DOWNSTREAM PATTERNS AND CATCHMENT CONTROLS ON SUSPENDED SEDIMENT TRANSPORT IN A HIGH ARCTIC RIVER

by

Elena Angelica Favaro

A thesis submitted to the Department of Geography

In conformity with the requirements for

the degree of Master of Science

Queen's University

Kingston, Ontario, Canada

(September, 2013)

Copyright © Elena Angelica Favaro, 2013

Abstract

A study of downstream suspended sediment transport dynamics in the West River at Cape Bounty, Melville Island, Nunavut, was undertaken in 2012. The first component of the research quantified the sediment mobilized in the West River during the 2012 season. A nival bed-contact survey was undertaken to identify areas of the river in which stream flow was isolated from the bed, and was combined with a reach-based sediment budget approach to assess sediment entrainment and downstream movement. This analysis revealed the propensity of the West River to store suspended sediment through much of the season. Permafrost disturbances in 2007 inundated the West River with fine sediments, the majority of which are progressing from the headwaters as a sediment slug that is subject to substantial downstream storage. Diurnal and event hysteresis analysis from 2004-2012 demonstrate the change in sediment delivery inter-annually, transitioning from a system characterized by clockwise hysteresis prior to the 2007 disturbances, to counter-clockwise hysteresis post 2007. The latter is reflective of the important contribution of the headwater sediment slug from disturbance to downstream sediment transport and common net sediment storage in the lower reaches of the river.

The second project studied the delivery of suspended sediment following late season major rainfall events (MRE) and the control antecedent catchment conditions prior to rainfall exert on the magnitude of stream runoff and suspended sediment transport. Two MREs on July 9 and July 23, totalling 35.4 and 10.6 mm, respectively, resulted in exceptionally low discharge response and sediment mobilization. Analysis of synoptic level pressure patterns and catchment soil moisture revealed low volumetric water content preceding both MREs, a result of sustained exceptional early summer warmth under stable regional high pressure. Compared to similar MREs in 2007-2009, the soil in 2012 did not become saturated, and substantial runoff did not occur.

These studies contribute to an understanding of the processes of sediment transport in response to disturbances, rainfall, and antecedent catchment conditions, all of which are becoming important components of the Arctic fluvial systems but have had limited study due to the emphasis on snow melt processes and hydrological fluxes.

Co-Authorship

Field research at the Cape Bounty Arctic Watershed Observatory in 2012 was organized and directed by Dr. Scott Lamoureux. The author carried out field measurements in 2012 and performed all laboratory analysis for suspended sediment concentration. Discharge rating curves from previous seasons were used for the creation of inferred sediment budgets. Soil moisture data was provided by Dr. Elyn Humphreys of Carleton University. The author wrote all chapters, with discussion and editorial input from Dr. Scott Lamoureux.

Acknowledgements

I would first like to extend my deepest gratitude to my supervisor Dr. Scott Lamoureux, without whom this thesis would not be possible. His guidance over the past two years has been unwavering and his patience only surpassed by his enthusiasm for Arctic research. I have learned a great deal from you, Scott, and I'd like to especially thank you for keeping me on as a Master's student after I struck you out twice in Arctic Baseball.

To all of those I have shared an office, a lab with, a weather-haven, and a friendship with, I sincerely thank you for your support, encouragement, and unwavering dedication to your work, which has encouraged me to strive for nothing but the very best.

To my parents, Nicolina and Joseph, who allowed me to eagerly explain my research, even when I lost them at "fluvial"; to my sister Laura for her sharp wit and wisdom beyond her years; and to Ali, who was there to bring my moments of self-doubt into perspective and offer words of encouragement; your love and faith in me means more than words can properly convey.

This research would not have been possible without the financial backing and logistical support of ArcticNet, the Natural Sciences and Engineering Research Council, the Polar Continental Shelf Program, and Queen's University.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ACIA	Arctic Climate Impact Assessment
ALD	Active Layer Detachment
AMAP	Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2011 Overview Report
AOGCM	Global Coupled Atmospheric-Ocean General Circulation Model
a.s.l	Above Sea Level
CBAWO	Cape Bounty Arctic Watershed Observatory
GCM	Global Climate Model
HI	Hysteresis Index
IPCC	Intergovernmental Panel on Climate Change
MDD	Melting Degree Day
MRE	Major Rainfall Event
Q	Discharge
RR	Runoff Ratio
RTS	Retrogressive Thaw Slumps
SDR	Sediment Delivery Ratio
SSC	Suspended Sediment Concentration
SSQ	Suspended Sediment Discharge
SSY	Suspended Sediment Yield
SWE	Snow Water Equivalence
VWC	Volumetric Water Content
WRGS	West River Gauging Station

Chapter 1

Introduction

Recent literature focused on the Arctic has emphasized a common concern: warming in this region is accelerating and projections for the next century are looking increasingly severe with respect to natural systems dominated by climate. The Arctic Climate Impact Assessment report (ACIA) (2005) notes that mean annual air temperatures in the Arctic have warmed twice as fast as the rest of the globe, and another 4-7°C increase could be observed by 2100 if current model trajectories are upheld. Potential consequences of this warming include an increase in permafrost disturbances and summer precipitation, and a decrease in seasonal river discharge (IPCC, 2007; ACIA, 2005; AMAP, 2012), among others, all of which have the potential to cause geomorphic and hydrological alterations to the landscape and impact related ecosystems. In particular, altering the timing and magnitude of sediment and water release into lakes and oceans stresses downstream aquatic and terrestrial ecosystems (Gordeev, 2006).

Despite a relatively short hydrological season compared to temperate settings, the 3-4 months of the year when surface flow occurs have been recognized as having a significant impact on the landscape (Woo, 2012). These snowmelt driven systems are impacted by the rapid melting of in-channel snow, resulting in what is known as the nival flood or the nival melt phase. This period of rapid transition can represent upwards of 90% of the water discharge and sediment transport for the entire season (Forbes and Lamoureux, 2005; McDonald and Lamoureux, 2009). While subsequent baseflow dominates the majority of the hydrological season in northern environments, this period has the potential to either transport substantial amounts of sediment materials and water as a result of cumulative environmental impacts, or to store that material as a result of landscape alterations.

Given these concerns, studying the fluvial and geomorphological processes and changes to river systems as a result of climate change is an important, but understudied topic. The Cape Bounty Arctic Watershed Observatory (CBAWO), Melville Island, Nunavut, is an ongoing field site for sedimentological and fluvial investigations, as the island is uninhabited and only subject to human influence during the short summer season. The West Watershed (8.0 km^2) and West River (both unofficial names) have been the subject of hydrologic, meteorlogic, and sediment transport investigations since 2003. The benefit of these types of studies in small High Arctic catchments is that they can be used to up-scale processes and explain the complex interactions seen in larger catchments where investigations may be hindered by the size of the watershed.

Investigations into suspended sediment transport at Cape Bounty provide the means to evaluate the spatial and temporal variability in sediment source areas and subsequent suspended sediment transport on a seasonal and annually resolved basis. Additionally, investigations of antecedent catchment conditions and the mechanisms by which they are realized, aid in our understanding of the magnitude of late season sediment transport dynamics. As such, the goals of this research are as follows:

1. To identify source and sink areas of the West River and to track the change in these areas on a seasonal basis through the use of a sediment budget approach;
2. To determine how both sediment transport and discharge characteristics have been changed in the West River over the period of 2004-2012; and
3. To evaluate the fluvial and suspended sediment mobilization in response to major rainfall events (MREs) as they are affected by antecedent catchment conditions in years with major rainfall events (2007-2009, 2012).

To examine these questions, continuous hydrological and sediment monitoring was undertaken on the West River in addition to hydroclimatic monitoring of the watershed. Complex interactions between suspended sediment concentration (SSC) and discharge in the catchment were examined through river surveys, sediment budgets, and hysteresis relationships, while insights into antecedent catchment conditions prior to late season rainfall served to explain the response of the river to major rainfall events during the baseflow period.

A literature review is presented in Chapter 2.

Results from Chapter 3 suggest that a combination of warming temperatures, which cause short-lived permafrost disturbances, and a decrease in overall nival discharge have changed the way in which the West River delivers sediment to downstream outlets. Chapter 4 investigates the mitigating influence that antecedent catchment conditions have on rainfall-generated runoff events.

Fluvial investigations have been conducted in the Arctic over the past 50 years (e.g., Cook, 1967; Cogley and McCann, 1976; Woo, 1983; Lewkowicz and Wolfe, 1994; Braun et al., 2000; Lewis et al., 2012), however, comparatively little is known about dynamics, patterns, and norms for these fluvial systems in this part of the world when compared to temperate regions (Woo, 2012). Further research is needed in this underrepresented area to establish a baseline from which future perturbations resulting from climate warming can be assessed.

