	10	538.8	1,353	10.0	76	9

IS3										
Variables	Rainfall events					Snowmelt events				
	Mean	Max.	Min.	CV (%)	n	Mean	Max.	Min.	CV (%)	n
VolR ($m^3\ ha^{-1}$)	398.9	1020.2	27.1	88	10	468.6	1204.7	11.0	82	10
AvFR ($m^3\ s^{-1}$)	0.1	0.5	0.0	118	10	0.4	11.0	0.0	84	10
PkFR ($m^3\ s^{-1}$)	6.1	18.3	0.0	111	10	3.5	11.0	0.3	85	10
FWMCTSS ($mg\ L^{-1}$)	780.0	1807.8	9.9	75	10	583.8	1217.1	10.0	61	9

[a] VolR, Volume of runoff; AvFR, average flow rate; PkFR, peak flow rate; FWMCTSS, flow-weighted mean concentration of total suspended sediment.

[b] Because there was no snowmelt runoff in 2002, the number of observation was 9 in snowmelt events and 10 in rainfall events during the 10-yr study.

2.6.3 The relationship between particle size of suspended sediment and water discharge (data collected in 2013)

The particle size characteristics of in-stream suspended sediment exhibits appreciable temporal variation within individual storms. The variation in particle size with water discharge for sediment carried as suspended load is shown in Fig. 2.6. The largest discharges were observed during April-June due to the high peak of runoff usually happened from snowmelt in winter-spring and from rainfall in spring- and early-summer (Table 2.6).

Table 2.6 Statistical summary on daily discharge at IS1, 2013

Month	April	May	June	July	August	September	November
Mean ($m^3 s^{-1}$)	1.4	2.4	1	0.07	0.02	0.005	0.01
Max ($m^3 s^{-1}$)	14	15.4	14	0.13	0.065	0.052	0.034
Min ($m^3 s^{-1}$)	0	0.23	0.10	0.041	0	0	0

The particle size distribution in suspended sediment is related to discharge, season and sediment concentration. Sediment transported both in suspension and channel bed was carried by extremely high flow, which can cause the greatest changes in particle size distribution due to size selection and deposition. High flow rate had a tremendous effect on sediment transport, the most obvious observation was the increased percentage of sand on May 23 and 31th at discharges of 1.7 $m^3 s^{-1}$ and 15.4 $m^3 s^{-1}$, respectively (Fig. 2.6). Apparently, more silt and clay was in suspension in the flood period than in the pre-flood period (i.e., April 29). Normally, the percentage of silt and clay was higher in snowmelt events than rainfall events due to the flow rate increased in late snowmelt events. The sand proportion was as much as 34.2% of the suspended sediment during rainfall events.

The particle size distribution of suspended sediment was clearly expected to vary temporally in response to variations in water discharge (Walling and Moorehead, 1989).

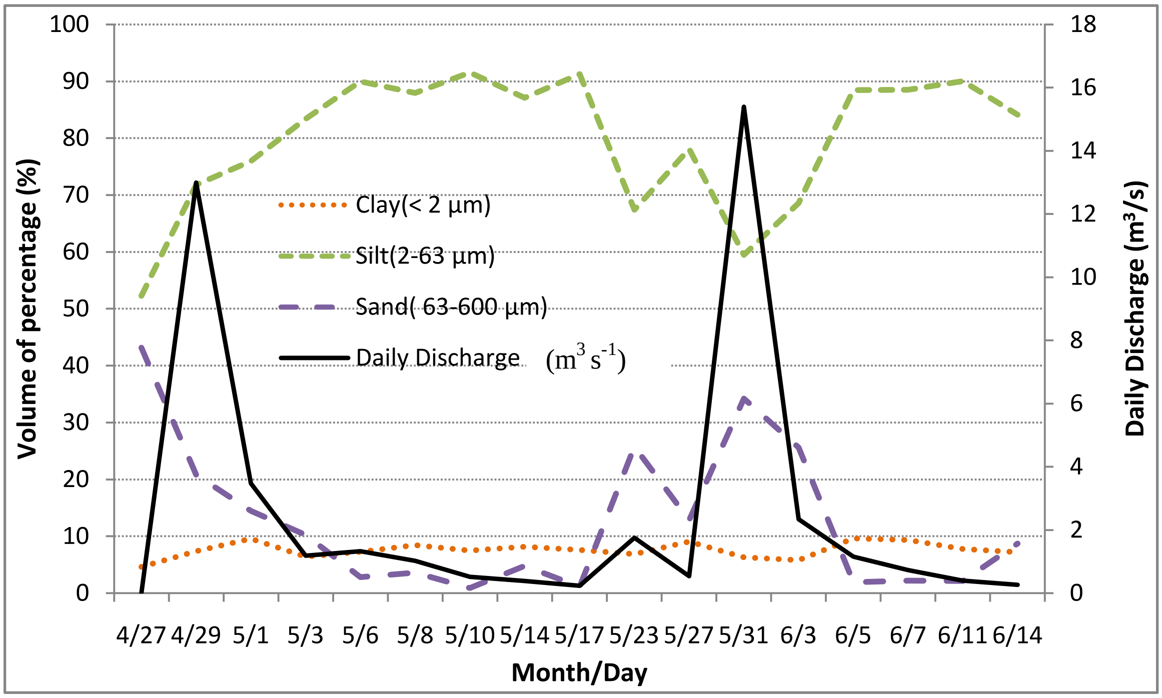

Figure 2.6 Particle size distributions of suspended sediment and daily discharge at IS1, 2013.

A study conducted in the Eel River in California (Brown and Ritter, 1971) indicated the proportion of sand increased and the proportion of clay decreased in response to increasing discharges. Similar results were also reported by Vice et al. (1969). However, the reverse trend was found in the Lower Kansas River (USA) (Mundorff and Scott, 1964) and in the Blue Ridge region in USA (Kennedy, 1964) showing that decreased sand proportion and increased proportion of clay and silt occurred when the discharge increased. Walling and Moorehead (1989) summarized that the sand content of suspended sediment increased as water discharge increased while the clay content decreased at three locations of River Exe.

Data collected during the period from 1963 to 1977 at IS1 indicated that there was an uncertainty in the relationships between particle size characteristics of suspended sediment and water discharge (Table 2.7). In most of the year during the study period, the coarser materials increased as water discharges increased. The increased turbulence or shear velocity occurring at high flow can explain the increased sand transport and reduced proportion of clay. Seasonal variations occur in erosion process and source areas experiencing floods generated by spring snowmelt and summer storms. Seasonal variations in sediment character may override any relationship between particle size of sediment and discharge.

Table 2.7 The relationship between the particle size characteristics of suspended sediment and water discharge during 1963 to 1977

Year	Response to increasing discharge
1963	Not enough data
1964	No significant difference
1965	Proportion of sand increases, proportion of clay and silt decreases
1966	Proportion of sand and clay increases, proportion of silt decreases
1967	Proportion of sand increases
1968	Proportion of silt increases, proportion of clay decreases
1969	No significant difference
1970	Proportion of sand and clay increases, proportion of silt decreases
1971	Proportion of silt and clay decreases
1972	No significant difference
1973	Not enough data
1974	Not enough data
1975	No significant difference
1976	Not enough data
1977	Proportion of silt and clay decreases

2.7 Conclusions

This chapter characterized the water discharge, sediment concentration and particle size of suspended sediment in three study periods. The results presented above demonstrate a number of important features relating to the controls of particle size of suspended sediment transported within the South Tobacco Creek Watershed.

Both water discharge and suspended sediment concentration data showed clear seasonal patterns. In spring, it had higher mean water discharge due to rainfall and snowmelt, while summer-fall had relative lower mean discharge but higher maximum discharge and higher variation due to relatively more intensive rainfall over the period from June to November. The suspended sediment concentration was generally higher during snowmelt and was more variable during rainfall events. These patterns indicated that seasonal sediment transport maybe controlled by climate and seasonal variability of land cover. The relationship between water discharge and particle size of suspended sediment for data from 1963-1977 and 2013 was examined. The results showed the sediment was dominated by fine-size particles (< 62 μm) at the outlet of the study watershed. A long-term hydrological and sediment study indicated that the concentration of sediment was typically greater in winter-spring (snowmelt events) than during summer-fall (rainfall events). Total runoff was dominated by snowmelt, with most sediment export occurred during snowmelt.

The hydrology, sediment concentration and sediment particle size demonstrates appreciable temporal variation in the study watershed. Hydrologic regime affects the variation in particle size and sediment concentration of suspended sediment. The influence of hydrology on the variation in particle sizes of suspended sediment can be used to explain in the spatial variation in particle size of sediment. Discharge and the flow conditions at the time of sampling were all shown to exert a significant influence on the particle sizes of suspended sediment. Further studies can focus on the influence of suspended sediment properties on the nutrient content and its spatial and temporal variability.

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3. PARTICLE SIZE CHARACTERISTICS OF SEDIMENT IN THE TOBACCO CREEK WATERSHED

3.1 Abstract

Particle size characteristics of suspended sediment are important in understanding, and modeling sediment entrainment, transport and deposition processes. Particle size of sediment also plays a significant role in tracing sediment sources and fates. In the current study, suspended sediment and fine fraction of channel bed sediment were collected twice per year, following snowmelt events (May-June) and rainfall events (July-November), in the Tobacco Creek Watershed to analyze the particle size characteristics. Three potential sediment sources were identified from the field observations, including the topsoil from cultivated fields, topsoil from riparian areas and streambank material. The spatial and temporal variations in particle size of these samples were analyzed using a laser diffraction instrument and analysis of the correlation between the potential source materials and the suspended sediment was conducted. Across the spatial scales examined in this study, the particle size of suspended sediment was generally coarser in the upper reaches (above the escarpment) than that in the lower reaches (below the escarpment). Across the temporal scales, particle size distribution of suspended sediment showed a significant seasonal variation between snowmelt and rainfall events. At most of the sampling sites, over 60% of the suspended sediment was in silt-sized particles (2-63 μm). The source materials were dominated in fine-sand particles (63-600 μm). Comparing the

particle size of suspended sediment with that of potential source materials provided some support for the processes of size selectivity during the sediment transport and deposition.

3.2 Introduction

Sediment has been identified as an important part in the hydrological, geomorphological, and ecological functioning of rivers. Sediment transport in the stream is very complex, and suspended sediment concentration and suspension duration depend on flow hydraulics, upstream sediment supply and sediment transport capacity. At the watershed scale, dynamics of suspended sediment transport is still poorly understood.

Suspended sediment is an important medium in the transfer and sequestration of nutrients and contaminants in streams, including phosphorus, pesticides, heavy metals and micro-organics (e.g., Horowitz, 2008; Walling, 2013; Juracic et al., 1986; Phillips and Walling, 1995; Walling et al., 2000). Particle size is one of the most important physical characteristics of sediment which influences its capacity to adsorb the nutrients and contaminants. From a physical perspective, the particle size characteristics of suspended sediment affect its settling velocity (Gibbs et al., 1971) and thus its entrainment, transport and deposition (Walling et al., 2000). From a chemical perspective, the particle size of sediment plays an important role on controlling its mineralogy and geochemical properties (Horowitz, 1985), radionuclide concentrations (He and Walling, 1996) and mineral magnetic properties (Foster et al., 1998). For example, silicate minerals dominate very fine fractions (< 2 μm), whereas larger fractions are dominated by quartz (Walling and Moorehead, 1989). The specific surface area increases rapidly with decreasing particle size, which is a major control of chemical concentrations of sediment (Walling and Moorehead, 1989).

Recent work has demonstrated that much of the suspended sediment leaving an area of soil that is undergoing erosion is a combination of primary particles and secondary or aggregated soil materials (Walling and Moorehead, 1989). It has been observed that the particle size distribution of sediment can change dynamically during rainfall-driven erosion (Hairsine et al., 1999) and flow-driven erosion (Asadi et al., 2007*b*) due to numerous factors such as selective erosion of sediment, preferential deposition, abrasion and selective delivery during sediment transport (Walling and Moorehead, 1989; Stone and Walling, 1997; Hairsine et al., 1999). It has been widely accepted that the particle size distribution of suspended sediment varies both spatially and temporally (Ali and de Boer, 2007; Walling and Kane, 1982). Some studies have emphasized that selective transport is a more significant factor than abrasion in explaining observed downstream fining trends of sediment (e.g., Rice, 1999; Stone and Walling, 1997; Knighton, 1975). The eroded materials transported in stream are usually enriched with relatively fine particles (clay and silt-sized) and depleted of coarser fraction materials when compared to the original sediment source materials (Farenhorst and Bryan, 1995; Martinez-Mena et al., 2002; MalamIssa et al., 2006; Walling et al., 2000). However, some studies have found sediment eroded from cohesive agricultural soils became coarser (e.g., Meyer et al., 1992) or have bimodal (e.g., Asadi et al., 2007*b*) particle size distribution with one small and one larger size class dominating the eroded sediment compared to the source material.

In many sediment fingerprinting studies, particle size analysis only focused on the fine fraction material (e.g., < 63 μm) and absolute particle size to facilitate a comparison between suspended sediment and potential sources (e.g., Collins et al., 2001; Martínez-Carreras, 2010*b*). However, none of the studies focused on the dynamics of sediment transported in stream. There are issues with the restricted analysis range in particle size, such as sample representativeness. In soil erosion, much of the soil is moved as aggregates, which are a cohesive agglomeration of both inorganic and organic matter. It is better to draw conclusion about the mobilisation and transport of sediment based on the effective or aggregate particle size distribution and to increase analysis range in particle size.

Since many factors affect the particle size of suspended sediment during transport, the use of particle size to determine the sediment sources is limited. It is important to have a solid understanding of the size selective nature of soil erosion and sediment transport processes. An improved understanding of sediment-water interactions is required to enhance the knowledge of the factors governing spatial and temporal variations in the particle size distribution of suspended sediment. The objectives of this study were: 1) to characterize the spatial and temporal variations in particle size of in-stream suspended sediment and channel bed sediment; 2) to characterize the particle size distribution of potential sediment sources; and 3) to evaluate the relationship in particle size between potential source materials and suspended sediment.

3.3 Study Area

The South Tobacco Creek Watershed (STCW) is 74.6 km^2 (49^{o}22’ N, 98^{o}14’ W) in size and located on the edge of the Manitoba Escarpment in south-central Manitoba, within the greater Tobacco Creek Watershed (TCW) (1,040 km^2). The Tobacco Creek flows into the Red River and Lake Winnipeg, and ultimately into Hudson Bay.

The surface materials above the escarpment are mainly thin glacial tills which are predominated by mixed deposits of shale, limestone and granite. The lower layers are mainly comprised of lacustrine sediment of glacial Lake Agassiz. The main landscapes are undulating to hummocky landscapes with slopes of up to 10% (Tiessen et al., 2010). The dominant soil types are the Dezwood soil series (Orthic Dark Gray Chernozems) with primarily clay-loam texture on upper and mid-slope positions of the landscape and Zaplin soil series (Gleyed Dark Gray Chernozem) in the lower slope positions. The surface soil materials below the escarpment are mainly medium-to coarse-grained glaciolacustrine deposits, and become fine-grained particles in the downstream.

The STCW lies in the Prairies ecozone, with tall grass prairie covering the dominant form of vegetation above and below the escarpment and deciduous trees along the riparian corridors of tributaries and main river channels within the escarpment. The regional climate is semi-arid to sub-humid, with pronounced seasonal variations where summers are short and cool and winters are long and cold (Tiessen et al., 2010). The average annual temperature of the site is 2.2 ^{o}C and 3.3 ^{o}C above and below the escarpment, respectively. The mean annual precipitation above the escarpment (almost

590 mm) is higher than that below the escarpment (500 mm) due to the different terrains. Snowfall accounts for approximately 25% of the precipitation while snowmelt runoff typically accounts for 80% of surface water recharge.

Agriculture is the major human activity in the study watershed. The land was first developed for both crop and livestock production since the early-1900s. The current agricultural system in the study watershed is dominated by oilseed (e.g., canola) and cereal production (e.g., corn, wheat). A part of the study watershed has remained under conventional tillage practices and another part of field has experienced three types of tillage operation. The intensity of tillage practices has decreased since 1970s (Li et al., 2006).

3.4 Materials and Methods

3.4.1 Sample Collection

To evaluate the dynamics of sediment delivery to surface waterways, three potential sources were identified based on field observations. These potential sources were: (1) agricultural fields (i.e. canola, corn, wheat and soybean fields); (2) riparian areas adjacent to the creek; and (3) streambank. Topsoil sampling area extended from the edge of the streambank through the whole riparian zone and into the adjacent fields which were close to the suspended sediment samplers. Two or four transects were established at each sampling site. Each transect had four to eight individual sampling points and soil samples were collected from the upper 5 cm of the A-horizon using a soil probe (Koiteret al., 2013). The streambank profile was also sampled at five selected sites. Under low flow conditions, soil samples were collected in 5- to 10-cm increments down the streambank profile using a box-core sampler by inserting it perpendicular to the streambank wall.

In order to measure spatial and temporal variations of the particle size characteristics of suspended sediment within the TCW, samples were collected at 9 sampling sites twice per year in snowmelt (May-June) and rainfall events (July-November) in 2012. The 9 sampling sites along the TCW are shown in Fig 3.1, where the sampling sites from left to right are, IS5, IS4, ISF, IS3, IS2, IS1, ISG, ISB1 and ISB2. IS5 is established at the head of the STCW, while IS1 is established at the outlet of the watershed near Miami, approximately 150 km southwest of Winnipeg, and ISG, ISB1 and ISB2 are established in the downstream along the TCW. A passive time-integrated sediment trap following the design of Phillips et al. (2000) was used to collect the suspended sediment. Sediment traps were connected to a steel rod using chains and quick links that allows the samplers to be fixed to the channel bed. Two sediment traps were installed along the flow path in the middle of the main channel at each sampling site to ensure that a representative sample could be collected. The sediment traps were checked two to four times per month depending on stream flow conditions. The channel bed consists largely of unconsolidated sediment and shale fragments. Field observations indicated that there was considerable channel bed sediment transport as the pattern of channel bars changed between site visits (Koiter et al., 2013). Therefore, channel bed sediment was collected using a small trowel to a depth of 5 cm. A summary of suspended sediment, channel bed sediment and potential source materials sampling is presented in Table 3.1.

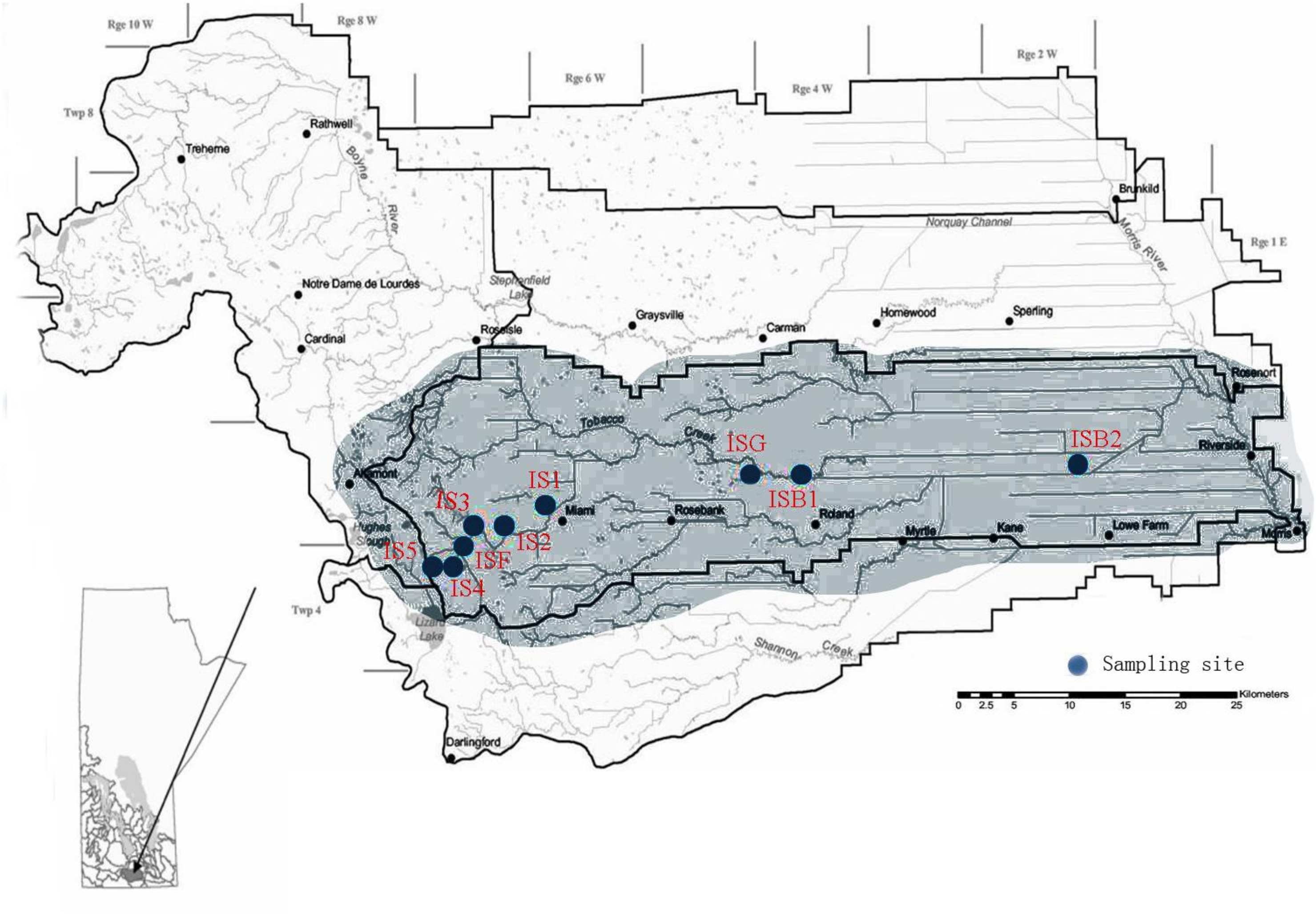

Figure 3.1 Location of sampling sites in the Tobacco Creek Watershed (shaded) which lies within the Boine-Morris Watershed.

Table 3.1 Summary of samples collection (a), and number of potential source materials in the TCW (b)

(a) **Year**	**Events**	**Month**	**Sampling site**								
			IS5	IS4	ISF	IS3	IS2	IS1	ISG	ISB1	ISB2
2012	Snowmelt	May-June	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL
	Rainfall	July-November	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL	SS+BL

Note: SS = suspended sediment; BL = channel bed sediment

(b) **Sediment source**†	**Sampling site**								
	IS5	IS4	ISF	IS3	IS2	IS1	ISG	ISB1	ISB2
TF	NS	3	NS	1	3	3	NS	NS	NS
TR	NS	1	NS	3	3	3	NS	NS	NS
SB	4	4	NS	19	14	18	NS	NS	NS

†SB = streambank; TF = topsoil from agricultural fields; TR = topsoil from riparian area
NS, No sample

3.4.2 Particle size analysis using laser diffraction

Two grams of potential source materials were mixed with 40 ml of distilled water into a 120-ml container for particle disaggregation. The in-stream suspended sediment and was immediately brought to the laboratory and sub-sampled. The channel bed sediment was subsample and mixed with 40 ml of distilled water a 120-ml container for particle disaggregation. The sediment-water mixture was sieved through a 600-μm sieve. The particle size distribution of each sample was measured using a Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK) with a Hydro S wet cell attachment. The instrument measured the intensity of light scattered as a laser beam passed through a dispersed particulate sample. Generally, smaller particles scattered lower intensity light to larger angles, while larger particles scattered relatively stronger intensity light toward smaller diffraction angles.

Sample representativeness is very important for characterizing sediment particle size distribution since only a small amount of sample was taken for the instrumental analysis. Additionally, sediment can be easily settled in containers within a short time. To prevent sedimentation, complete mixing of the sample is therefore an essential step. After gently inverting the container 4 to 5 times, a small aliquot of the sediment-water mixture was injected into the instrument using a pipette. The particle size of sediment was measured when the suspension was continuously injected into the system. This ensured random orientation of most particles through the laser beam, and the equivalent spherical cross-sectional diameter was measured. The manufacturer recommended that the value of obscuration ranges between 10% and 20%. Pump and stirrer speeds were kept constant throughout the analysis.

3.4.3 Data interpretation

The pattern of sediment particle size was investigated separately for three sediment-size classes: (a) clay-size (< 2 μm); (b) silt-size (2-63 μm); and (c) fine sand-size (63-600 μm). Statistical significance was determined using a Mann-Whitney U test (90% level of confidence) by Minitab 17 software (Minitab, Inc), which was used to compare the median particle size of sediment collected between March-May (snowmelt events/spring) and June-November (rainfall events/summer and fall). One way analysis of variance (ANOVA) was done to compare the spatial and temporal variations in particle size of sediment. The threshold level of statistical significance was $\alpha = 0.1$ for the analysis.

3.5 Results and Discussion

3.5.1 Spatial variation in particle size characteristics of suspended sediment

Median particle size (d_{50}) of the suspended sediment collected at 9 sampling sites is presented in Fig. 3.2. The median particle size of suspended sediment was shifted towards fine-grained particles from the upper reaches (e.g., IS5, IS4 and ISF) to the lower reaches (e.g., IS3, IS2, IS1, ISG, ISB1 and ISB2) following snowmelt events. The median particle size of suspended sediment (d_{50}) was typically in the range of 39.6-51.2 μm in the upper reaches, and decreased to the range of 10.8-14.5 μm in the lower reaches. Similar trends were observed following rainfall events, where the median particle size of suspended sediment varied from 74.1 μm in the upper most reach (e.g., IS5) to 6.8 μm in the lower reach (e.g., IS3). The results were consistent with the findings of downstream fining which was reported in other studies (e.g., Walling et al., 2000; Stone and Walling, 1997).

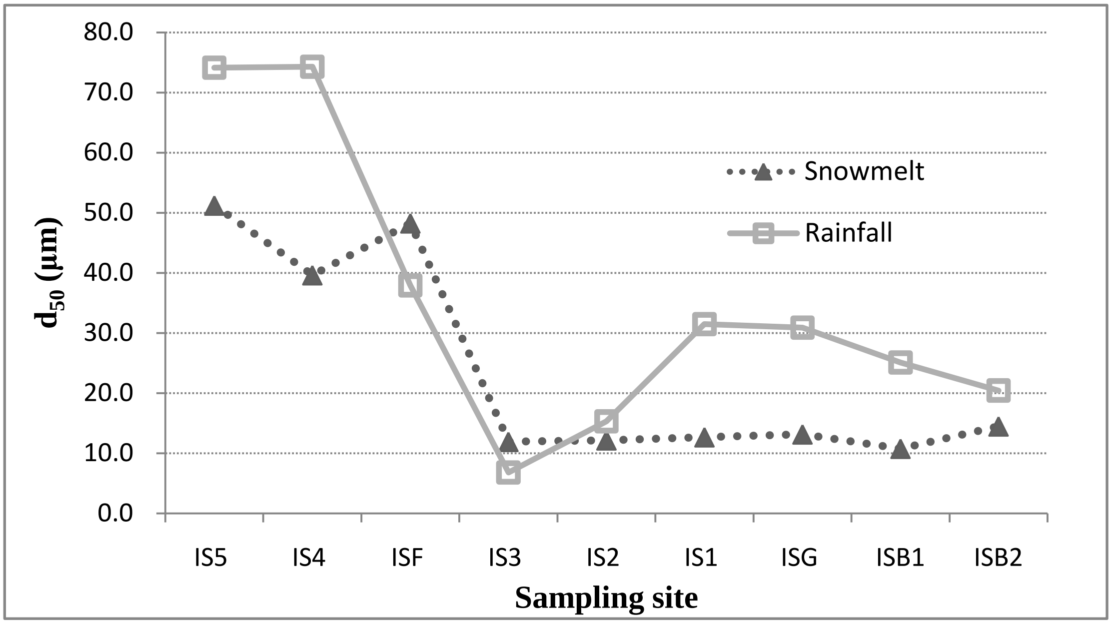

Figure 3.2 Median particle size (d_{50}) of the suspended sediment collected at 9 sampling sties in 2012.

Fig. 3.3 and Fig. 3.4 present particle size distributions for each of the 9 sampling sites following snowmelt and rainfall events, respectively. The figures highlight the appreciable spatial variation in the particle size distribution of suspended sediment that exists in the study area. Overall, approximately 53-63% of the suspended sediment transported from the upper reaches above the escarpment (e.g., IS5, IS4, ISF) was fine-grained materials (< 63 μm), while in the lower reaches below the escarpment (e.g., IS3, IS2, IS1, ISG, ISB1 and ISB2) it was over 82.8% of the total suspended sediment in snowmelt events (May-June). The similar pattern was also observed in rainfall events (July-November). The percentage of particles size finer than 63 μm ranged from 40% in

IS5 (upper reach) to 99.2% in IS3 (lower reach) in rainfall events. In all sampling sites, the suspended sediment samples contained only small proportions of clay-sized particles (< 2 µm) rarely exceeding 10%, and specifically 1.8-7.1% and 1.2-9.1% in snowmelt and rainfall events, respectively. IS3, IS2 and IS1 had lower sand content than other sampling sites (e.g., ISG, ISB1 and ISB2). This can be related to the local geology. The surficial materials above IS3 are predominately thin glacial tills which are mixed deposits of shale, limestone and granite, while those below IS1 are largely medium-to coarse-grained glaciolacustrine deposits along the base of the escarpment. The coarse fragments below the escarpment can become a source of fine-grained sediment into the stream (Koiter et al., 2013). The suspended sediment collected from upper reaches was significantly coarser than that in lower reaches following snowmelt events and rainfall events (Table 3.2). The loss of fine particles can be associated with size selectivity that coarser particles are selectively deposited. Therefore, the sediment found above the escarpment is considerably coarser than that below the escarpment.

Table 3.2 A comparison of the mean particle size characteristics of suspended sediment collected above and below the escarpment following snowmelt and rainfall events

Events	**Site**	**d_{50} (cm)**	**Particle size fraction (%)**		
			< 2 µm	**2-63 µm**	**63-600 µm**
Snowmelt	Above the escarpment	46.4	2.1	60.9	36.6
	Below the escarpment	12.5	6.3	84.2	9.5
Rainfall	Above the escarpment	62.1	1.9	49.9	48.2
	Below the escarpment	21.7	5.7	68.3	26.1

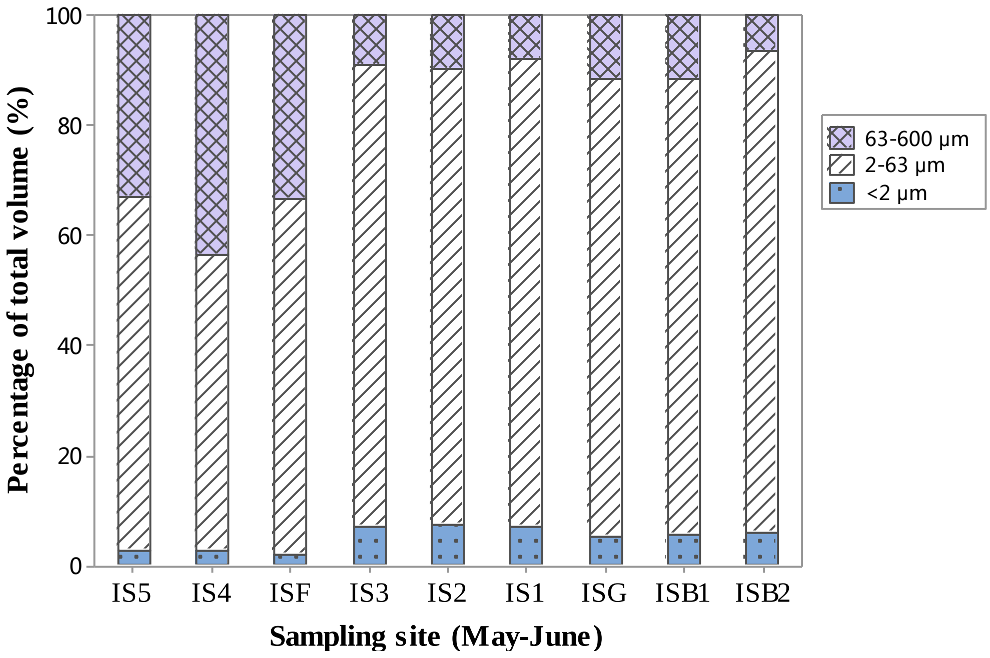

Figure 3.3 Particle size compositions of in-stream suspended sediment collected at 9 sampling sites following snowmelt event (May-June).