Chapter 2

Literature Review

2.1 Introduction

The circumpolar Arctic has been well-documented as an area sensitive to changes in climate, and will undergo significant warming if projected trends continue (ACIA, 2005; IPCC, 2007; AMAP, 2012). As a result, the Arctic biome may suffer severe impacts, especially with regard to changes in established hydrological regimes. These changes may manifest themselves in a number of ways: a lengthening of the hydrologic season, an increase in winter and summer precipitation, a transition from a nival (snowmelt) - driven runoff regime to a pluvial (rainfall) - driven regime, and changes to established sediment delivery patterns, which may impact downstream marine and aquatic ecosystems (McKnight et al., 2008; Lyons and Finlay, 2008). This chapter will outline and summarize relevant research pertaining to Arctic hydrology and suspended sediment transport in the circumpolar Arctic, with particular emphasis on the Canadian High Arctic.

2.2 Snow Hydrology

It has long been recognized that snow plays an integral role in the hydrology of Arctic watersheds. In areas of continuous permafrost (see section 2.2), over 250 days of snow cover typically are recorded every year (Woo, 2012). Snow falls during the fall freeze-up, continues into autumn, and is subject to extensive redistribution by wind during the winter and spring. Snowpacks several meters thick accumulate in channels, gullies, and depressions. The snow is held until the spring thaw when above-freezing temperatures and 24-hour solar radiation warms the snowpack, generating runoff during the short melt season.

2.2.1 Snowpack Energy Exchange

In the High Arctic, a net loss of energy occurs between snow and atmosphere, resulting in extremely cold snow that does not melt as readily as snow found in lower arctic regions, such as Alaska (Woo, 2012). Only when a snowpack ripens and becomes isothermal does melting occur (DeWalle and Rango, 2008). The energy budget for a snowpack,

$$Q_i = Q_{ns} + Q_{nl} + Q_h + Q_e + Q_r + Q_g + Q_m \quad (2.1)$$

where Q_i is the change in snowpack internal sensible and latent heat storage, Q_{ns} is the net shortwave energy exchange, Q_{nl} is the net longwave radiant energy exchange, Q_h is the convective exchange of sensible heat with the atmosphere, Q_e is the convective exchange of latent heat of vaporization and sublimation with the atmosphere, Q_r is the rainfall sensible and latent heat, Q_g is ground heat conduction, and Q_m is loss of latent heat of fusion due to meltwater leaving the snowpack (DeWalle and Rango, 2008). Of these terms, perhaps the most important is net shortwave energy exchange, Q_{ns},

$$Q_{ns} = K\uparrow - K\downarrow \quad (2.2)$$

which represents the sum of incoming and outgoing fluxes of shortwave energy,

$$K\uparrow = \alpha\, K\downarrow \quad (2.3)$$

where K is the shortwave radiation and the incoming or outgoing fluxes are denoted by the directionality of the arrows, and α is the albedo of the snowpack (DeWalle and Rango, 2008; Woo, 2012). Incoming and net radiation are reduced by the high albedo of snow, which can range between 0.95 for freshly fallen snow to 0.40 for dirty snow, and it is not until late April or early May, when 24-hour daylight has returned to the Arctic, that the net radiation budget becomes positive (DeWalle and Rango, 2008; Woo, 2012). As the air temperatures rise, the surface of the snowpack conducts heat into the snow, producing melt at the surface, despite possible below-freezing temperatures in the snow closer to the ground (Woo, 2012).

2.2.2 Snowmelt

Generally speaking, snowmelt occurs in three phases: warming, ripening, and output (Dingman, 1994). The warming and ripening phases occur when incoming solar radiation warms the snowpack and raises the temperature of the snowpack to 0°C. The snowpack is now said to be ripe, but in High Arctic regions, the entire snowpack may not be uniformly ripe. Melting at the surface of the snowpack can introduce meltwater to deep layers of the snowpack still below 0°C. The meltwater then refreezes, forming ice layers and lenses, which release latent heat, further warming the snowpack. Additionally, melt can be hastened when small amounts of energy from spring precipitation are added to the snowpack. Finally, the output phase occurs when meltwater percolates through the snowpack, and becomes water output (Dingman, 1994).

2.2.3 Channel Development

Channels begin to develop when the snowpack has reached saturation along its length, resulting in flow, and ends when a stable channel reaches the bed. Due to the uneven distribution of snowpack depth and ripening, as well as percolation of water from surrounding slopes, the initial movement of meltwater progresses 'in steps and halts', depending upon the degree of snowpack ripening and whether or not it requires further water to saturate, and whether additional water is available downstream (Woo and Sauriol, 1980). Channeled flows can occur in three locations: on the snow surface, within snowpacks as tunnels, or between the snowpack and the valley slope (Woo and Sauriol, 1980). Initial meltwater movement can occur as subsurface flow in snow, sheet-flow on the snow surface, or as slush flow.

An increase in hydrostatic water level in the snow signals the start of subsurface flow within the snowpack (Figure 2.1). As the water levels increase and reach the top of the snowpack, flow is carried downstream as sheet flow on the snow surface. Due to the variable nature of downstream channel development - a function of available water and snowpack ripening, among other causes, and the occurrence of snow blocks, snow jams, and snowdrifts, ponding can occur until the pond breaks through the obstruction. This results in a rapid release of water and further facilitates downstream snowmelt (Woo and Sauriol, 1980). The variability in channel development within the valley snowpack is contingent upon the type of valley in which it is formed (Figure 2.2), and it has a direct impact on the runoff regime, controlling various aspects of the resulting hydrograph, such as magnitude and timing of peak flow, duration of the nival melt, and overall catchment discharge (Woo and Sauriol, 1980).

The final location of channelized flow seldom coincides with its initial location. This is due to undercutting, and the eventual absence of channel snow, as well as the undercutting of channel banks over the duration of the melt season (Woo and Sauriol, 1980).

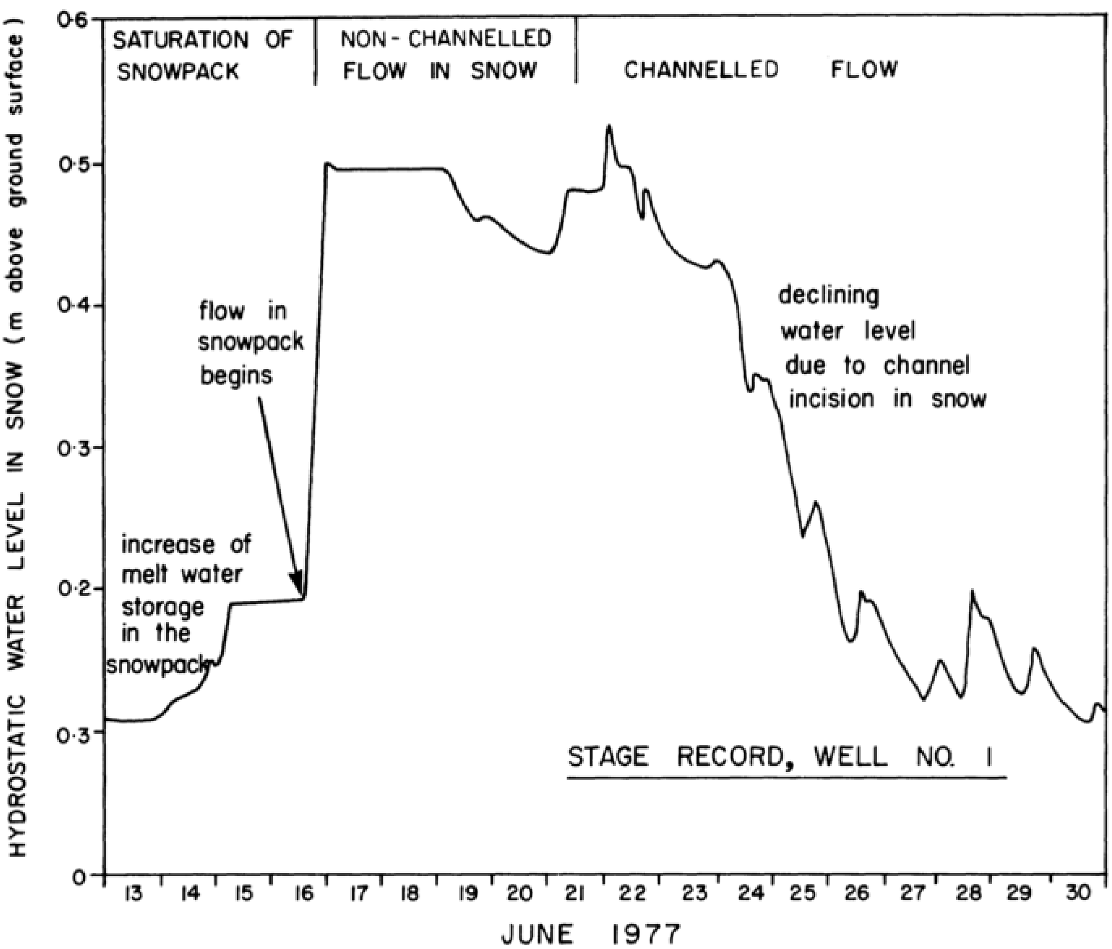


Figure 2.1 The hydrostatic response to water level during channel development in a drainage basin at Resolute Bay (Woo & Sauriol, 1980)