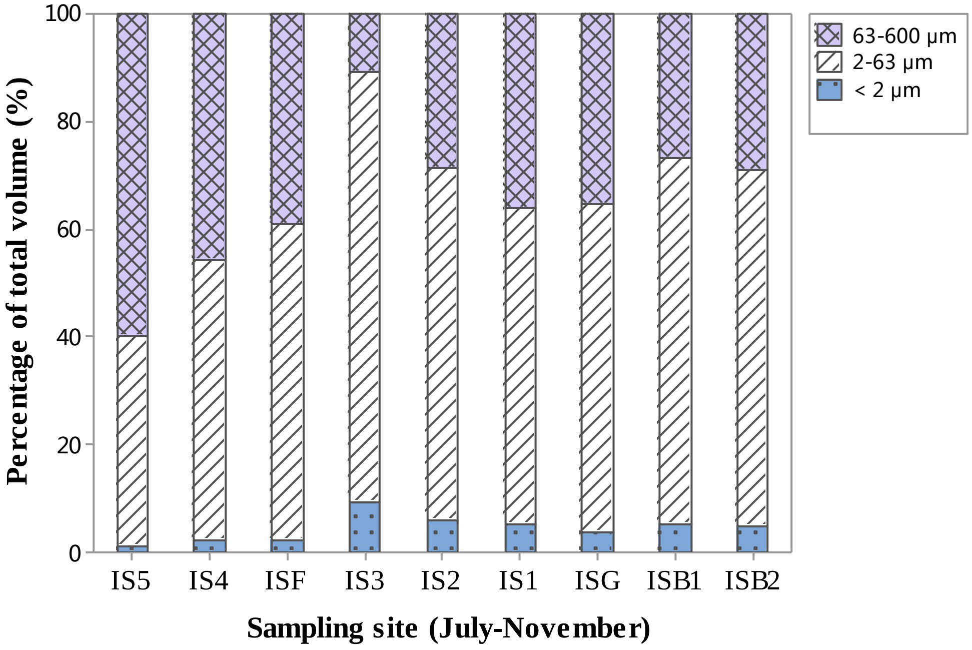

Figure 3.4 Particle size compositions of in-stream suspended sediment collected at 9 sampling sites following rainfall event (July-November).

3.5.2 Temporal variation in particle size characteristics of suspended sediment

Table 3.3 shows of all 9 sampling sites, the percentage of silt (2-63 μm) and sand (63-600 μm) in the suspended sediment following snowmelt events was significantly different from that following rainfall events ($p = 0.01$ and $p = 0.03$, respectively).

Table 3.3 Particle size composition of suspended sediment following snowmelt and rainfall events

Events		**Particle size fraction (%)**		
		< 2 μm	**2-63 μm**	**> 63 μm**
Snowmelt	Mean	4.9	76.4	18.6
	SD	0.7	4.1	4.7
	Min	1.8	53.4	6.7
	Max	7	87.4	43.5
Rainfall	Mean	4.4	62.1	33.5
	SD	0.8	4.6	5.3
	Min	1.3	38.8	0.8
	Max	9.1	90.1	60

Clear evidence of temporal variations in median diameter (d_{50}) of suspended sediment transported by rivers in the TCW is also showed in Fig. 3.5. The value of median diameter (d_{50}) of suspended sediment was significant smaller following snowmelt events than that following rainfall events above and below the escarpment. The figure shows the particle size of suspended sediment was finer following snowmelt events that that in rainfall events. Although daily discharge was not measured at all sampling sites, stream discharge exerted a substantial influence on particle size composition (cf. Chapter 2). As climate warms, reduced snow accumulation can lead to snowmelt runoff occurring earlier in spring, thus, snowmelt contributions to discharge along the creek is larger than during rainfall events. Rainfall intensity can also be a contributing factor to the runoff and sediment generation. Runoff volumes were greater in winter-spring than summer-fall, but there would be an inverse relationship between flow and the particle size of sediment. This transport of sediment involves particle size selectivity. The temporal variation in particle size of suspended sediment has been considered to reflect either hydraulic condition (e.g., stream discharge) in the channel or erosion dynamics within the watershed.

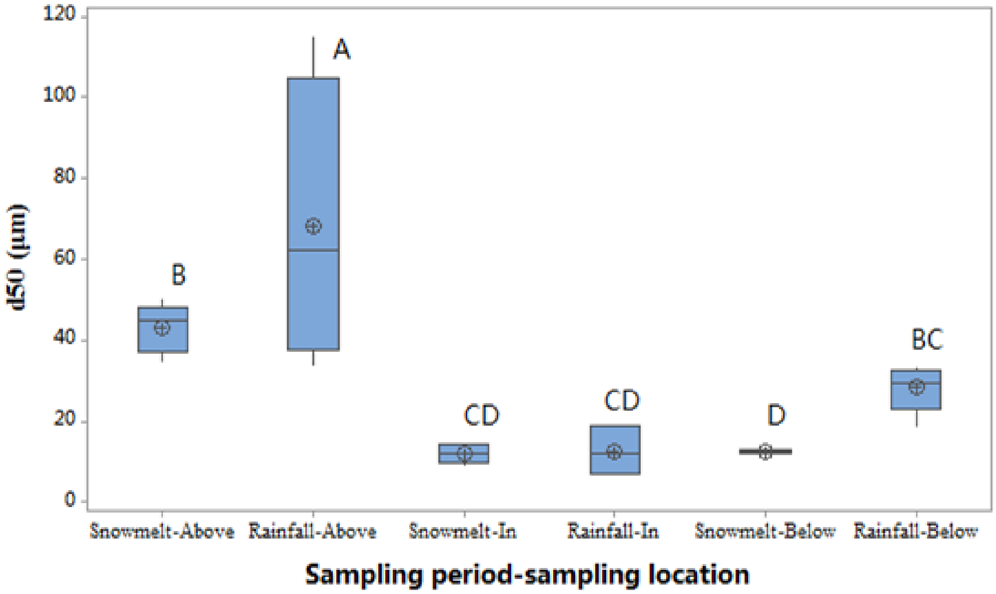

Figure 3.5 Temporal variation in median diameter (d_{50}) of suspended sediment following snowmelt and rainfall events.

3.5.3 Spatial variation in particle size characteristics of channel bed sediment

The overall trend of median particle size of channel bed sediment is presented in Fig. 3.6. Particle size of channel bed sediment decreases in the downstream direction. Median particle size is somewhat greater at IS5, IS4 and ISF, particularly following snowmelt events. Downstream of ISF, there is a dramatic decrease followed by a more gradual decrease. The particle size composition of the channel bed sediment shows that the samples collected above the escarpment were significantly coarser than that below the escarpment (Table 3.4). In the upper reaches, sand forms a large proportion of the channel bed sediment (e.g., IS5, IS4 and ISF), and in contrast, fine material (silt and clay) forms a large proportion of the bed sediment in the lower reaches (e.g., IS3, IS2, IS1, ISG, ISB1 and ISB2). This variation can probably be attributed to the irregularity with which material is supplied to the stream in the headwater area, because the stream crosses alternating strata with different rates of breakdown and tributaries introduce additional material at frequent intervals (Knighton, 1975).

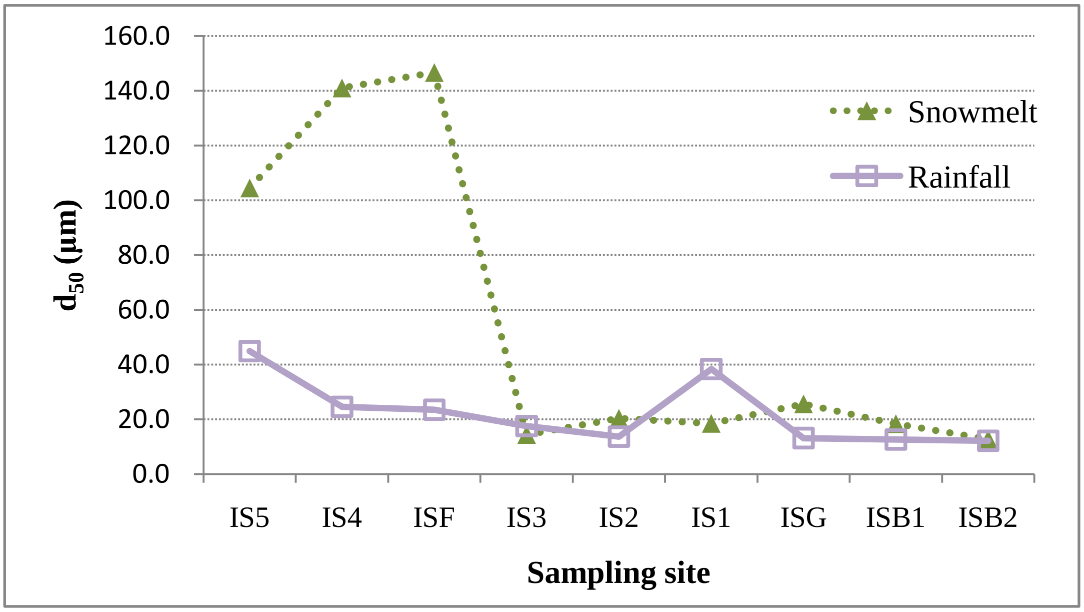

Figure 3.6 Median particle size (d_{50}) of channel bed sediment collected at 9 sampling sites in the TCW following snowmelt and rainfall events.

Geologic structure and geology at the ground surface should be taken into account when analyzing the spatial variations in particle size distribution of channel bed sediment. The change in particle size could be explained by the different weathering mechanisms and local geology. A considerable proportion of moderately to strongly calcareous rocks in the upper watershed are removed in large clast from steep slopes (e.g., slopes up to 10% above the escarpment) of contributing valley walls, whereas weathering of medium- to coarse-grained glaciolacustrine deposits along the lower watershed results in considerable quantities of fine-grained materials that is delivered to drainage channels. The abrupt change in valley slope resulted in abrupt particle size decreases from upper reaches to lower reaches.

Table 3.4 Comparison of particle size characteristics of channel bed sediment collected above and below the escarpment following snowmelt and rainfall events

Events	Sampling site		d_{50}	Particle size fraction (% total)		
				< 2 µm	2-63 µm	63-600 µm
Snowmelt	Above the escarpment	Mean	130.8	1.4	26.9	71.7
		Min	104.6	1.2	22.6	64.7
		Max	146.7	1.7	33.6	76.1
	Below the escarpment	Mean	18.4	6.4	70.8	22.8
		Min	12.8	4.2	49.7	11.9
		Max	25.7	8.4	79.7	46.1
Rainfall	Above the escarpment	Mean	31.0	4.4	69.5	26.1
		Min	23.6	3.4	62.6	21.9
		Max	44.9	5.2	73.6	34.1
	Below the escarpment	Mean	17.9	7.3	76.2	16.5
		Min	12.2	5.6	72.7	14.0
		Max	38.4	9.1	80.1	18.8

3.5.4 Temporal variation in particle size characteristics of channel bed sediment

The relative importance of the particle size classes varies in channel bed sediment, and evidence for the particle size selectivity of the deposition process is provided by median particle size (d_{50}) and particle size composition data presented in Fig. 3.6 and Table 3.5, respectively. The particle size distribution of channel bed sediment showed a different seasonal trend with the particle size distribution of suspended sediment. Table 3.5 illustrates the seasonal variation in the particle size characteristics of channel bed sediment, a distinct trend can be discerned for all the sampling sites. The temporal variability is also found in the median particle size data of channel bed sediment, with a range in median particle size (d_{50}) from 12.8 to 146.7 μm following snowmelt events, and from 6.8 to 74.3 μm following rainfall events, respectively. At all sampling sites, the volume percentage of particle size of silt (2-63 μm) and clay (< 2 μm) proportions of the rainfall samples was significant greater than that of the snowmelt samples. In addition, the percentage of fine sand (63-600 μm) of the snowmelt samples was greater than that of the rainfall samples. These results suggest that the particle size composition of channel bed sediment following the snowmelt events was generally coarser than that following the rainfall events. The seasonal variation in particle size distribution of channel bed sediment could be explained by variations in water discharge such that the increased discharge following snowmelt event period mobilized larger particles (Walling and Moorehead, 1989; Stone and Walling, 1997).

Although site-specific hydraulic data were not collected, the trends of particle size distribution suggest that hydraulic sorting mechanisms occur along channel bank during moderate and high flows. Therefore, the temporal change in particle size of channel bed material is probably more dependent on the increased magnitudes and frequencies of high-flow events following snowmelt and rainfall events.

Table 3.5 Particle size composition of fine fraction channel bed sediment collected at 9 sampling sites

Events	Study site	Particle size fraction (% of total)		
		< 2 µm	2-63 µm	63-600 µm
Snowmelt	IS5	1.7	33.6	64.7
	IS4	1.4	24.3	74.2
	ISF	1.2	22.6	76.1
	IS3	4.2	49.7	46.1
	IS2	6.8	77.1	16.0
	IS1	6.1	75.2	18.8
	ISG	6.3	69.7	24.0
	ISB1	6.6	73.1	20.3
	ISB2	8.4	79.7	11.9
Rainfall	IS5	3.4	62.6	34.1
	IS4	5.2	72.3	22.5
	ISF	4.6	73.6	21.9
	IS3	5.6	80.1	14.4
	IS2	7.9	78.1	14.0
	IS1	6.1	75.2	18.8
	ISG	7.6	76.5	15.9
	ISB1	7.5	74.5	18.0
	ISB2	9.1	72.7	18.0

3.5.5 Particle size characteristics of potential source materials

In a small watershed, the particle size characteristics of suspended sediment reflect the particle size of the eroded source material to some degree (Walling and Moorehead, 1989). Table 3.6 shows the particle size composition of the three primary sources of soil, namely, topsoil from riparian areas, topsoil from cultivated fields and stream bank in the South Tobacco Creek Watershed. The median particle size and particle size composition of topsoil (including riparian areas and cultivated field) were significantly finer than that of stream bank material in the upper reaches (e.g., IS4). In contrast, the size changed dramatically where the particle size was significantly coarser than that of channel bank material in the lower reaches (e.g., IS2, IS1). The results indicated that the relative contribution of topsoil and channel bank sources to the suspended sediment transported by the study river varies considerably between sampling sites. Such variation in the relative contribution of the three primary sediment sources may partly explain the spatial variability of the particle size composition of suspended sediment shown in Table 3.3.

To characterize the particle size characteristics of the suspended sediment transported from eroded soil into the stream, it is useful to compare the particle size distribution between suspended sediment and potential source materials. The information can be used to establish the degree of size selectivity associated with sediment mobilization and delivery in future studies. In general, the suspended sediment is enriched with finer fractions and depleted of coarser fractions relative to the potential source materials (Table 3.7). The proportions of clay, silt and sand in suspended sediment collected in the lower reaches when compared with the potential source material show that the source materials are seen to be substantially coarser. Other studies (e.g., Owens et al., 1999; Walling et al., 1999; Walling et al., 2000) also showed the particle size of suspended sediment collected from the lower reaches was finer than the potential source materials. These could be explained by the particle size selectivity of sediment mobilization on hillslopes, the size selectively of sediment delivery from hillslopes to channels, and the selectivity of the transporting fine particle sediment through channel network itself (Stone and Walling, 1996; Walling et al., 2000). A study undertaken on erosion plots reported by Lal (1976) also demonstrate significant contrasts between the particle size composition of eroded sediment and the original soil. Lal (1976) demonstrated that the degree of enrichment varied according to the slope angle and in response to differences in land use practice.

Table 3.6 Particle size compositions and median particle size of potential source materials

Sampling site	Source†	< 2 µm	2-63 µm	63-600 µm	d_{50} (µm)
IS5	SB	0.1	16.7	83.2	220.0
	TF	ND	ND	ND	ND
	TR	ND	ND	ND	ND
IS4	SB	0.2	14.4	85.4	192.0
	TF	1.3	27.5	71.2	126.5
	TR	1.6	37.0	61.4	85.8
ISF	ND	ND	ND	ND	ND
IS3	SB	1.1	20.6	78.3	171.2
	TF	1.6	26.2	72.1	124.5
	TR	0.7	20.9	78.5	169.3
IS2	SB	2.6	35.7	61.8	83.1
	TF	0.7	13.3	86.0	103.9
	TR	2.4	33.5	64.1	183.8
IS1	SB	0.9	29.4	69.7	114.4
	TF	2.7	38.5	58.9	121.0
	TR	1.6	26.8	71.6	178.1
ISG	ND	ND	ND	ND	ND
ISB1	ND	ND	ND	ND	ND
ISB2	ND	ND	ND	ND	ND

†SB = streambank; TF = topsoil from agricultural fields; TR = topsoil from riparian area; ND, no data

Table 3.7 Particle size compositions and median particle size of suspended sediment at 9 sampling sites following snowmelt and rainfall events

Events	Sampling site	d_{50} (μm)	Particle size fraction (%of total)		
			< 2 μm	2-63 μm	63-600 μm
Snowmelt	IS5	51.2	2.4	64.7	32.8
	IS4	39.6	2.2	53.4	43.5
	ISF	48.3	1.8	64.6	33.6
	IS3	11.9	7.0	83.9	9.1
	IS2	12.2	7.0	82.8	9.9
	IS1	12.7	7.0	85.0	8.3
	ISG	13.1	5.1	83.1	11.7
	ISB1	10.8	5.6	82.8	11.6
	ISB2	14.5	5.8	87.4	6.7
Rainfall	IS5	74.1	1.3	38.8	60.0
	IS4	74.3	2.1	52.1	45.8
	ISF	37.9	2.4	58.7	38.9
	IS3	6.8	9.1	90.1	0.8
	IS2	15.3	6.1	65.1	28.8
	IS1	31.5	5.3	58.6	36.1
	ISG	30.9	3.6	61.2	35.2
	ISB1	25.1	5.1	68.2	26.7
	ISB2	20.5	4.7	66.4	28.9

3.6 Conclusions

Detailed particle size analysis is a valuable tool for quantifying the physical characteristics of sediment. The results showed considerable spatial and temporal variability in particle size in the Tobacco Creek Watershed. The particle size of suspended sediment was generally smaller than 600 μm, and over 60% particles were silt- and clay-sized (< 63 μm) at most sampling sites. Based on comparison of suspended sediment and potential source materials, we conclude that finer sediment was more easily mobilized from hillslopes, but coarser sediment remained *in situ*.

There is appreciable spatial and temporal variation in the particle size of the suspended sediment in the study watershed. In the case of spatial variation, different patterns among different sites primarily reflect the particle size selectivity, associated with sediment transport and delivery from upstream to channels, and the fine particles transported in sediment through the watershed. The particle size of suspended sediment at the lower reaches was significantly finer than that at the upper reaches. Additionally, similar patterns of particle size distribution were also found in the fine fraction of the channel bed sediment.

There is considerable temporal variation in the particle size characteristics of suspended sediment at each sampling sites during two events. The d_{50} values of suspended sediment indicated that the particle size of suspended sediment was coarser following rainfall events (July-November) than following snowmelt events (May-June). In contrast with the suspended sediment, the d_{50} values of fine fraction channel bed sediment showed that the particle size was finer following rainfall events than following snowmelt events.

In conclusion, suspended sediment contained less sand than silt and clay compared to the potential source materials. Particle size distribution also provides information essential for the ongoing evaluation of BMPs in the study watershed. The particle size characteristics of the sediment transported in the watershed have been shown to vary both spatially and temporally. An understanding of the particle size selectivity of sediment mobilization and delivery processes is, therefore, crucial for understanding the particle size dynamics of suspended sediment. Furthermore, because of the relatively fine-grained nature of the suspended sediment transported by the study river, there is a large potential for the transport of sediment-associated contaminants, which are generally preferentially associated with fine fraction of sediment, particularly the material < 600 μm. The particle size characteristics of suspended sediment and potential source materials have important implications for understanding, monitoring and modelling the transport of suspended sediment, and sediment-associated nutrient within watersheds.

3.7 References

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4. PARTICLE MORPHOLOGY OF ROCK FRAGMENTS IN SOUTH TOBACCO CREEK

4.1 Abstract

Shape is a fundamental property of sediment particles, but it is difficult to quantify. The size and shape of the rock fragments and their spatial distribution provides insight into geomorphic processes of particle transport in stream channels. This study characterized the particle shape of rock fragments that were collected from the selected outcrops and compared them to rock fragments collected downstream. This was done by simple computer image analysis software. Three shape indices including circularity, roundness and aspect ratio were used. The particle size of rock fragments was characterized by Feret’s diameter. The result showed that particle size and circularity were negatively related. Feret’s diameter decreased with distance while circularity increased downstream from their outcrop sources. Values of roundness and circularity from outcrop source were smaller than that from downstream which indicated the rock fragments with angular shape were usually found in the outcrop sources. Rock fragments showed no clear evidence of becoming rounded during transport, but they reduced in size in a short distance. The particle morphology helps with understanding of the dynamics and delivery and any modifying processes that may have occurred during transport within a watershed.

4.2 Introduction

Nutrients and contaminants can be exchanged on the surfaces of sediment particles. The morphological structure of sediment particles directly affects surface characteristics that regulate these biogeochemical processes. Particle size and shape reflect material composition, geomorphic processes, and are determined by mechanical and chemical processes once they are released from the mineral matrix (Cho et al., 2006). Sediment transport processes in stream result in changes of particle shape relative to the distance, duration and type of the transport involved (Cho et al., 2006). Changes in the shape of particles are strongly related to geological locations and seasonal variation. The shape distribution of sediment collected along the channel indicated the abrasion and selective transport process (Morris and Williams, 1999). Measuring the shape of sediment particles is important for a better understanding of sedimentary processes.

Despite shape being a fundamental property, it remains the most difficult feature to be quantified. Several terms such as shape (Barrett, 1980) and form (Whalley, 1972) have been used to describe the external morphology of a particle. Though many particle shape indicators have been used to describe the shape of non-spherical particles (e.g., Wadell, 1932; Barrett, 1980), it remains difficult to develop a universal shape indicator used to distinguish all kinds of shapes (Yu and Hancock, 2008). In the previous work, the sedimentary particles were represented as a sphere. However, the morphology of irregular particle was not fully understood. Wadell (1932) first developed methods to quantify sphericity and roundness of particles. However, Wadell’s method (1932) used to determine the roundness involves measurements of multiple radii of particles and is time consuming. Sphericity calculation is also a complicated process and requires a comparison of surface area of a particle to a sphere with equivalent volume. Krumbein (1941) created a chart to identify particle shapes by classifying the roundness of pebbles into nine classes, and calculated sphericity by measuring three particle diameters (short, long, and intermediate) manually. The application of Krumbein's method is limited to larger size particles only, because measuring three diameters of small particles is not practical. In conclusion, sphericity, roundness (cf. angularity) and smoothness (cf. roughness) are three important variables commonly used by many researchers to characterize particle shape. The definitions and their conventional evaluation were described by Cho et al. (2006).

In a few sediment fingerprinting studies, particle shape has been used to trace sediment origins. De Boer and Crosby (1995) found considerable differences in the particle morphology in clay particles of suspended sediment samples derived from forest and farmland soils. The particles of sediment derived from forest soil were irregular, while those in farmland were rounded. This finding demonstrated that the potential of particle shape to distinguish sediment source. Many researchers have emphasized that after random abrasion, the corners and edges of rock fragments are removed and rocks become smoother and more rounded (Krumbein, 1941; Frings, 2008; Domokos et al., 2014). Generally, angular particles are preferentially observed in the upstream, while corners of particle become smoother in the downstream (Roussillon et al., 2009).

For better understanding the particle shape evolution of sediment, particle size should be taken into account when considering sediment dynamics. Changes in particle size and shape of sediment are significantly affected by sediment-transport dynamics, bed-form dimensions and hydraulic roughness. The shape evolution of particles can be used as an indicator of the transport distance of a particle. In many studies on soil erosion focused on the role played by the fine particles (i.e. silt- and clay sized) when consider the soil's behaviour (Walling et al., 2000; Stone and Walling, 1997). Much less attention has been devoted to the effects of the coarse fraction (i.e. rock fragments) (Poesen and Lavee, 1994). A better understanding of changes in particle shape and size during sediment transport is of fundamental importance in understanding the fluvial geomorphology and hydrological processes.

Digital image analysis has been widely used to characterize morphological features of sedimentary particles (e.g., Roussillon et al., 2009; Miller and Henderson, 2010; Gelinas and Vidal, 2010). Image analysis methods involve capturing the contour of particles to obtain particle shape and size. The image analysis method has the advantages of allowing visualization of sedimentary features, less processing time, cost-effectiveness, and high storage and transmission efficiency. Most importantly, the image analysis technique has been found to provide highly accurate estimates of particle size compared to manual sieving (Ibbeken and Schleyer, 1986).

In this study, image analysis was used to quantitatively characterize the shape of coarser particles (e.g. rock fragments). The objectives of this study were: 1) to characterize the morphology of rock fragments collected from bedrock outcrops exposed along the streambank of South Tobacco Creek Watershed (STCW) and deposited in the channel; and 2) to evaluate the relationship between the morphology of rock fragments from these sources and the rock fragments collected downstream.

4.3 Study Area

Within South Tobacco Creek Watershed (STCW) (cf. Chapter 3), many steep valley walls and actively eroding cut-bank shale bedrock outcrops exist along the channel. These outcrops are overlain by a sequence of friable deposits of siltstone, glacial tills and gravels. For better understanding the shape evolution of sediment, choosing a clear source and isolated outcrop is important. Therefore, three outcrops, namely, Outcrop 2, Outcrop 4 and Outcrop 7 (Figure 4.1) in the STCW were selected to study the size and shape of rock fragments. A summary of the three outcrop characteristics and coordinates are presented in Table 4.1.

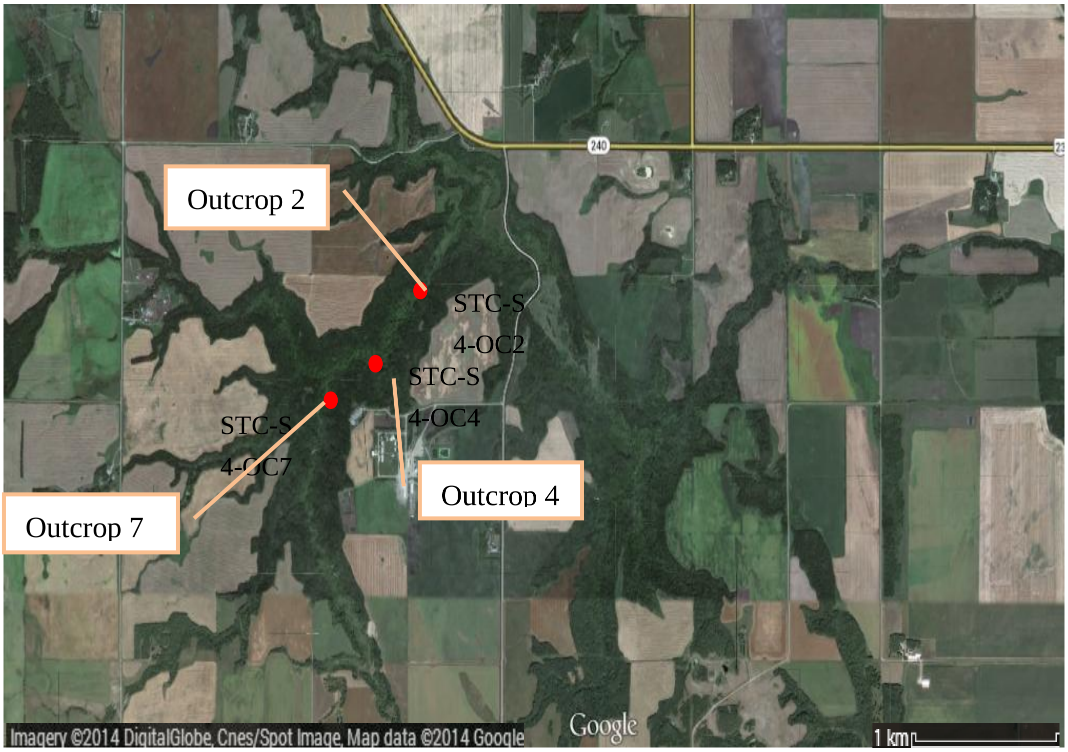

Figure 4.1 Location of outcrops in the South Tobacco Creek Watershed.

4.4 Materials and Methods

4.4.1 Photographic acquisition and rock fragments collection

Digital photographs of rock fragments were taken in September, 2012 when the channel was dry and easy to access. A schematic of photographic acquisition and rock fragment collection is presented in Figure 4.2. Photographs of outcrop surface and the channel at the three selected outcrops were taken using a Canon 60D digital SLR. The digital camera was mounted on a 1.5 m high tripod. At each of photographic sites, a 1 m^2 experimental plot was placed on the ground before digital photographs were taken. Photographic sites were located at approximately 10 m intervals along channel and are referred to as bedrock, PT1 to PT8. The sampling site of bedrock is located at the bottom of the selected outcrop, and PT1 is the closest sampling point to the bedrock, and PT8 is the farthest sampling point to the bedrock in downstream. At those photographic sampling sites, rock fragments to a depth of 3 cm were collected using a trowel and stored in a bucket. The sampling locations were recorded using a hand-held GPS.