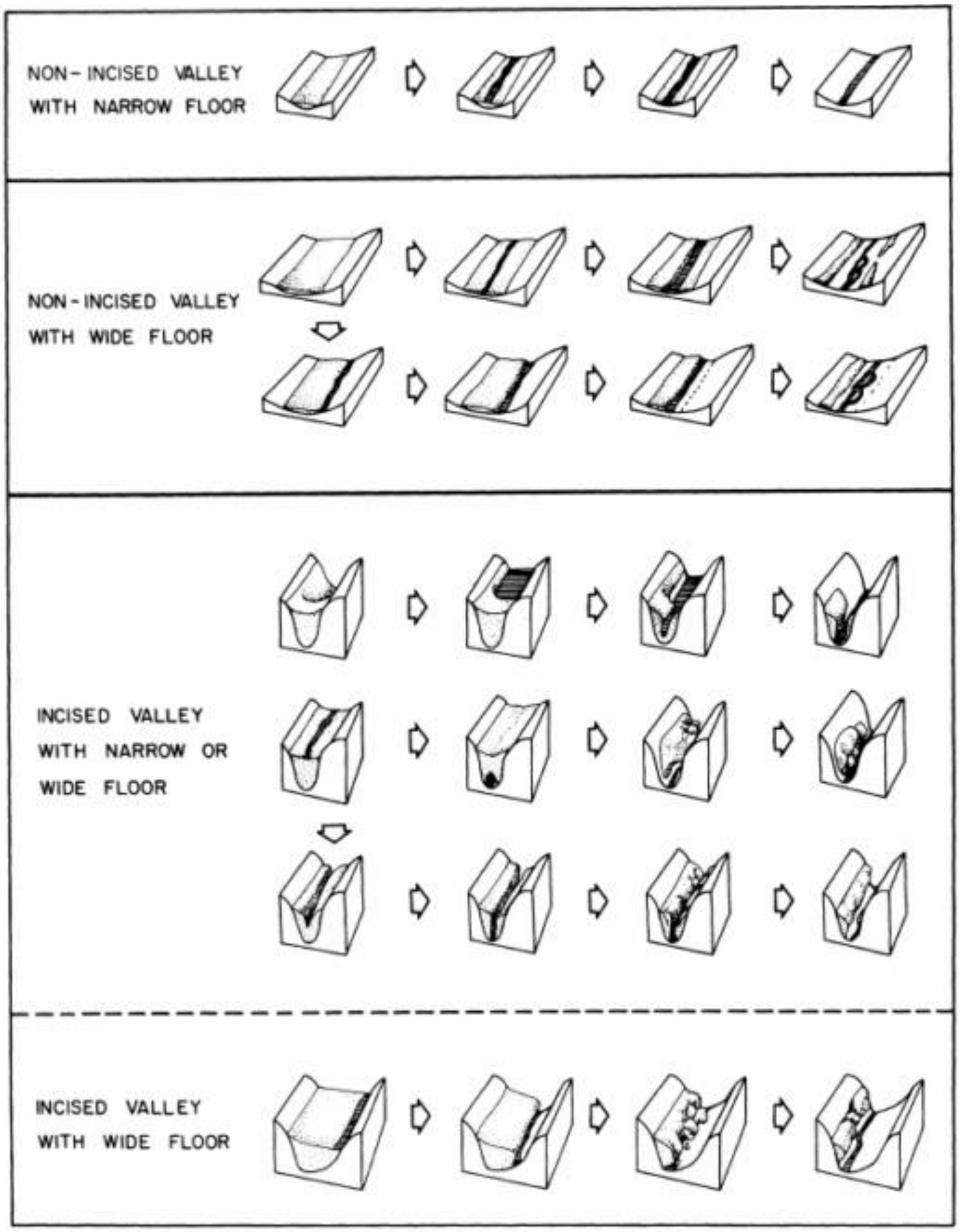


Figure 2.2 Stream channel development in several common snow-filled valley types (Woo & Sauriol, 1980)

2.3 Permafrost Hydrology

Ground which remains frozen for at least two consecutive years is classified as permafrost. Permafrost underlies approximately 22% of the Northern Hemisphere (Woo, 2012) and 80% of the Arctic drainage basin (Frey and McClelland, 2009), although spatial distribution is not uniform. Relief and orientation, hydrogeology, and lithology all exert control on the physical variations of permafrost extent and depth. Permafrost can be described as isolated (0-10% land cover, 10-15 m depth), sporadic (10-50%), discontinuous (50-90%, 25-50 m) or continuous (90-100%, 100-800 m) (Frey and McClelland, 2009; Rowland et al., 2010). A continuous permafrost zone exists in a geographic region where at least 90% of the area is underlain by permafrost, while a discontinuous zone exists in a region where both permafrost and non-permafrost ground are present (Woo, 2012). The majority of the Canadian High Arctic is considered a continuous permafrost zone (Figure 2.3)

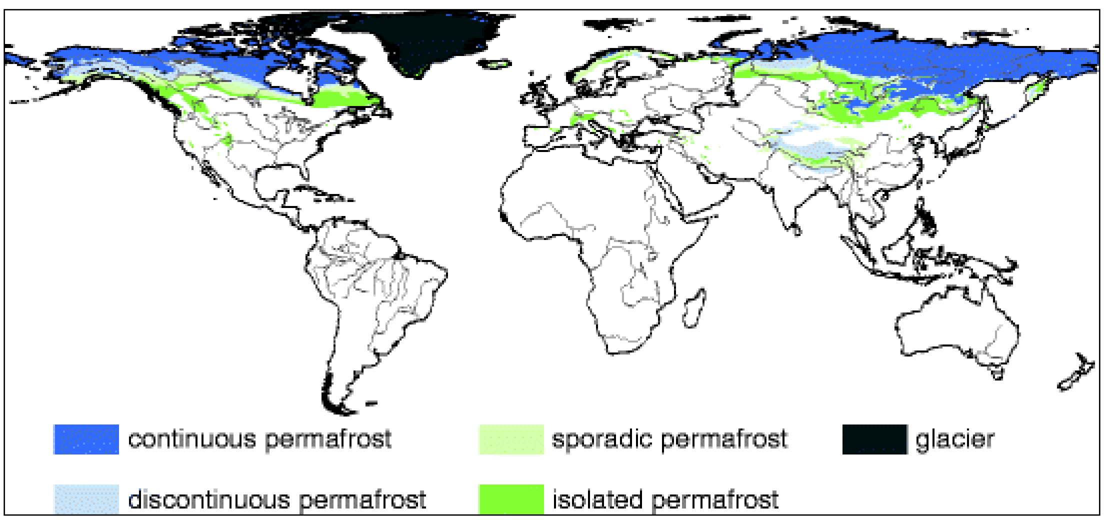


Figure 2.3 The spatial distribution of global permafrost (excluding Antarctica) (Woo 2012).

Hydrologic activity during the melt season in areas underlain by continuous permafrost is restricted to lateral inflows of water through either infiltration by the seasonally-thawed active layer, or from overland flow. Woo et al. (2008) noted that where it is present, permafrost limits deep percolation of infiltrated moisture, creating a semi-impermeable aquatard.

2.4 Streamflow Regimes

Summer streamflow patterns in northern settings are reflections of the climate, the presence (or absence) of permafrost, the primary source of streamflow, as well as the storage mechanisms which modify discharge (Woo, 2012). Streamflow hydrographs respond to inputs from melting ice and snow, as well as groundwater recharge and late season precipitation events.

Basins underlain by permafrost respond quickly to snowmelt and rainfall due to the restrictions placed on downward percolation of water. As such, the seasonal hydrographs for these basins are characterized by four distinct periods: break-up, snowmelt, late summer, and freeze-back (French, 2007; Woo, 2012). To various extents and broadly depending upon latitude, all Arctic runoff regimes are dominated by the rapid depletion of snow during spring, which typically constitutes the highest discharge peaks of the season. These single-peak runoff regimes are referred to as nival (French, 2007). As the season progresses and the contribution of snowmelt decreases, runoff decreases to baseflow conditions unless impacted by summer precipitation (French, 2007; Woo, 2012). Researchers have identified many northern runoff regimes, but only two are considered nival: the Arctic and Subarctic nival regimes (Woo, 2012).

2.4.1 Arctic Nival Regime

Nival, or snowmelt-dominated hydrologic regimes, are common in the Canadian High Arctic in areas underlain by continuous permafrost. These hydrographs are characterized by their short hydrologic seasons where discharge peaks rapidly soon after the initiation of snowmelt, brought about by above-freezing temperatures and high levels of solar radiation reaching the surface. This rapid rise from zero to peak discharge occurs within a few days, while the longer nival period, also called the spring freshet, lasts between 2 and 3 weeks. The freshet often constitutes the most energetic period of the melt season, with upward of 90% of all water and sediment being transported during this period of high flow - also referred to as the 'annual flood' (McDonald and Lamoureux, 2009; Woo, 2012). Diurnal cycles are apparent with low flow in the morning, reaching peak flow in the late afternoon and evening. Over the course of the nival period, as basin snow is depleted, the hydrograph wanes and quickly reaches baseflow conditions, where it remains unless interrupted by late season precipitation events (Figure 2.4) (Woo, 2012).