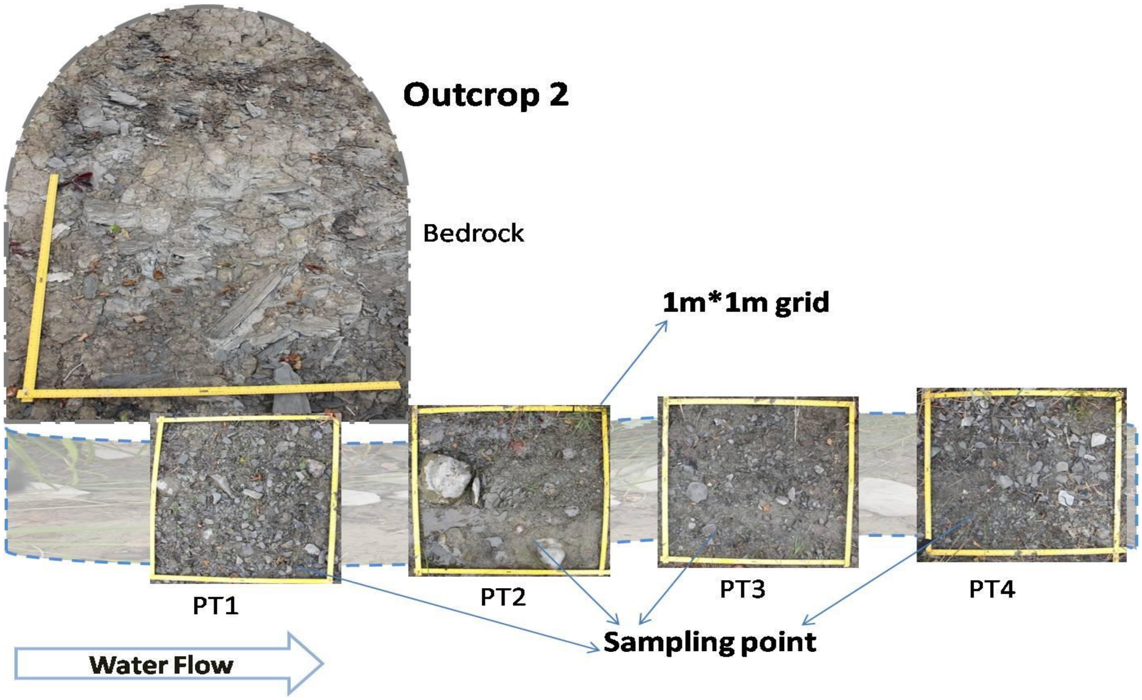

Figure 4.2 Schematic of photographic acquisition and rock fragments collection (e.g., Outcrop 2).

Table 4.1 Summary of the GPS coordinates and characteristics of three outcrops

Site	GPS Coordinates	Height (m)	Width (m)	Description
Outcrop 2	14 U 547189 N 5467837 E	14.6	20.5	First full outcrop in the downstream relative to IS 3 A mixture of gravel and sandstone is in the upper portion and rougher non-conformed gravel and sandstone are near bottom A large amount of till fallen from the top covers the bottom of the outcrop
Outcrop 4	14 U 546827 N 5467306 E	25.7	76.9	Largest outcrop till this point White/beige sandstone and gravel exist in most of the upper portion The bottom portion is characterized by dark black non-calcareous shale that laid in a straight linear fashion.
Outcrop 7	14 U 554068 N 5469654 E	19.7	31.4	Large outcrop right at the bottom of the pit A thin layer of grayish/blue shale is near the top portion of the outcrop Light grayish/blue shale covers the entire lower portion of the outcrop. It is a soft shale which is easily broken to crumbles

4.4.2 Image acquisition processes

About 200 rock fragments with longest dimension (> 3 cm) were randomly collected and cleaned from each bucket. The rock fragments were spread in a single layer over a white paper sheet. In order to obtain more accurate measurement, rock fragments were spaced so that they did not contact one another (Figure 4.3a). In this arrangement, thickness (cf. short axis) of particles cannot be measured directly since 2-D images measure only the long and intermediate axes. All images of rock fragments were obtained under the same light condition. A ruler was placed at the bottom of the paper sheet to adjust dimensions in mm since default images size is expressed in pixels.

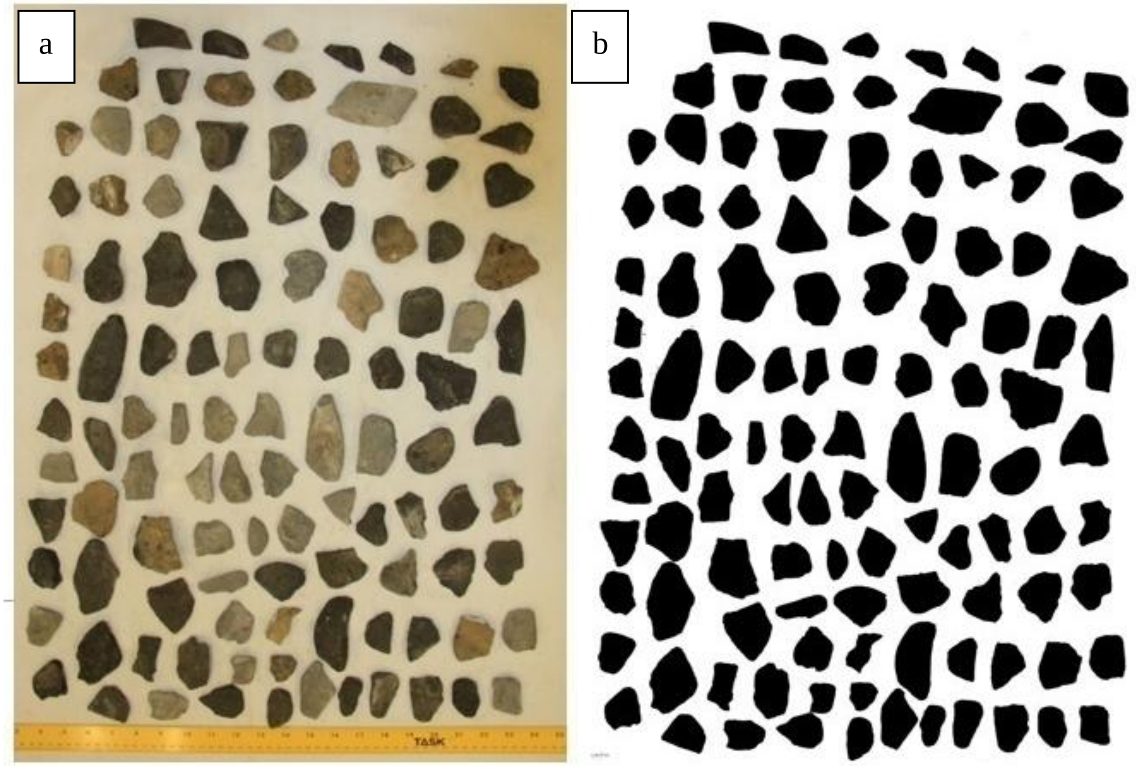

Figure 4.3 Original image (a), and binary image (b) of rock fragments.

4.4.3 Image analysis using computer software

The computer software ImageJ (v1.45, Wayne Rasband) was used to analyze particle shape, and to rectify and standardize the images of rock fragments. During the ImageJ image analysis process, the original color image of spread particles was firstly converted into grey-scale (8-bit) image and further to binary image characterized by black object with white background through a pre-processing phase namely threshold. According to the pixel value of the images, ImageJ produces such output parameters as number of particles, projected area, perimeters, roundness, circularity and major and minor axes. The size and shape of individual rock fragments can be expressed by the dimensions of the axes obtained from the image analysis. An original image was first converted into a binary image as shown in Figure 4.3b. With the scale calibration before image process, ImageJ converts an original image from pixels to millimeters. All unwanted pixels from the edge of black objects were removed using a function called *Erode* in the ImageJ. To avoid light interference, a function called *Fill Holes* was used to fill white spots on black objects. Lastly, shape parameters of rock fragments were computed by the *Analyze particle* function. A minimum size for analysis was set as 500 pixel to eliminate the interference by ultra fine particles or ash (i.e. < 0.8 mm^2), which were not included in this research.

Shape parameters used to describe the shape of each rock fragment included roundness and circularity. Definitions and their calculations are the following:

a. Roundness is a measure of the extent to which the edges and corners of a particle are round. The roundness was calculated as:

$$\text{Roundness} = \frac{4*A}{\pi*(\text{Major axis})^2} \qquad (1)$$

Where *A* is the surface area and *Major axis* is the transverse diameter of a rock fragment.

Krumbein (1941) created a chart (Fig. 4.4) shows examples of pebbles for which roundness of particle outline was calculated using Wadell’s method and classified the rock fragments into 9 classes. It provides a visual estimate of rock fragments roundness based on the chart.

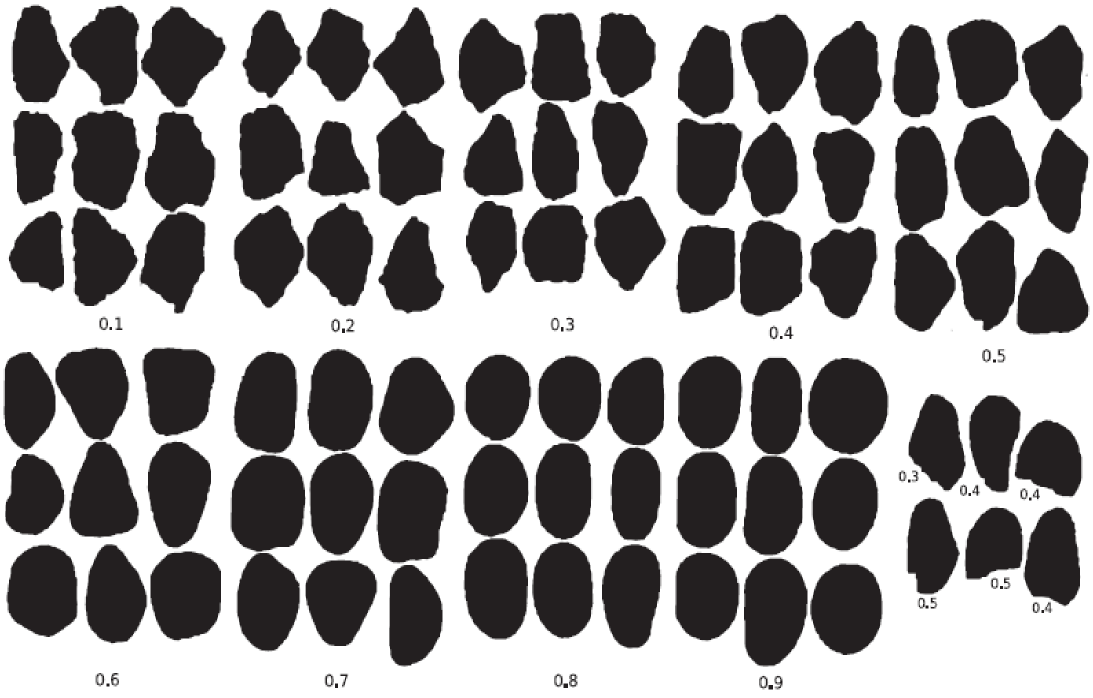

Figure 4.4 Roundness of pebbles of Krumbein’s chart (Krumbein, 1941).

b. Circularity is a measure of how close the shape of an object to the shape of a circle. The circularity of a perfect circle is 1.0. As the value is approaches to 0, and shape is increasingly elongated. In addition, the projected area of rock fragments is determined from each digital image. Circularity was calculated as:

$$\text{Circularity} = \frac{4\pi * A}{P^2} \qquad (2)$$

Where *A* is the surface area and *P* is the perimeter of a rock fragment.

Additionally, the shape of rock fragments was also quantified using aspect ratio expressed as the ratio between major axis and minor axis (Ferreira and Rasband, 2011). Feret's diameter was also calculated as the longest distance between any two points on the perimeter of a particle.

4.4.4 Statistical analysis

The analysis was based on morphologic observations of rock fragments (> 3 cm) from three outcrops within the South Tobacco Creek Watershed (STCW). Data for particle morphology and size of rock fragments were analyzed using Minitab 17 software (Minitab, Inc) to test the difference between rock fragments collected from sources and from downstream. Mann-Whitney U test (95% confidence) was used to compare the difference of rock fragments between source and downstream sampling points. The results are presented with box plots with 75%, median and 25% value of each shape parameter and size distribution. The box plots also include lines extending vertically from the boxes (whiskers) indicating variability outside the upper and lower quartiles.

4.5 Results and Discussion

Figure 4.5 presents photographs of each outcrop and the surface material of rock fragments at three sampling sites. The height of the vertical rock wall varied from 14.6 m (Outcrop 2) to 25.7 m (Outcrop 4) (Table 4.1). Rock fragments covered the bottom of the outcrop which fell down from the face of outcrop wall. The rock fragments are predominated with sandstone and gravel in the top portion of the outcrop, and are mainly composed of black shale in the lower portion.

Figure 4.5 Photographs of each outcrop and sampling points.

4.5.1 Shape distribution of rock fragments

The median values of each shape parameter at three outcrops are presented in Table 4.2. The number of rock fragments in each image varied from 12 to 223 particles. No statistical analysis was conducted for PT3 sampling points at outcrop 7, because there are not enough number of rock fragments for statistical summary.

Table 4.2 Summary information on the median values of shape parameters at the three outcrops along the South Tobacco Creek

Site	Sampling point	n†	Distance from outcrop (m)	Circularity	Roundness	Feret's diameter (cm)	Aspect ratio
Outcrop 2	Outcrop	101	0	0.64	0.57	1.79	1.76
	PT1	100	10	0.67	0.7	4.85	1.42
	PT2	108	24	0.68	0.71	5.57	1.4
	PT3	165	34	0.7	0.66	4.45	1.52
	PT4	204	40	0.71	0.68	4.59	1.47
Outcrop 4	Outcrop	91	0	0.68	0.63	7.09	1.58
	PT1	142	6	0.69	0.62	6.28	1.61
	PT2	245	14	0.7	0.68	5.56	1.47
	PT3	223	35	0.66	0.65	5.88	1.55
	PT4	129	47	0.64	0.69	5.04	1.45
	PT5	93	62	0.72	0.69	5.18	1.45
Outcrop 7	Outcrop	62	0	0.65	0.65	6.93	1.55
	PT1	140	6	0.64	0.71	5.58	1.41
	PT2	158	13	0.67	0.7	4.84	1.42
	PT3	12	4	NA	NA	NA	NA
	PT4	130	61	0.71	0.69	4.57	1.46
	PT5	136	87	0.67	0.67	5.42	1.49
	PT6	155	95	0.68	0.7	5.42	1.44
	PT7	148	103	0.71	0.72	5.41	1.38
	PT8	115	108	0.72	0.69	3.93	1.46

†n = number of rock fragments

4.5.1.1 Circularity

The circularity of rock fragments at three sampling sites is presented in Fig. 4.6. In general, these rock fragments were not significantly different (Mann-Whitney Test 95% confidence, $p > 0.05$) from samples collected from each sampling point in downstream in three selected outcrops. This may be explained by the friable nature of local shale bedrock which was easily reduced in size (cf., Koiter et al., 2013), while retaining angular shape of the original shale materials. Therefore, there was no significant difference between sampling points progressively downstream. The rock samples collected from downstream had significant differences to those collected from bottom of the selected outcrop. This may be because the rock fragments collected from downstream had travelled from other sources and been deposited in those sampling points downstream.

The median circularity increased downstream and the values of circularity varied from 0.64 at the bottom of the outcrop to 0.71 at PT4 at Outcrop 2. A similar pattern of circularity was observed at Outcrop 4 and Outcrop 7, where the median value of circularity varied from 0.65 at the bottom of the outcrop to 0.71 at PT5 at Outcrop 4, and from 0.62 at the bottom of the outcrop to 0.70 at PT8 at Outcrop 7, respectively. The circularity did not show a well structured trend from the source to downstream, which demonstrates the complex origin of the particles located in the main channel.