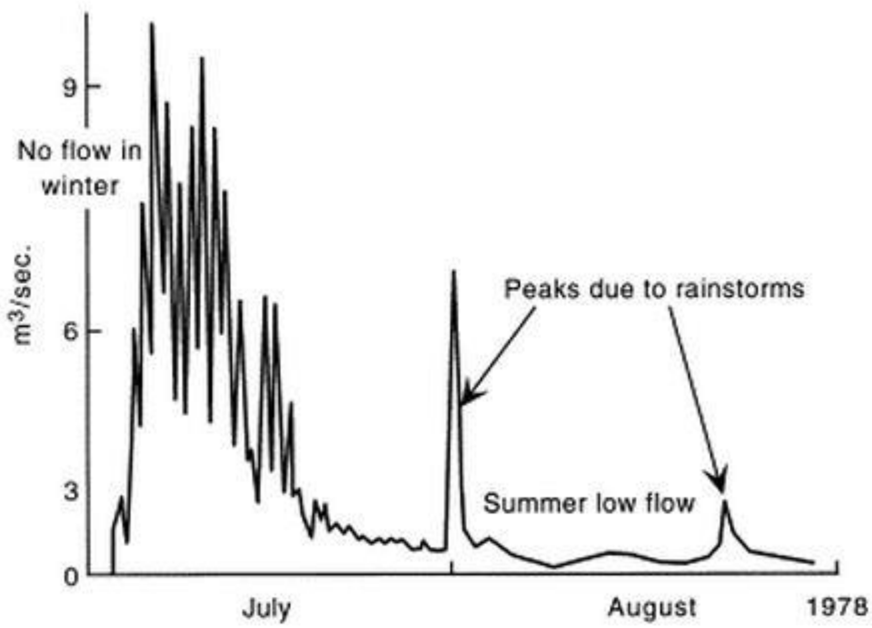


Figure 2.4 Typical flow for an Arctic nival runoff regime (adapted from French, 2007).

Considerable year-to-year variations in hydrographs exist, as exemplified by hydrographs from the McMaster River between 1976 and 1981 (Figure 2.5). These variations can be attributed to climate - which affects the first day of flow, peak discharge, the length of the hydrologic season, and the occurrence and importance of late season inputs to the system.

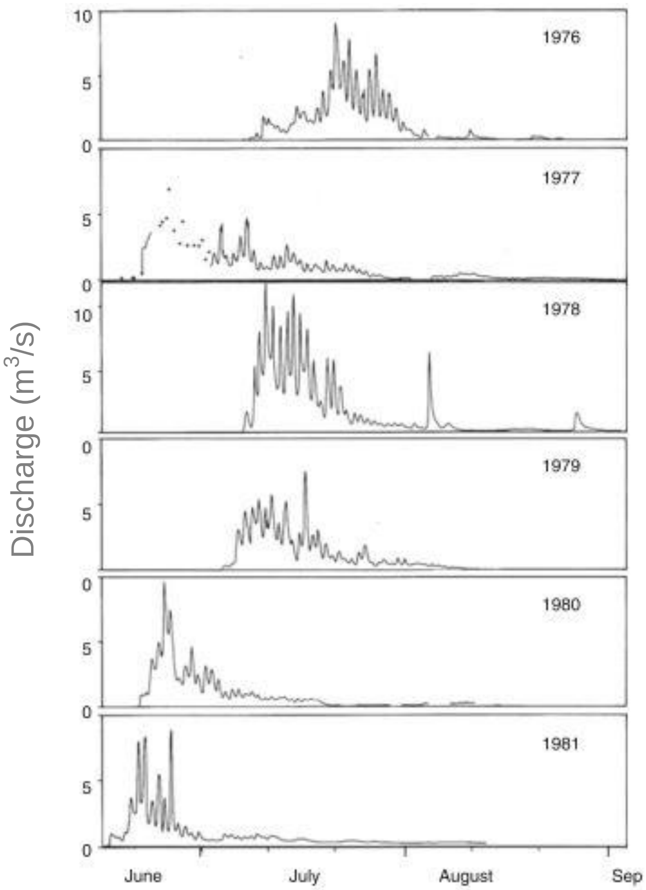


Figure 2.5 Variability in hourly Arctic nival hydrographs from the McMaster River, Nunavut (Woo, 2012).

2.4.2 Subarctic Nival Regime

Arctic and Subarctic nival regimes are similar in many respects. Just as in the Arctic, the Subarctic is characterized by a prominent high flow period, early in the melt season, which is attributed to snowmelt. However, Subarctic basins have longer streamflow seasons, as freeze-up occurs later in the summer-winter transition period, and more frequent summer high flows, which result from rainfall events. In some Subarctic areas, winter can be considered a low flow period, as discharge is maintained by subpermafrost and intrapermafrost groundwater introduced to a channel through taliks (Figure 2.6) (Woo, 2012).

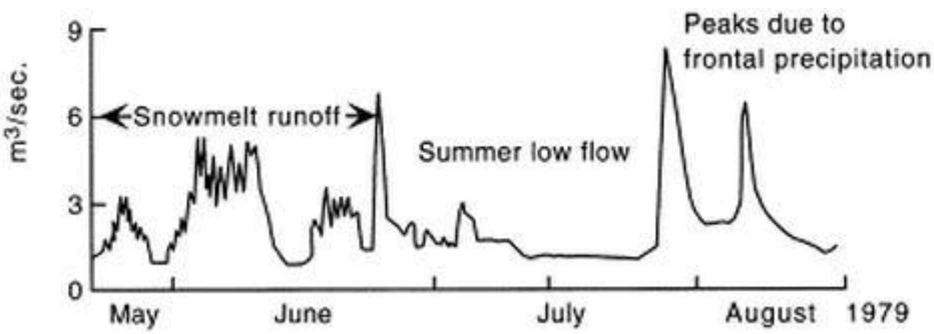


Figure 2.6 Typical flow for a Subarctic nival flow regime (adapted from French, 2007).

2.5 The Dynamics of Sediment Transport in Fluvial Environments

Sediment sources are temporally and spatially variable in a system, occurring as a response to the complex interactions between factors governing sediment erosion and movement. These are most notably hydrometric and climatological factors such as shear stresses, stream power, stream velocity, as well as the presence of in-channel snow and ice (Collins & Walling, 2004; McDonald and Lamoureux, 2009). These factors, together with the dominant hydrological regime of an area, dictate when, where, and what type of sediment is mobilized, when peak and nominal discharge is reached, and when and how sediment is entrained. Zones of entrainment and deposition can occur at many locations within a drainage basin, and may not remain static throughout a season.

One of the most fundamental constraints in the study of sediment transport is the challenge of linking on-site rates of erosion to the total sediment yield at the outlet of the basin, otherwise known as the ‘sediment delivery problem’ (Walling, 1983). This challenge is made more difficult considering the inconsistent and variable nature of hydrologic connectivity, and whether the findings are the results of disruptions to lateral and longitudinal linkages, or the presence of in-channel snow, a common feature in Arctic environments.

2.5.1 Initiation of Sediment Transport

Before sediment transport can be initiated, each particle must first overcome a threshold shear stress, or critical shear stress value (τ_0), before the particles can begin to move. Each critical shear stress value is dependent upon seven variables, which fall into liquid, solid, and flow phases (Table 2.1).

Table 2.1 The phases and associated variables of shear stress (Crowe et al., 2005)

Liquid Phase	Solid Phase	Flow
Density of Fluid (ρ)	Particle Density (ρ_s)	Submerged Specific Weight of particle (γ_s)
Kinematic Viscosity (ν)	Diameter of particle(D)	Depth (h)
		Shear Velocity (v_*)

These seven variables are the basis for the two-phase motion equations which govern sediment transport. Of these equations, Reynolds Number (Re_*)

$$Re_* = u_* D / \nu \tag{2.4}$$

where u_* is the friction velocity, and D and ν are particle diameter and kinematic viscosity, respectively, which, when plotted against particle shear stress

$$\theta = \tau_{cr} / (\rho_s - \rho) gD \tag{2.5}$$

where θ is Shields number, τ_{cr} is critical shear stress, ρ_s and ρ are the densities of sediment and water, respectively, g is the force due to gravity, and D is particle diameter, allows researchers to use Shields Curve to determine whether sediment transport has been initiated (Figure 2.7).