In general, the value of circularity of all rock fragments collected from all three outcrops was in the range of 0.4-0.9. The circularity distribution become less skewed in the lower downstream at Outcrop 2 (Fig. 4.6), indicating an increase in the frequency of circular rock fragments and a decrease in the number of angular shaped rock fragments in the lower downstream. At Outcrop 2, PT1 had a wider range of circularity distribution than other sampling points (i.e. PT2, PT3 and PT4), demonstrating that the shape of rock fragments close to the source rock had a relatively large variation. The reason for the large variation at PT1 is that various types of rocks and stones are transported from the upper portion of the outcrop to this sampling point (i.e., PT1) and/or that there may be other sources contributing rock fragments. At Outcrop 4, the value of circularity of rock fragments was slightly increased from the bottom of the outcrop to downstream sampling points, except PT3 and PT4 where a significant decrease was observed (Fig. 4.6b), which means there were more angular rock fragments at PT3 and PT4 than at other sampling points (i.e., PT2 and PT5). Outcrop 4 mainly contained the friable shale bedrock which can be easily pulverized by hand. Within a certain transport distance, some shale still exhibited an angular shape which is similar to the source. At Outcrop 7, rock fragments were characterized by smoother edges and round corners in the lower reaches. The circularity is slightly increased from the bottom of the outcrop to the downstream sampling points (Fig. 4.6c), which showed that the rock fragments (from PT1 to PT8) became more uniform and increases in the number of circular particles.

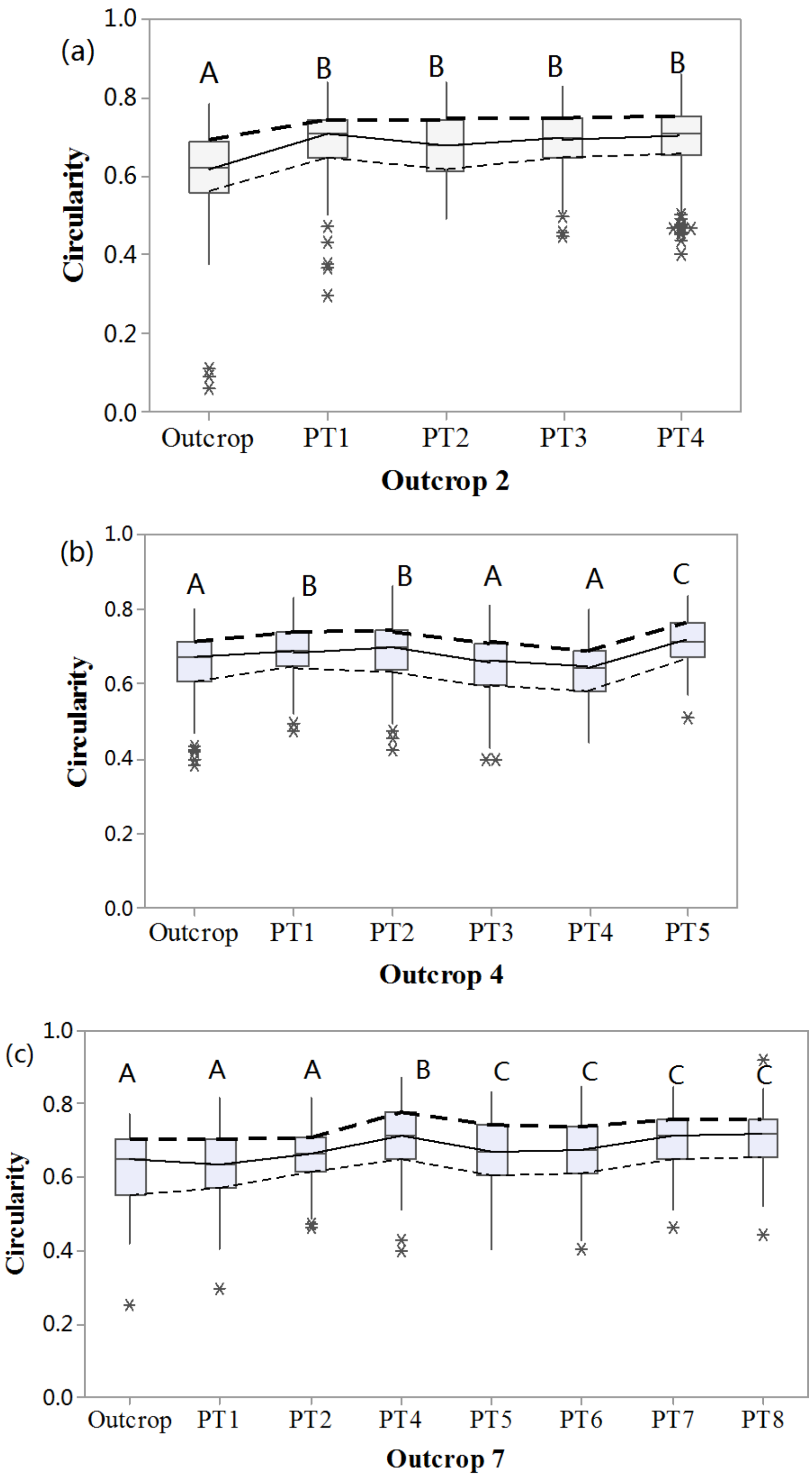

Figure 4.6 Variation in the 25th, median and 75th percentiles of circularity of rock fragments in the source and downstream from three outcrops.

4.5.1.2 The relationship between circularity and Feret’s diameter

The relationship between circularity and Feret’s diameter for rock fragments is shown in Figure 4.7. There was a strong coefficient of correlation between circularity and Feret’s diameter (Outcrop 2: $R^2 = 0.66$, Outcrop 4: $R^2 =0.66$ and Outcrop 7: $R^2 =0.60$). Generally, high circularity values were observed in the small rock fragments. The results indicated that rock fragment with larger size were less rounded than that of smaller size. These results were consistent across all the three selected outcrops.

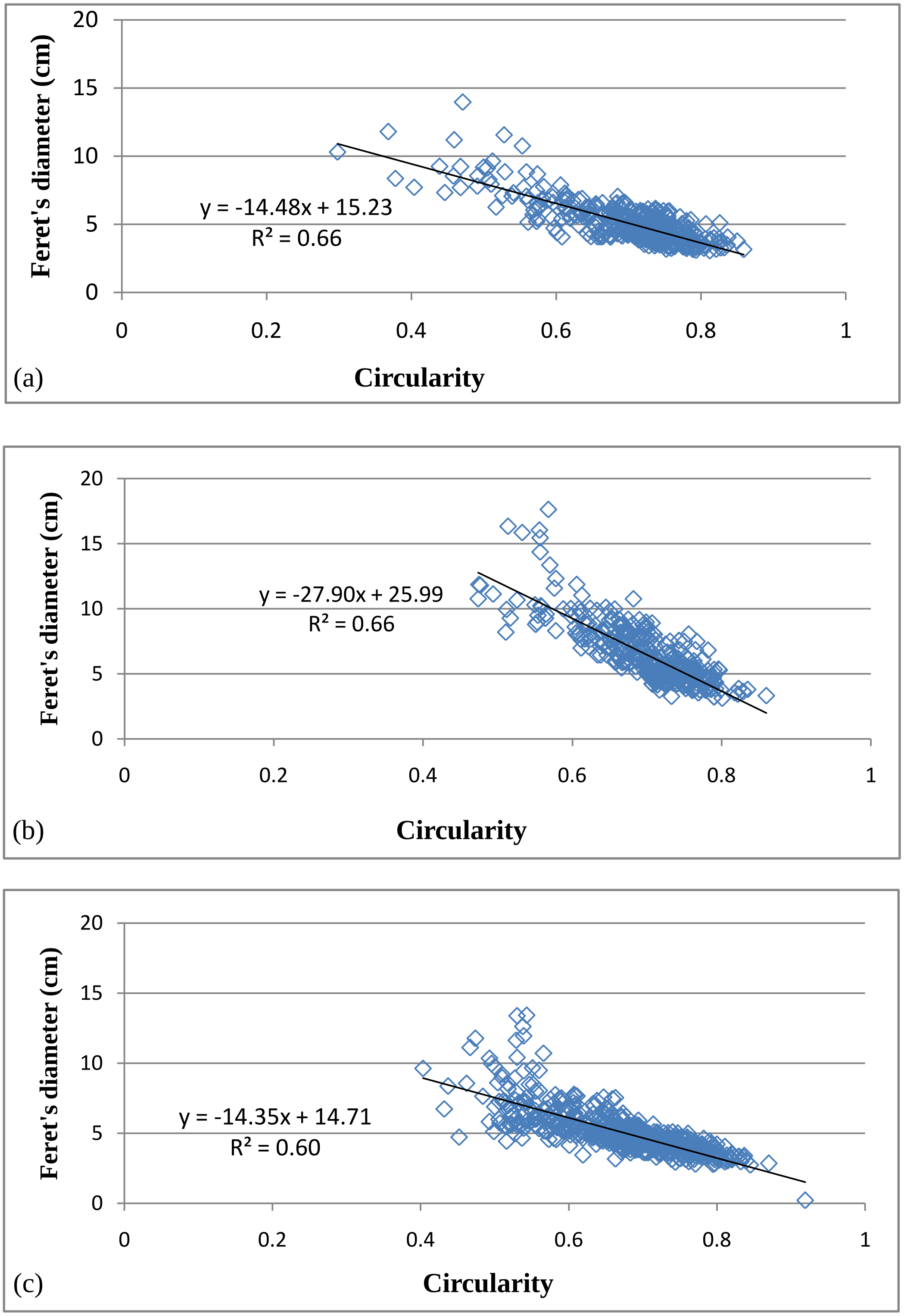

Figure 4.7 The relationship between circularity and Feret's diameter for rock fragments collected from (a) Outcrop 2, (b) Outcrop 4, and (c) Outcrop 7.

4.5.1.3 Roundness and aspect ratio

Fig. 4.8 shows roundness of rock fragments at three outcrops. Rock fragments collected in the downstream sampling points was significantly different from that of rock fragments collected from the outcrop source ($p < 0.01$) at the three selected outcrop sites. Roundness of rock fragments collected from the outcrop source appeared to have more angular corners than that in the downstream sampling points. This might be explained by the fact that the shale materials break down during transport and become less angular and smoother. The median value of roundness of rock fragments was larger downstream than that of the source, which indicated an increase in the number of smooth edged rock fragments and a decrease in the number of sharp cornered rock fragments appeared in downstream. However, there was no significant difference in roundness among the sampling points downstream. The roundness did not show a well structured trend from the source to downstream, which demonstrates roundness of rock fragments not change progressively downstream.

The value of aspect ratio is commonly associated with the orientation of rock fragments. The aspect ratio of rock fragments collected in the downstream sampling points exhibited significant difference than that from the outcrop source. The aspect ratio of rock fragments collected at the three outcrops showed a decreasing trend from outcrop source to downstream sampling points (Fig. 4.9), which indicated the rock fragments become less elongated.

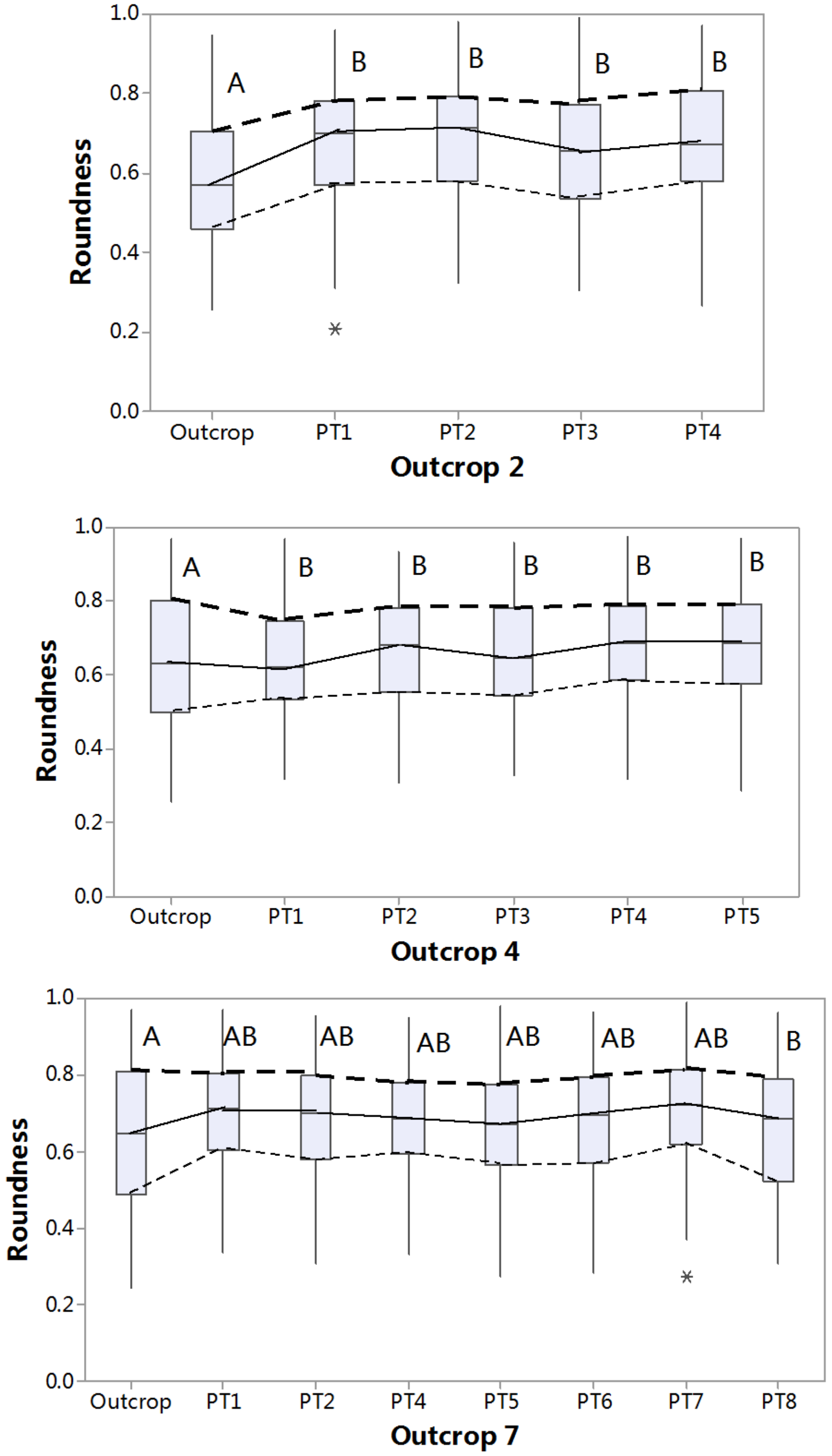

Figure 4.8 Variation in the 25th, median and 75th percentiles of roundness of rock fragments in the source and downstream from three outcrops.

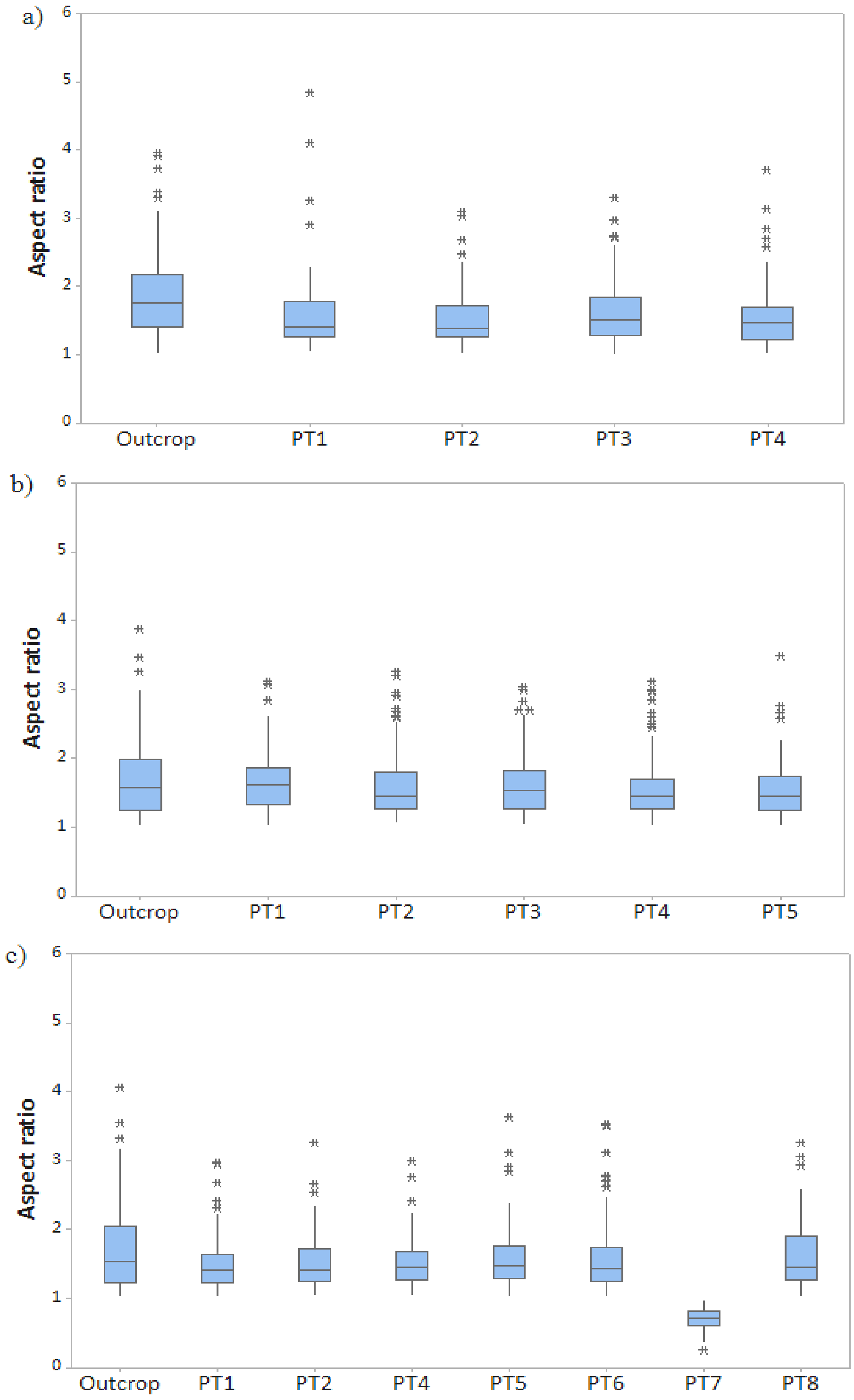

Figure 4.9 Changes in the aspect ratio of rock fragments collected from (a) Outcrop 2, (b) Outcrop 4, and (c) Outcrop 7.

4.5.1.4 Feret’s diameter

In addition, at three selected outcrops, size of rock fragments was found to decrease downstream. Feret’s diameter decreased from outcrop source to those sampling points downstream across all three outcrops (Fig. 4.10). Although there is significant variation in the size of rock fragments at different sampling points, larger rock fragments were observed at the bottom of three outcrops. Changes in the size distribution of rock fragments from outcrop source to downstream sampling points suggested a preferential reduction in the number of larger particles. A figure presented in Koiter et al. (2013) demonstrated the friable nature of sediments entering STCW; therefore, the sediment particle size and shape is likely to change quickly during fluvial transport over a short distance. The friable nature of the material (e.g., shale) in the STCW makes it difficult to trace the sources of sediment as the coarser rock fragments can become a source of fine-grained sediment.

Thermal expansion and contraction due to extremes of diurnal temperature variability, significant seasonal or short-term temperature variations, are believed to be a likely mechanism for cracking formation and break down of rock fragments (Eppes et al., 2010). With large fluctuations in temperature at in the study site, rock fragments are likely to break down within a short time. In addition, chemical and biological activities, abrasion and collision among rock fragments could also contribute to particle breakdown (Cooke et al., 1972).

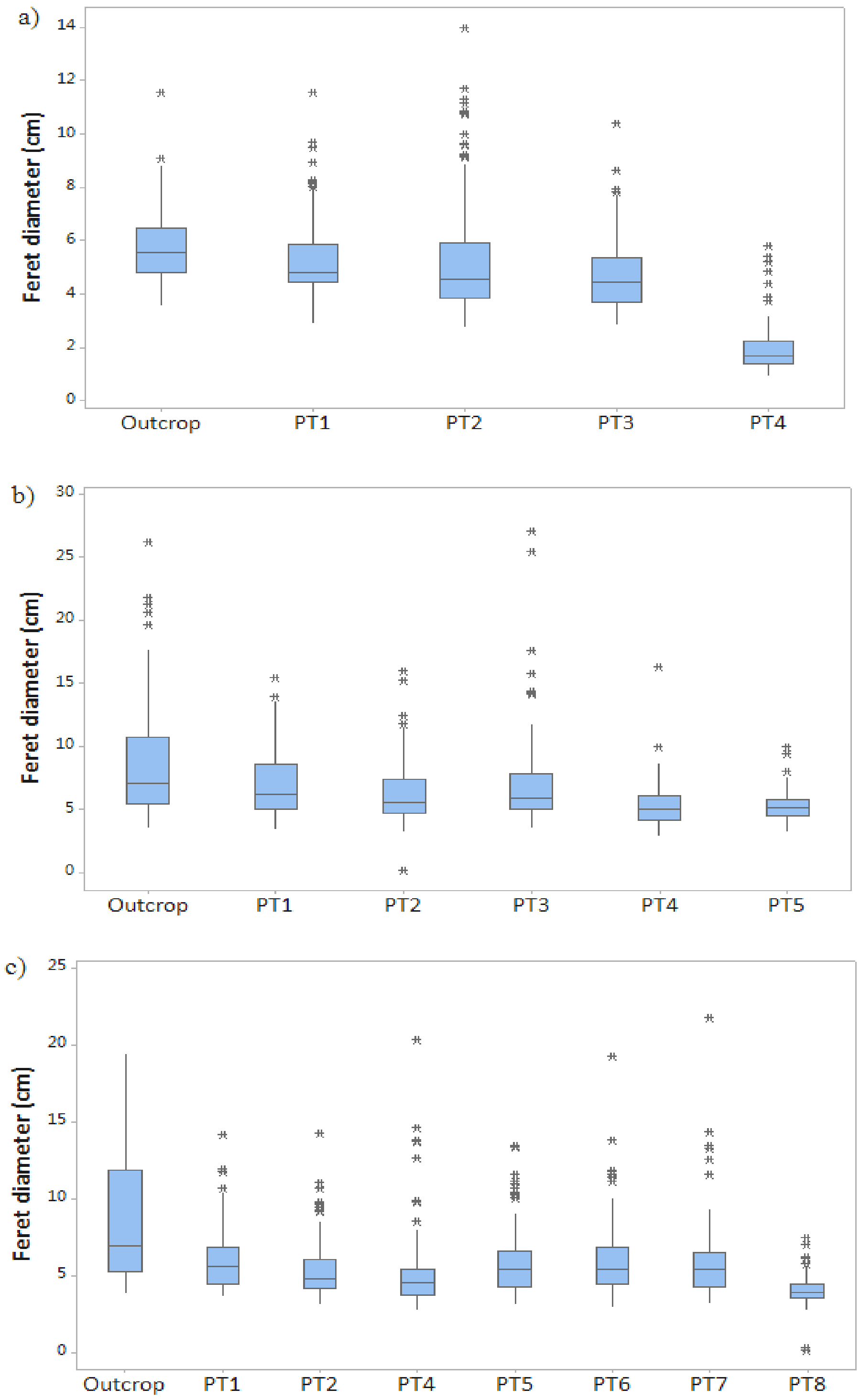

Figure 4.10 Changes in Feret's diameter of rock fragments collected from (a) Outcrop 2, (b) Outcrop 4, and (c) Outcrop 7.

4.6 Conclusion

This study examined the spatial variation in size and shape of rock fragments collected from outcrop sources and downstream sampling points using image analysis. Image analysis using ImageJ has proved to be an inexpensive, simple and fast tool in characterizing the size and shape of irregular particles. However, during the image acquisition process, only 2-D image of rock fragments can be captured for shape analysis. Thus, the image analysis method has a sampling bias because the surface of rock fragments is not enough to represent the characteristics of the entire sample. Moreover, a relatively small amount of rock fragment was collected and only rock fragments > 3 cm were measured. Therefore, few samples might not represent the entire characteristics of selected outcrops. For the future studies could use 3-D image to characterize particle morphology.

Although rock fragments collected from the outcrop sources are more angular and elongated than that collected from the downstream, there was no significance difference in circularity and roundness of rock fragments downstream which disagreed with our hypothesis. The friable nature shale materials were dominated below the escarpment, which easily break by hand. Those shale materials reduced in size in a short distance but still retained their angular shape. This study proved that the friable nature shale materials still have angular shape when they break down into smaller particles. The materials can become a source of fine-grained sediment, which may explain the particle size distribution of suspended sediment becoming finer from the upper reaches to the lower reaches (cf. Chapter 3).

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5. CONCLUSIONS AND FUTURE PROSPECTIVE

This research was conducted as a part of the “Development of environmental fingerprinting techniques for sources of sediment and associated phosphorus within agricultural watersheds of Canada” project funded by the Natural Sciences and Engineering Research Council of Canada (NSERC). The results of this research have helped to enhance the understanding of dynamics of the sediment transport in stream, and characterizations of the spatial and temporal variation in particle size and shape of sediment in the Tobacco Creek Watershed (TCW).

The study in Chapter 2 has contributed to the overall project by providing detailed information on spatial and temporal variation in particle size of suspended sediment. The results showed the suspended sediment was dominated by fine-size particles (< 62 μm) at the outlet of the study watershed. Particle size was relatively finer following snowmelt events than rainfall events. In addition, the hydrologic data from 1963 to 1977 that was available at two monitoring stations (IS3 and IS1) was summarized and quantified. The relationships between sediment load, sediment concentration and water discharge were examined for those two stations. The water discharge showed significant difference by seasonal that water discharge following snowmelt events was higher than rainfall events. The water discharge time series can be divided into two phases: an increasing phase (1963-1970) and a decreasing phase (1971-1977). Climatic and land cover change may be the reasons to influence annual water discharge. Additionally, precise relationship between stream discharge and particle size of sediment was examined for those stations.

The detailed information on hydrologic pattern and sediment load distribution obtained in the lower reaches gave a better understanding the dynamics of sediment transport, and better comparisons with other sites. This is important as hydrologic systems vary greatly from region to region. This aids understanding of how sediment transport in streams is affected by seasonal and spatial factors.

The results from Chapter 3 demonstrated the spatial and temporal variation in the particle size of suspended sediment and channel bed sediment. Over 60% suspended sediment was dominated by silt- and clay-sized (< 63 μm) at most sampling sites in the lower reaches. The TCW is characterized as a highly variable flow regime, sediment transport and abrupt geologic transitions above and below the escarpment. As a result, downstream characteristics of sediment deposits were different from those of upstream. The difference in particle size distribution for suspended sediment and channel bed sediment are predominantly controlled by watershed geology setting and hydraulic variations. Physical weathering and erosion in the upper reaches of the watershed above the escarpment result in relatively coarse-grained (most sand and silt) suspended sediment and channel banks. Abrupt geologic structural changes occur in the escarpment where steep valley walls and actively eroding cut-bank shale bedrock outcrops occur along the channel. This change coincides with an abrupt change in particle size distribution of suspended sediment. The spatial variation in particle size of suspended sediment and channel bed sediment may be related to the finding of Koiter et al. (2013) that there was a switch in sediment sources between the headwaters above the escarpment and the outlet of the watershed below the escarpment in the South Tobacco Creek Watershed (STCW). The study also compared the particle size distribution of suspended sediment and channel bed sediment following snowmelt and rainfall events through year-round study. The particle size was coarser following rainfall events (July-November) than following snowmelt events (May-June). Climatic changes may be influence the water discharge which affects the particle size distribution of suspended sediment. This part of study is consistent with the results from Chapter 2. Further consideration of the particle size distribution of suspended sediment in response to flow conditions (e.g. stream discharge) should focus on individual discharge events. Suspended sediment contained less sand and more silt and clay sized when compared to its potential source materials. The information on particle size can reflect the soil types and land use, the selectivity of erosion and sediment delivery processes responsible for sediment mobilization and transportation through the watershed. This research also provides an understanding of the shifts in sediment sources that can occur in a watershed due to the change in particle size of sediment above and below the escarpment. This study highlights the importance of the sampling location. For example, sample cannot be sampled only at the outlet of the watershed when the suspended sediment at the outlet was dominated by fine-sized particle. Therefore, understanding of suitability sediment sampling locations is important in fingerprinting studies.

The Chapter 4 showed the spatial change in particle size and morphology of the coarser fraction of sediments (e.g., rock fragments). The evolution of rock fragments was examined by using image analysis. It was demonstrated that image analysis is a fast and easy tool to quantify the particle size and shape of coarser particles. Shape parameters including circularity, roundness, and aspect ratio were used in this study to characterize the particle shape of rock fragments. Rock fragments collected from the outcrop sources are more angular and elongated than that collected from the downstream. However, there was no significant difference in circularity and roundness in shape factors of rock fragments between downstream sampling points, but the size was reduced in a short distance. The findings showed the friable nature shale materials are dominated in the study watershed, so that these coarser materials can be the source of fine particles. These materials can become a source of fine-grained sediment, which may explain the particle size distribution of suspended sediment become finer from the upper reaches to the lower reaches (cf. Chapter 3).

This thesis provides a better knowledge of dynamics in particle size and shape of sediment transported in this particular watershed. The particle size distribution of suspended sediment in the Tobacco Creek Watershed not only shows particle size selectivity, but also shows the percentage of fine particles (silt and clay sized) are very much increased by the overwhelmingly greater sources, such as the large outcrops downstream. The alarming results of particle size changes from the upper reaches to the lower reaches in this watershed, which need to be considered by the constructed upstream of dams. The knowledge in the processes (erosion and transport processes) of sediment sources (inputs) and collected sediment samples (outcrop) occur in the watershed is relative lacking. Major processes of sediment transported are schematically illustrated in Figure 5.1. As sediment moves through the landscape, the sediment properties can be representative of its nearest source. Wetlands and dams also act as buffering features within the watershed. In the upper reaches, a small dam slows the flow of water resulting in the deposition of sediment. Research by Tiessen et al. (2011) found that small dams in an agricultural basin retain approximately 70% of the annual sediment load. Sediments moves through dams have often represented the sources of sediment within river basins. But it should be taken into account that the representativeness of the sampled sediment. Sediments deposited on floodplains may have different characteristics during high and lower flow periods due to differences of sediment transport capacity. The sampling location is important when considering these features. It is important to sample upper and lower reaches within a watershed to get a more comprehensive picture of changes in sediment dynamics. In stream suspended sediment is the final product of many intermediary processes that occur during the sediment transport continuum from the upland areas to the point of collection. Sediment fingerprinting techniques should be used to incorporation the processes that link the sediment sources (inputs) to the collected sediment (outputs). Below the escarpment, there are approximately 20 outcrops with the friable nature of rock fragments. Those coarser fragments can become a new source of fine sized sediment which also makes it difficult in fingerprinting techniques. Since the properties of sediment usually reflect the nature of nearest sources, multiple sampling locations along the channel are important for better understanding the contribution of different sources (inputs) to sediments (output). Detailed particle size and shape study provides information on sediment dynamics, which reflects the geomorphic history. The variation in particle size was observed at different sampling sites which may be due to differences in geological structure and hydrology. The difference in particle morphology can be explained by the difference in land uses and the results may provide a distinct fingerprinting for sediment source. The size and shape of suspended sediment may reflect the origin of the suspended load and any modifying processes that occur during transport and storage in the stream.