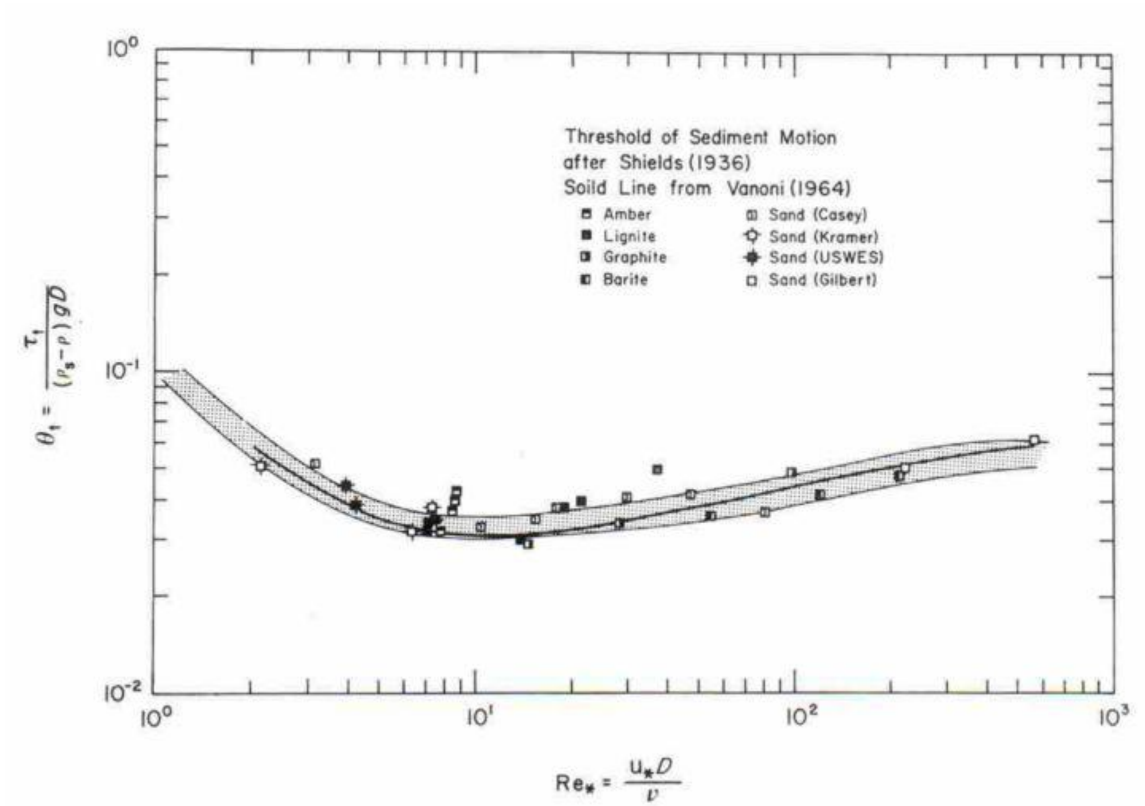


Figure 2.7 The relationship between Shields and Reynolds number allows for Sheilds curve to be used in determining whether or not sediment transport has been initiated (Miller 1977).

Should a particle's velocity lie below the curve, the particle does not move. If the particle lies directly on the curve (critical stage) or above the curve (supercritical stage) particle transport has begun.

2.6 Transported Materials

Sediment in Arctic environments can be transported as bedload, suspended load, or dissolved load. The movement of each type of sediment is contingent on highly variable hydrometric parameters such as stream power, stream velocity, and shear stress (Yalin and da Silva, 2001). Composed of particles which exceed 2 mm in diameter, bedload constitutes the largest particles in suspension to be carried by ensuing flow. During peak flows, bedload particles are carried in suspension for only short distances, owing to the high energies needed to sustain their movement.

Suspended load consists of particles smaller than 2 mm, made up mainly of clays, silts, and sands. Suspended sediment loads are carried in higher proportion than any other type of load because the fine sediments carried have low entrainment thresholds (Reid and Frostick, 1994), and the relationships between suspended sediment concentrations (SSC) and discharge have been reported extensively in the literature. Clifford et al. (1995) suggests that the controls governing sediment transport are of considerable geomorphological importance to an understanding of the discontinuous nature of sediment entrainment and transport. (The data presented in this thesis will focus on suspended sediment only).

Finally, dissolved loads are those materials transported in solution, which, unlike bedload and suspended load, do not affect channel morphology (Reid and Frostick, 1994).

2.6.1 Modes of Sediment Transport

Particles in water can move in one of four ways: sliding, rolling, saltation, and suspension. Sliding particles remain in constant contact with the bed and experience no consistent rotation. Rolling particles are also in constant contact with the bed, but move about a flow-transverse axis. Particles which are saltating appear to be ‘jumping’ along the bed, moving some short distance before returning to the bed. These three types of moving particles collectively form bedload, and have shear velocities very close to the critical thresholds. Suspended load, which can occur simultaneously with bedload movement, carries particles downstream with no contact with the bed (Reid & Frostick 1994).

2.7 Sources of Sediment

Sediment availability changes through the hydrological season in the Arctic, as the alluvial pathways are impacted by snow and cold temperatures during the early season, low discharge (and therefore low carrying capacity) in the late season, and permafrost disturbances and rainfall events, both of which are highly variable year to year (Nistor and Church, 2005).

Access, erosion, and transport of fluvial sediment are dependent upon many factors, the most significant of which are the size of the drainage basin, and the relief within it. Other factors include but are not limited to, climate, precipitation, runoff, snow cover, ice cover, and the presence of lakes (Gordeev, 2006). The material entrained in the channel and moved by the flow of the spring melt may have potential impacts on the timing and magnitude of sediment release to the downstream aquatic and marine ecosystems (Gordeev, 2006; McKnight et al., 2008; Lyons & Finlay, 2008).

Suspended sediment material can come from three main sources: (i) the sediment deposited on top of the snow during initial flow and utilized by the stream well after the spring freshet or subsequently stored in the channel; (ii) materials on the bed armored by coarser material; and (iii) sediment mobilized by late season rainfall events or as a result of permafrost terrain disturbances.

2.7.1 In-Channel Sources of Sediment

Initially, channel snowpack makes discontinuous contact with the bed as the channel re-establishes itself through progressive thermal erosion of the snowpack by flow (Clifford et al., 1995; McDonald & Lamoureux, 2009). As channelized flow begins to establish, and meltwater begins to erode the channel snowpack, sediment is released as previously isolated and/or armoured bed materials are mobilized as “pulses”. Clifford et al. (1995) suggest this may serve to explain the control(s) upon the behavior of sediment entrainment, erosion, and transport. Eventually, when channel connectivity is established, sediment deposited on the snow, (which can be accessed by the channelized flow) can be mobilized in the channel. The period of complete channel connectivity often coincides with the peak discharges of sediment for the nival melt. However, not all in-channel sources of sediment are mobilized during the nival melt. Snowpacks along channel walls or which are no longer in contact with the flow will slowly re-enter the system as the snowpack melts.

2.7.2 Catchment Sources of Sediment

Despite the preponderance of windswept snow accumulation in fluvial channels, the catchment can maintain a shallow snow covering, which then effectively buffers the catchment soil and prevents it from entering the fluvial system during the nival melt. In areas underlain by permafrost, shallow active layers begin to develop early on in the melt season, restricting the downward percolation of water to a zone only a few centimeters thick. As the snow melts, the ability of water to infiltrate the soil becomes overwhelmed, thereby creating saturation overland flow. This flow runs off the surface of the catchment, carrying with it sediment particles which it has entrained, and then delivers it to a downstream location, and possibly to a river channel. During the nival melt, it is generally agreed that the overwhelming majority of suspended sediment mobilized is from within the channel itself, and that catchment contribution to the sediment flux is minimal.

2.7.2.1 Permafrost Slope Disturbances

Of growing concern in the Arctic is the effect warming temperatures are having on the stability of the permafrost and the stability of their overlying landscapes. Disturbances such as active layer detachments (ALDs) and retrogressive thaw slumps (RTS) have been documented throughout the Canadian Arctic, and research suggests that future warming will further enhance the melting of ice-rich permafrost and increase the frequency of these disturbances (Lewkowicz & Harris, 2005; Lantuit & Pollard, 2008). These disturbances have been known to deliver substantial amounts of sediments to the fluvial systems which lie in proximity. For example, Bowden et al. (2008) noted that over a period of 2 to 3 years, an RTS in the Toolik Lake region of Alaska delivered 18 times more sediment than would have normally been delivered to the watershed. Lamoureux and Lafrenière (2009) observed widespread active layer detachments upstream of the main river channel after exceptional summer warmth and late season rainfall in 2007. These disturbances dammed the river, increased suspended sediment transport within the channel, and ultimately contributed 89% of the seasonal sediment load (Lewis et al., 2012).

2.7.2.2 Summer Rainfall

It has long been recognized that summer rainfall events in the Arctic have the potential to liberate substantial amounts of sediment otherwise protected by snow during the nival melt, and then deliver it to downstream marine and aquatic ecosystems (Forbes & Lamoureux, 2007; McKnight et al., 2008; Lyons & Finlay, 2008). Even in the absence of permafrost disturbances (such as was reported by Lamoureux & Lafrenière in 2009) rainfall has been seen to exert considerable influence on seasonal sediment fluxes (Woo and McCann, 1994). Cook (1967) reported rainfall had an extensive effect on late season sediment transport in the Mecham River, Resolute Bay, Nunavut. Lamoureux (2000) noted that substantial sediment loads derived from rainfall events are present in sedimentary lake records. Beel et al. (2011) recognized sediment transport dynamics similar to Cook, in the Southern Alps of New Zealand.

During the summer months, after catchment snow cover has melted or sublimated, and in the presence of a thick active layer, rainfall impacting the catchment will encounter the soil directly, and either infiltrate the soil matrix, or otherwise flow off the land as saturated overland flow. The amount of water able to infiltrate the soil matrix is a function of the hydraulic capacity of any given soil, and is dependent on the pore size and connection between pores. Soil water content at saturation is the amount of infiltrated water a soil matrix can store without becoming saturated and is a function of the soil moisture content of the soil. When the soil moisture content is overwhelmed by precipitation input and soil water holding capacity has been reached, any further precipitation will flow off the land as saturation overland flow. When such overland flow occurs, particles dislodged by the interaction between rainfall and bare soil are carried by the ensuing flow, and may then enter a fluvial channel to be carried downstream (Davie, 2008).

There is no straightforward explanation of sediment delivery based solely upon summer rainfall events. It has been suggested that rainfall first must exceed some catchment water storage threshold before suspended sediment impacts can be realized (Cook, 1967; Dugan et al., 2009). Furthermore, research suggests that the sediment delivery responses during these hydrologic events are due to antecedent soil moisture conditions in the catchment prior to rainfall inputs (Dugan et al., 2009; Beel et al. 2011).

2.7.3 Suspended Sediment-Discharge Hysteresis

Early in the melt season in northern environments, the downstream delivery of suspended sediment and water is impeded by channel snow and ice, and frozen bed and bank conditions, which hinder sediment erosion. As the season progresses and accessible material increases, accessibility, rather than river competence, determines the amount of transported material. The change in source area throughout the season complicates empirical relationships between suspended sediment and discharge.

The roles of sediment supply and transport mechanisms within runoff events can be considered through suspended sediment-discharge hysteresis plots (herein referred to as hysteresis), which highlight the relationship between these two variables at short and longer (event) timescales (Nistor and Church, 2005). The shape, magnitude, and direction of hysteresis curves are used to describe how discharge and suspended sediment transport are spatially and temporally interacting. In river systems, these complex relationships help to explain where sediment is being sourced and when it is being transported relative to stream power. The most common hysteresis relationship observed in fluvial settings is the clockwise hysteresis curve, which is indicative of sediment depletion during the runoff event. Counter (anti)-clockwise and complex loops are less common in natural settings and indicate a delay in sediment entrainment or sediment supply replenishment during the runoff event (Klein, 1984; Nistor and Church, 2005; McDonald and Lamoureux, 2009) (Figure 2.8).

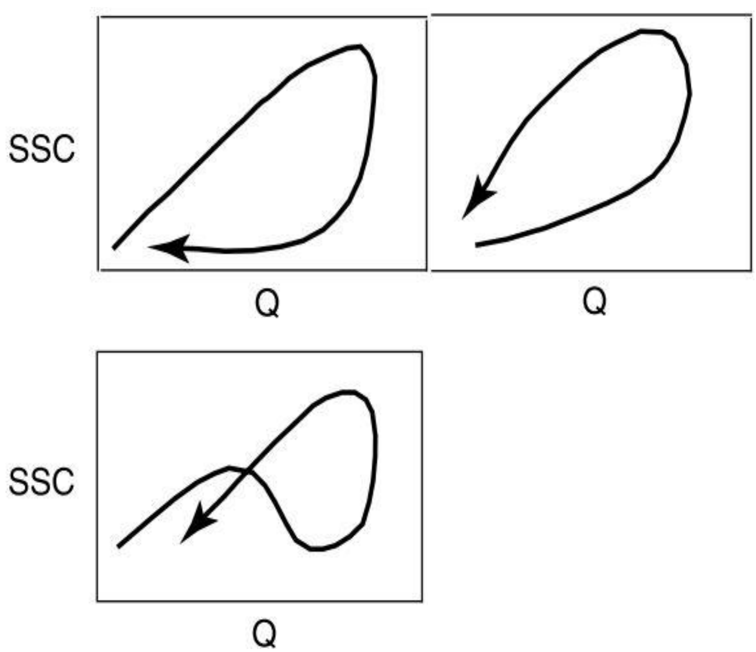


Figure 2.8 Examples of the most common types of suspended sediment (SSC) – discharge (Q) hysteresis curves found in nature. Panel A shows clockwise hysteresis; Panel B shows counter (anti)- clockwise hysteresis; Panel C shows complex/figure eight hysteresis (Adapted from Nistor & Church, 2005).

The shape of hysteresis curves can be broadly interpreted in terms of sediment supply and source area. Klein (1984) suggest clockwise curves indicates transportable material is sourced from the bed and banks of the channel or from areas adjacent to the channel, while counter-clockwise and complex reflects transport of material sourced from upstream areas or further from the channel. Alternative interpretations can be drawn from hysteresis data, and Nistor and Church (2005) provide a comprehensive list of hysteretic relationships noted in the literature, along with other possible mechanisms of sediment and discharge for each type of curve.

While temperate studies have utilized hysteresis relationships to explain sediment transport dynamics (e.g. Klein, 1984; Brasington and Richards, 2000; Seeger et al., 2004; Lawler et al., 2006), comparatively few published Arctic studies have used this approach. In one Arctic study to examine hysteretic relationships, McDonald and Lamoureux (2009) suggest that, in years with extensive channel snowpack and larger catchment snow water equivalence (SWE), sediment becomes increasingly available following peak discharge, resulting in counter-clockwise hysteresis during the nival melt event. Conversely, in years with comparatively smaller SWE and less extensive channel snowpack, clockwise hysteresis was observed as there was less of a barrier to accessible sediment sources, resulting in sediment exhaustion early during the nival melt.

Suspended sediment-discharge hysteresis curves in fluvial environments are a useful approach to evaluate fluvial dynamics and changes as they highlight the evolving temporal relationship between SSC and discharge. In particular, hysteresis analysis at diurnal, event, seasonal, and interannual timescales can aid in providing a more complete understanding of the complex and evolving patterns of sediment sources and mobilization dynamics in a catchment.

2.8 Deposition

Sediment in suspension will be deposited on the channel bed when the shear velocity is no longer sufficient to transport the material. As the shear velocity decreases, the largest of the bedload particles begin to settle out, followed by increasingly smaller suspended load particles. When particles fall out of suspension, they impact the bed forms already present in the channel, and influence the deposition of further bed forms in the river (Reid & Frostick, 1994).

2.9 Landscape Connectivity

The nature of sediment transport and geomorphic responses to fluvial events is contingent upon both catchment configuration and connectivity (Fryirs et al., 2007). In an idealized setting, a catchment sediment budget would accurately calculate the inputs from the headwaters of the fluvial channel and represent those inputs at the outlet of that channel. However, the downstream migration of water and sediment rarely follows such an uninhibited route, since fluvial disconnectivity disrupts lateral and longitudinal linkages within catchments (Walling, 1983; Fryirs et al., 2007). Only a fraction of the eroded material in a catchment will be delivered to the downstream outlet and be represented in a sediment yield, as the vast majority of eroded material is deposited or stored within the catchment. Walling (1983) identified this as the 'sediment delivery problem'. This problem is exacerbated by the spatial and temporal variability of landscape barriers which disrupt slope-channel, channel-floodplain, and vertical linkages of sediment and water (Fryirs et al., 2007).

Connectivity conditions also influence how a system responds to disturbance, and are central to understating how a geomorphic system responds to major environmental perturbations, for example, glacial retreat.

2.9.1 Landscape (De-) Coupling

Landscape coupling is the degree to which a landscape is connected and therefore sensitive to change (Harvey 2002). The degree to which a landscape is coupled determines how well or how poorly the system responds to disturbances and/or environmental change, whether climatically-induced, human-induced, or otherwise. Such coupling operates in both downstream and upstream directions. However, it is the efficacy of downstream coupling which is concerned with the transmission of water and sediment from the headwaters to the outlet for fluvial systems, and from hillslopes to fluvial systems in a broader catchment context (Harvey, 2002).

Buffers, barriers, and blankets are three types of fluvial formations which contribute to landscape decoupling and inhibit the efficiency of sediment transfer relationships (Fryirs et al., 2007). External to the channel network, buffers are considered sinks which disrupt lateral and longitudinal linkages within a catchment. They can block sections of the main channel, effectively disconnecting the supply of material downstream in the channel network. And they can have residence times ranging from hundreds to thousands of years. Barriers such as bedrock steps and valley constrictions disrupt longitudinal linkages through their impact on the bed profile of a channel. More common types of barriers to sediment movement are sediment slugs (Table 2.2). These act as plugs, and may have a minor or major impact upon fluvial systems and residence times, depending on their size, may vary (Nicholas et al., 1995; Fryirs et al., 2007).

Table 2.2 Classification of sediment slugs (Nicholas et al., 1995).

Slug Scale	Dominant Controls	Impact of fluvial system
Macroslug	Fluvial process-form interactions	Minor channel change
Megaslug	Local sediment supply and valley-floor configuration	Major channel change
Superslug	Basin-scale sediment supply	Major valley-floor adjustment

Blankets are the final type of landscape-disconnected features which can disrupt downstream coupling of a fluvial system. These features are most commonly found as bed armour, and serve to disrupt vertical linkages as they effect the entrainment of sediment. In northern settings, early season snow and ice in channels act as effective blankets, buffering the channel bed from extensive scouring and entrainment. As the melt season progresses, blankets of large materials, most often moved in suspension as bedload, armour smaller materials to the channel floor, thus disrupting the downward movement of sediment, and creating sink areas.