There are still some limitations in the present research. First of all, limited number of coarser rock fragments (> 3 cm) were collected and measured which may result in reduced sample representativeness. Finer fraction fragments (< 3 cm) should also be included in the future study which can provide a more complete picture of any changes of sediment dynamic. Secondly, reference sample (e.g., soil material from the upper reaches) has not been analyzed in the present study. In the future study, particle size and shape of a reference sample should be examined for quantifying and comparing the particle morphology of source of rock fragments. The particle morphology of rock fragments collected before the new outcrop should also be examined for providing reference information on particle morphology dynamics. Thirdly, image analysis by a camera only captured the 2-D information of rock fragments. This 2-D image analysis method intuitively provides morphological information on the surface of particle. However, this method depends on the direction of a sample placed which exists a bias of how the sample can be captured. Future research emphasis should be focused on the development of a computerized image analysis system for measuring rock fragments depth in 3-D image. The probability 3-D image analysis method can provide more information on particle dynamics. Fourthly, the investigation of long-term water discharge influence on sediment concentration and particle size in the watershed should be done to quantify the precise relationship between particle size and water discharge. Fifthly, particle characteristics and transport processes can reflect the soil behavior. While a comprehensive confirmatory study about particle size and shape affects soil behaviour is still lacking. In order to obtain a more thorough understanding of the influence of weathering processes that occur in the study watershed, the natural weathering mechanisms of rock fragments can be artificially reproduced in the laboratory under controlled conditions. These weathering mechanisms can be carried out by simulating freezing-thawing cycles (e.g., Pardini et al. 1995), wetting-drying cycles (e.g., Pardini et al. 1995, Coombes, 2011), and tumbling (Kueppers et al., 2012) to evaluate the changes in particle size and shape of rock fragments.

Information on particle size distribution of sediment provides a quick and easy way to assess the sediment transport processes in the watershed. Although particle size varies across spatial and temporal scales, which cannot be used as fingerprinting technique. Understanding the role of transport processes on the particle size destruction of sediment is important in determining appropriate sampling techniques and locations. It is also important to consider that different particle size will exert an influence on the connectivity and subsequently the pattern of sediment transport and storage.

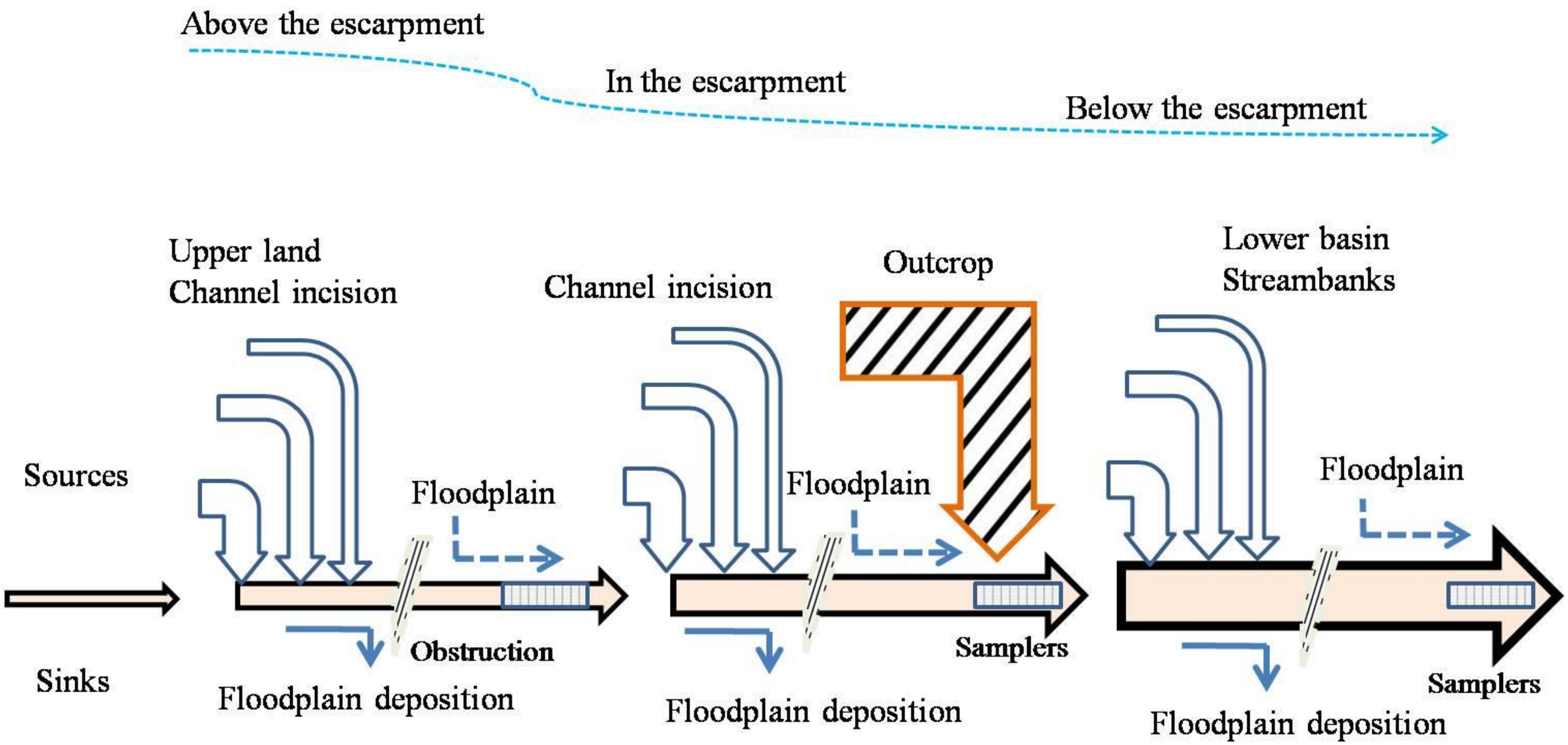

Figure 5.1 Schematic of sediment transport processes in the South Tobacco Creek Watershed.

Note: The watershed is classified into three parts according to the sampling location (above, in and below the escarpment). Obstruction includes all the flow control structures (e.g., bridges, beaver dams and culverts). The samplers are the sediment traps which mentioned in Chapter 3. The major sediment sources include channel incision from upper land, sedimentary rock from outcrops, and streambank from lower basin, in particular, the outcrop is a significant source of sediment below the escarpment. The floodplain as sediment sink has a significant proportion of the suspended sediment transported through the watershed.

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Appendix A:

Seasonal water discharge ($m^3\ s^{-1}$), sediment load ($t\ yr^{-1}$) and sediment concentration ($mg\ L^{-1}$) at IS1 based on daily discharge data in snowmelt event (March-may) and rainfall event (July-October) during 1963-1977.

Event	Year	Water discharge ($m^3\ s^{-1}$)	Sediment load ($t\ yr^{-1}$)	Sediment concentration ($mg\ L^{-1}$)	Event	Year	Water discharge ($m^3 s^{-1}$)	Sediment load ($t\ yr^{-1}$)	Sediment concentration ($mg\ L^{-1}$)
Snowmelt	1963	0	0	0	Rainfall	1963	1.2	137.2	6,980
	1964	20.9	1,323.4	17,995		1964	13.7	3,473.7	19,935
	1965	47.9	8,537.3	45,265		1965	3.7	223.3	18,083
	1966	69.7	10,238.5	50,628		1966	7.8	1,242.9	23,485
	1967	59.2	11,038.1	35,787		1967	3.1	423.9	13,590
	1968	18.4	3,782.4	27,784		1968	80.4	29,648.4	83,765
	1969	73.9	14,875.7	55,131		1969	28.7	4,705.4	49,478
	1970	131.3	34,166.9	71,823		1970	4.4	74.3	11,342
	1971	50.7	6,617.4	23,965		1971	23.7	3,012.9	40,789
	1972	73.8	4,548.2	35,801		1972	1.0	15.7	9,326
	1973	4.6	29.0	9,317		1973	0.7	17.4	4,325
	1974	127.3	37,276.4	65,555		1974	3.8	17.4	973
	1975	23.2	1,062.9	17,418		1975	8.8	1,851.9	15,451
	1976	55.3	7,431.3	35,878		1976	0.1	1.3	2,910
	1977	3.0	915.8	15,617		1977	3.8	196.2	7,559

Appendix B:

Particle size analysis of suspended sediment

The following tables were generated from the Water Survey of Canada and Environment Canada website (https://wateroffice.ec.gc.ca/) and represent particle size of suspended sediment data collected at South Tobacco Creek Watershed near Miami station from 1963 to 1977.

Station number: 05OB26

Date of collection	Percentage finer than indicated size in mm									
	0.002	0.004	0.008	0.016	0.031	0.062	0.125	0.25	0.5	1
1963/6/11	26	40	66	85	93	96	98	99	100	
6/18	10	22	38	47	62	85	95	98	99	100
6/19	8	18	77	98	99	100				
1964/4/15	26	40	74	93	99	100				
4/22	56	70	92	98	99	100				
5/4	63	76	95	100						
6/19	50	66	97	99	100					
7/22	11	20	78	96	100					
7/23	64	76	95	99	100					
7/23	60	72	93	99	100					
7/24	76	88	99	100						
8/3	50	61	84	97	99	100				
9/1	46	56	78	91	97	99	100			
1965/4/12	27	36	50	66	79	92	97	99	100	
4/14	34	46	64	80	93	97	99	100		
4/16	38	48	70	90	97	99	100			
5/5	6	18	67	86	93	99	100			
5/6	10	26	56	74	85	94	98	100		
5/26	46	57	75	82	92	99	100			
6/3	46	60	79	86	89	95	99	100		
7/1	12	20	34	55	80	97	99	100		
9/17	69	81	93	99	99	100				
1966/3/23	12	18	37	66	92	99	100			
3/31	65	67	72	84	94	99	100			
4/1	41	52	70	84	92	96	99	100		

4/4	48	60	84	92	96	99	100		
4/10	22	32	53	89	98	100			
4/15	37	48	69	86	95	98	99	100	
4/20	38	50	78	96	99	100			
4/26	40	52	79	92	97	98	100		
5/2	28	40	68	86	94	99	100		
5/5 a.m.	24	35	58	78	93	99	100		
5/5 p.m	32	46	60	75	86	93	98	99	100
5/10	44	56	81	92	97	99	100		
5/10	41	56	80	93	98	99	100		
5/16	31	45	69	87	95	98	99	100	
5/22	36	48	76	88	97	99	100		
6/2	20	60	86	94	99	100			
6/4	22	46	75	95	88	100			
8/9	31	51	63	71	80	93	99	100	
8/9	52	84	97	99	100				
1967/4/8	53	65	80	88	92	96	98	99	100
4/14	18	33	63	88	98	100			
4/22	25	34	48	63	76	88	95	98	100
4/29	29	42	67	73	78	90	99	100	
5/6	34	53	79	93	97	99	100		
5/10	46	59	83	94	98	99	100		
5/15	24	37	64	83	90	97	100		
7/7	37	51	75	88	96	99	100		
7/8 a.m	51	64	85	95	98	99	100		
7/8 p.m	63	74	91	97	99	100			
7/9	43	56	91	99	99	100			
1968/3/27	50	64	82	93	97	99	100		
3/30	58	72	93	98	99	99	100		
4/7	47	60	87	94	96	98	99	100	
4/10	71	87	97	98	99	100			
5/8	44	57	83	94	98	99	100		
5/15	30	49	76	88	95	98	100		
5/15	10	30	72	88	95	98	99	100	
5/15	48	60	90	98	99	100			
6/4	58	72	91	98	99	99	100		
7/1	46	63	84	96	99	100			
7/9	30	42	57	70	84	98	100		
7/16	48	60	78	92	98	100			
7/30	50	65	84	95	99	100			
7/30	15	42	84	95	99	100			

8/5	44	57	78	91	97	99	100			
8/19	51	64	85	97	99	99	100			
8/25	38	49	64	80	91	97	99	100		
8/29	46	59	82	97	98	99	100			
9/8	45	58	79	84	99	100				
1969/4/9	47	56	70	83	93	97	99	100		
4/9	44	54	69	83	93	98	100			
4/10	31	42	56	74	89	96	99	100		
4/13	34	46	63	77	89	95	98	99	100	
4/14	28	37	53	68	81	93	98	99	100	
4/18	41	53	75	91	96	99	100			
4/23	38	51	81	91	95	97	99	100		
4/26	13	20	52	80	93	98	99	100		
4/26	19	33	60	75	88	96	99	100		
5/2	39	48	72	88	95	98	99	100		
5/5	31	44	64	79	92	98	100			
6/26	7	14	80	91	97	98	99	100		
6/27	8	18	54	69	81	91	97	99	100	
6/30	29	40	59	75	87	93	97	99	100	
7/6	33	43	66	83	87	93	97	99	100	
7/8 a.m	24	36	59	70	83	93	97	99	100	
7/8 p.m	25	35	53	68	81	91	96	98	99	100
7/9	30	39	54	70	84	95	98	99	100	
7/14	15	25	45	63	75	90	97	99	100	
7/30	36	46	66	69	79	89	98	100		
1970/4/14	24	32	46	64	82	95	99	100		
4/18	15	23	36	57	81	93	97	99	100	
4/25 a.m	20	32	48	63	78	91	98	100		
4/25 p.m	27	39	54	68	78	87	94	97	99	100
4/26 p.m	31	39	52	67	79	90	95	98	99	100
4/27 p.m	27	38	52	67	79	93	97	100		
4/29	36	48	64	78	89	95	97	99	100	
5/4	29	40	57	71	82	92	97	99	100	
5/13	26	37	57	79	90	96	99	100		
5/24	46	70	85	93	97	98	100			
4/9	35	45	66	82	92	97	99	99	99	100
1971/4/10 a.m	41	52	70	85	94	98	99	99	99	100
4/10 p.m	23	33	47	63	77	91	97	99	100	
4/11	24	36	52	66	78	91	98	99	100	
4/15	38	50	71	88	95	97	99	99	100	
4/20	43	55	79	94	97	98	99	99	100	

6/6	27	40	67	93	95	98	99	99	100	
6/21	33	49	76	90	97	99	99	99	100	
6/21	33	47	74	85	94	99	99	100		
7/11 a.m	21	31	45	63	85	95	98	99	99	100
7/11-p.m	27	40	71	86	94	98	99	100		
9/5	47	61	82	96	99	99	99	99	100	
10/2	29	41	71	84	92	97	99	99	100	
10/19	50	62	81	93	98	99	99	99	100	
1972/4/9	32	42	59	78	93	97	99	100		
4/14	20	29	42	59	78	95	99	100		
4/17	32	44	61	78	90	97	100			
4/24	13	27	55	74	83	96	100			
5/1	46	59	87	96	97	99	100			
1973/7/7 16:00	6	10	17	26	41	61	85	97	100	
7/7 18:00	51	62	73	78	84	94	99	100		
1974/4/24	41	51	68	82	91	95	98	99	100	
1975/4/25	51	65	87	93	94	95	96	98	99	99
4/29 a.m	43	54	75	89	96	98	99	100		
/4/29 p.m	45	57	76	90	96	98	99	100		
5/24	34	44	62	74	83	93	100			
6/29	27	43	75	87	95	97	99	100		
1976/4/2	50	60	70	76	84	90	97	99	100	
4/5	25	32	51	73	89	98	99	100		
4/6	28	37	55	72	86	95	98	99	99	100
4/14	34	47	77	89	95	98	99	100		
4/17	15	30	65	79	92	97	99	100		
1977/5/18	14	25	63	93	98	99	100			
5/19	61	82	95	97	98	99	99	100		
5/20 a.m	37	50	83	95	97	98	99	100		
5/20 p.m	64	77	93	96	97	98	99	100		
9/9	40	65	90	98	98	99	100			
9/24	52	66	87	96	97	98	99	100		
9/25	50	62	86	94	96	98	99	100		
9/26	50	65	87	95	96	97	98	99	99	100