2.9.2 Snow and Channel Connectivity in the Early Season

In Arctic environments, the buffering effect of snow and the presence of permafrost exerts substantial control on early season sediment delivery to downstream outlets (Woo and McCann, 1994). Initially, in-channel snowpacks are unevenly melted, as a function of absorbed incoming solar radiation and snowpack depth. This inconsistent melting leads to major segments, or reaches, of the channel being hydrologically detached. As snowpacks continue to thermally erode, channel connectivity is re-established, facilitating a more direct means of downstream mobilization of sediment with accompanying flow.

2.9.3 The Sediment Delivery Problem

One of the most fundamental constraints in the study of sediment movement though a system is the challenge of linking on-site rates of erosion and soil loss within a specific drainage basin to that of the total sediment yield at the outlet of the basin. Walling (1983) recognized this as the ‘sediment delivery problem’.

Suspended sediment sources vary temporally and spatially within a system in response to the complex interactions between factors governing sediment mobilization and delivery (Collins & Walling, 2004). These factors, along with the dominant hydrological regime of an area, dictate when and where sediment is mobilized in a system, when peak and nominal discharge is reached, and when and how sediment is entrained. Deposition and temporary or permanent storage can occur at many locations within a drainage basin, including the slope, on the floodplain, or in the channel itself (Walling, 1983).

The sediment delivery ratio (SDR) is used to quantify the decoupling of upstream erosion to downstream sediment yield at the basin outlet (Nicholas et al., 1995), by describing the ratio of sediment delivered to the downstream outlet (t km^{-2} $yr.^{-1}$) to net erosion within the basin (t km^{-2} $yr.^{-1}$) (Walling, 1983). It is influenced by geomorphologic and environmental factors such as drainage pattern and channel conditions, the nature, extent, and location of sediment sources, soil type and texture, as well as relief and slope characteristics. Typically, northern environments have very low SDRs (Veillette, 2011), and many Arctic researchers have noted that an Arctic sediment yield is considerably less than that of more temperate sediment yields, with some research suggesting that only 1% of the global sediment flux originates from Arctic rivers (Syvtski 2002; Gordeev, 2006). Syvtski (2002) has identified five principal causes for low Arctic sediment delivery ratios:

1. The annual rate of freeze-thaw transitions decrease toward the polar region;
2. The soil surface is frozen for most months of the year, thereby limiting the erodibility of the terrain;
3. With annual precipitation falling mostly as snow, the potential for gullies to form, as in temperate climates with precipitation falling as a combination of rain and snow, decreases;
4. Large rainfall events are rare in the Arctic due to high-pressure cyclonic systems (Forbes and Lamoureux, 2007), which are not akin to the high-intensity convective rainfall that falls in temperate climates; and
5. Snow-or ice-melt flood waves are dampened relative to rainfall-induced flood waves.

As Arctic rivers are active for such a short period, inter- seasonal and intra- seasonal sediment storage is more likely to affect northern rivers than their more temperate counterparts.

2.10 Conclusion

Over recent decades, researchers have learned to understand and view northern environments as climatically sensitive regions, and studies carried out in these regions have led to a better appreciation of hydrologic systems. These systems are intrinsically linked to the host terrestrial systems, and changes in one will invariably have demonstrable repercussions on the other.

The short melt season makes the High Arctic an ideal location in which to study the interaction among temperature, snowmelt, landscape connectivity, and sediment transport. Geomorphic changes due to warmer temperatures, such as the establishment of new hydrologic pathways and the advancement of the melt season, affect the regions' sediment transport. While Arctic rivers may account for only a small portion of the global sediment flux, they are critical to downstream marine and aquatic ecosystems, which rely on the influx of nutrients to sustain their food webs. The timing and magnitude of sediment discharge is a function of the timing of the spring melt, the connectivity of the landscape, and the influence of rainfall events which release sediment long after the spring freshet. Should these dynamics be altered, downstream ecosystems may become vulnerable. It is therefore vitally important that the scientific community now be provided all necessary support to undertake impact studies in small Arctic watersheds, in order to better understand the current dynamics and to more accurately project likely impacts under future warming scenarios.

Chapter 3

Downstream Patterns of Suspended Sediment Transport in a High Arctic River

3.1 Abstract

Spatial and temporally variable suspended sediment transport from upstream sources was investigated in the West River (unofficial name) at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, Nunavut (74°5'' N, 109°35' W), a river with nearly a decade of hydrological and sediment transport research in the Canadian Arctic. During the 2012 season, a survey was undertaken during the nival period to identify areas of the river where the flow was isolated from the channel bed by snow and where it progressively reached the bed. During the nival period, and throughout the rest of the season, suspended sediment transport data were collected from a primary outlet station and six upstream locations to identify the sources and sinks of sediment in the various reaches of the West River. An inferred sediment budget approach was used to identify the storage and release dynamics in each reach. Both nival event-scale hysteresis and seasonal diurnal hysteresis patterns for 2012 were primarily counter-clockwise, suggesting sources of sediment were not readily available for transport during peak flows, but became available as discharge waned. Analysis of diurnal hysteresis relationships for the years 2004-2012 (excluding 2011) signal a shift in daily sediment-discharge hysteresis from primarily clockwise to counter-clockwise following an episode of permafrost disturbance and enhanced erosion in 2007. Results provide insights into the fluvial and geomorphological response to changes in sediment availability in Arctic rivers, and how these changes in turn affect sediment transport in these environments.

3.2 Introduction

Projected climate change is expected to have substantial impacts for Arctic systems, especially with regard to altering the stability of the landscape and hydrological regime. These changes will have implications for suspended sediment transport in Arctic rivers, which in turn has potential impacts on downstream aquatic and coastal marine ecosystems as sediment acts as a substrate for both nutrients and contaminants alike (Lyons & Finlay, 2008; McKnight et al., 2008). Central to the question of downstream sediment transport is the concept of hydrologic and sedimentological connectivity, which refers to the passage of water and the physical transfer of sediment through a drainage basin, respectively (Bracken and Croke, 2007). Walling (1983) notes in his classic review of the literature, that in many cases a very small fraction of sediment which enters a drainage basin reaches the outlet. Indeed, several studies noted in his paper calculated substantially less than half of the sediment entering a system is transported downstream. This disconnectivity exists because the nature and distribution of sediment sources and sinks both temporally and spatially that reflect the influence of a number of mitigating factors to sediment transport, such as catchment connectivity, the volume and type of material stored, the distance of these materials from the channel and the geomorphic response to disturbance events (Fryirs et al., 2007). In the Arctic, the dominant influence of snow represents a further factor, particularly as in-channel snow buffers and limits the downstream transport of sediment during the early nival melt, the most energetic time of the short hydrological season (Woo and Sauriol, 1980; McDonald and Lamoureux, 2009; Woo, 2012).

Despite the importance of quantifying and qualifying suspended sediment transport within Arctic catchments, little work has systematically evaluated the storage and release patterns of Arctic rivers. While data collection can be logistically challenging and costly in northern environments, it is necessary to assess the state of sediment mobilization, as research suggests these dynamics could undergo serious changes in future years (ACIA, 2005; IPCC, 2007, AMAP, 2012). The objectives of this research are threefold: (1) to map the discontinuous nature of bed contact by flow due to channel snowpack during the nival freshet; (2) to quantitatively assess net sources and net sinks of material within the West River by utilizing a sediment budget approach; and (3) to assess the patterns of suspended sediment mobilization within the river using hysteresis patterns. Further, an analysis of long term hysteretic characteristics also serves to highlight the impact of landscape disturbance on sediment transport in a small Arctic river catchment.

3.3 Study Site

Research was carried out at the Cape Bounty Arctic Watershed Observatory (CBAWO), located on the south-central coast of Melville Island, Nunavut, in the Canadian High Arctic (74°55' N, 109°35' W) (Figure 3.1). CBAWO was established in 2003 to undertake integrated watershed research in the paired East and West watersheds (unofficially named). Due to limited sediment data collection in 2003 and 2011, only data from 2004-2010 and 2012 were analyzed as part of this study.

The focus of this study is the West River, a second order, 3.1 km-long river with an 8.0 km^2 watershed. The landscape is composed of rolling hills and limited relief, and is underlain by thick continuous permafrost (Lewis et al., 2012) and forms a seasonal thawed active layer that can reach 0.7-0.9 m by late July (Rudy et al., 2013).

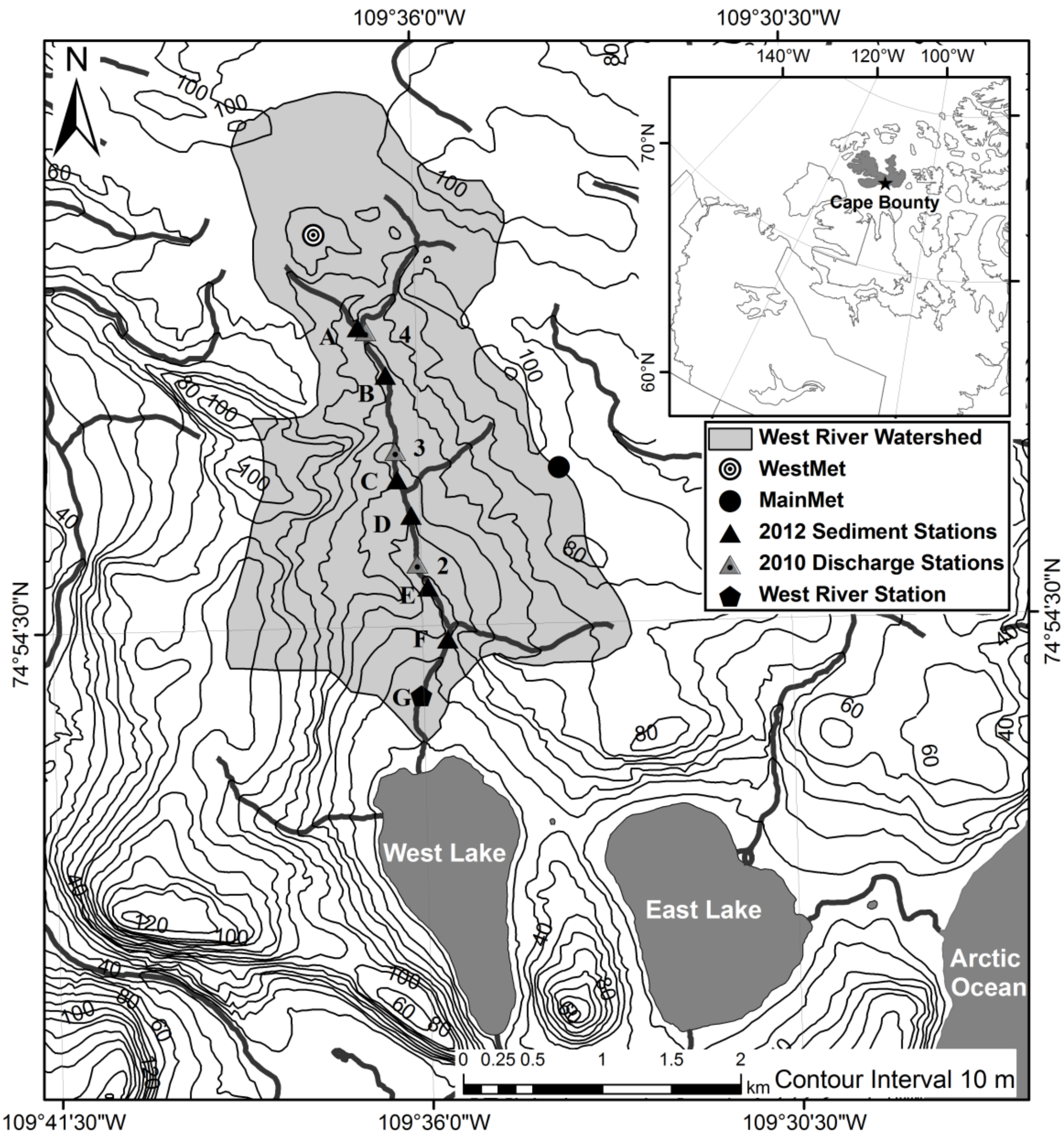


Figure 3.1 Cape Bounty Arctic Watershed Observatory (CBAWO) study site with West Catchment, meteorological stations, 2012 sediment sampling locations (A-G) and 2010 Discharge Stations (4-2). Inset map is location of CBAWO in the Canadian High Arctic.

Cape Bounty is a polar desert, experiencing long cold winters (September to late May) and short melt seasons (June to August). The mean annual temperature at the nearest long-term weather station, Mould Bay, NWT (200 km to the west) is -17.5°C, while monthly mean temperatures above freezing are recorded for May, June, July, and August. Precipitation primarily occurs as snow, which is subject to extensive redistribution in the catchment by wind and preferentially deposited in leeward slopes, low-lying areas, and within gullies and river channels. Initial flow in the West River typically begins in early to mid-June, with peak discharge occurring only a few days later (McDonald and Lamoureux, 2009; Lewis and Lamoureux, 2010). Discharge gradually recedes by early July and remains at baseflow until freeze up in late August or early September, in the absence of short-lived recharge due to infrequent rainfall events (Dugan et al., 2009; Chapter 4).

MacDonald and Lamoureux (2009) noted the presence of unconsolidated surficial sediment and sedimentary bedrock as the primary source of readily transportable suspended sediment. Transportable sediment is readily available from multiple sources within the catchment including upper channel reaches, channel banks and bed, and tributaries (MacDonald and Lamoureux, 2009; Lewis and Lamoureux, 2010). However, Veillette et al. (submitted) demonstrates through the use of catchment-wide sediment budgets that the majority of sediment in the West River is sourced in the channel system, particularly in the upper western reach. A lag between peak sediment discharge and peak flow is common as snow mitigates the movement of both materials (Woo and Sauriol, 1980) and can intercept sediment as it is being carried by the flow (McDonald and Lamoureux, 2009).

3.4 Methods

3.4.1 Meteorology

A meteorological station, MainMet, was established at the CBAWO in 2003 and lies on the boundary of the West and East catchments at approximately 80 m a.s.l. (Figure 3.1). Air temperatures reported in this study for the 2012 season were recorded with an Onset Temperature/RH smart sensor (± 0.21°C temperature, ±2.5% relative humidity) recorded hourly with an Onset U30 logger. Precipitation was measured using an Onset tipping bucket gauge (0.2 mm tip). Meteorological data from previous years used in this study is presented in MacDonald and Lamoureux (2009) and Lewis et al. (2012).

3.4.2 Channel Snow-Bed Contact Survey

In northern environments, snow is subject to extensive redistribution by wind, and as such preferentially accumulates in channels and streams (Woo, 2012). Snow in the channel acts as a systematic and potentially important barrier to sediment entrainment and erosion during early season flow when typically a substantial proportion of sediment transport occurs (Macdonald and Lamoureux, 2009). Progressive thermal erosion of the snowpack as the nival season progresses allows for flow to discontinuously access the bed and bed materials (Clifford et al., 1995). In order to assess the discontinuous and rapid nature of bed contact due to thick channel snow, a snow-bed contact survey was undertaken along the reach of the main channel of the West River twice daily between June 9th and 14th until the channel had made full contact with the bed. A handheld Garmin GPS unit was used to map locations (±3 m) where flow had become subnivean and assumed to have reached the bed.

3.4.3 Hydrology

Hydrology data were collected at the West River gauging station (WRGS) (Figure 3.1) throughout June and July. During the nival period West River sensors recorded at 15 second intervals (June 7th-June 20th). Owing to excessive power consumption and subsequent failure of some additional sensors towards the end of this period, logging was reduced to one minute intervals for the remainder of the season (June 20th-July 26th). Stage was recorded with a Unidata capacitive water depth probe logged with an Onset H22 Flexsmart logger. Discharge was calculated from point-velocity area measurements collected in 2010 at the WRGS (Veillette, 2011). Using a Swoffer 2100 current velocity meter (1% accuracy), cross-sectional velocity measurements were measured in the thalwag every 30 minutes over a 24 hour period during the highest discharge of the season (June 17-18) and again over a six hour period during low flow conditions (June 25). Discahrge (Q) was calculated by applying the velocity-area method equation:

$$Q = \Sigma \left(\Delta x * \left(\frac{h1+h2}{2} \right) * \left(\frac{v1+v2}{2} \right) \right) \tag{3.1}$$

where Δx is the interval (in m) between two consecutive measuring points, h is water depth (m), and v is the flow velocity (m/s). A polynomial rating curve (r^2=0.99):

$$Q = 26.836h^2 - 3.237h + 0.1157 \tag{3.2}$$

was derived (Veillette, 2011) and applied to stage measurements collected at the WRGS. For periods of extremely low flow, the rating curve overestimated discharge from stage measurements less than or equal to 0.06 m and a linear extrapolation was used for all stage measurements less than 0.06 m (34% of the record duration).

3.4.3.1 Estimated Relative Discharge

A sediment budget approach was undertaken in 2012 in order to calculate sediment yields of six river segments, or reaches, along the length of the West River and to identify sources and sinks of sediment. Discharge, however, was only recorded at the West River gauging station (WRGS) in 2012. Previous experience in 2010 indicated that placement of additional gauging stations in 2012 was not possible or reliable during the rapidly changing early snow melt period (Veillette, 2011).

In this study, suspended sediment samples were obtained from six fixed upstream locations (Figure 3.1) the discharge was estimated at each location based on relative discharge proportion determined from multiple gauging station data obtained in 2010 (Figure 3.1; Appendix B).

Daily instantaneous point discharge data measured at the approximate time of peak flow (1700-1800h) from 2010 for the three upstream gauging stations was compared to the hourly discharge record at WRGS (data from Veillette, 2011) to determine the proportion of WRGS discharge for each upstream station. These proportions were averaged and a polynomial curve was fit with longitudinal channel distance as the x-axis. The polynomial equation was then applied to the locations of the 2012 sediment sampling stations to estimate percentages of WRGS discharge at each location (Figure 3.2). This approach assumes that the magnitude of the relative longitudinal discharge in the West River does not vary significantly year to year or during the season, and therefore can be used to determine reach sediment yields based on discharge obtained from the single downstream gauging station.

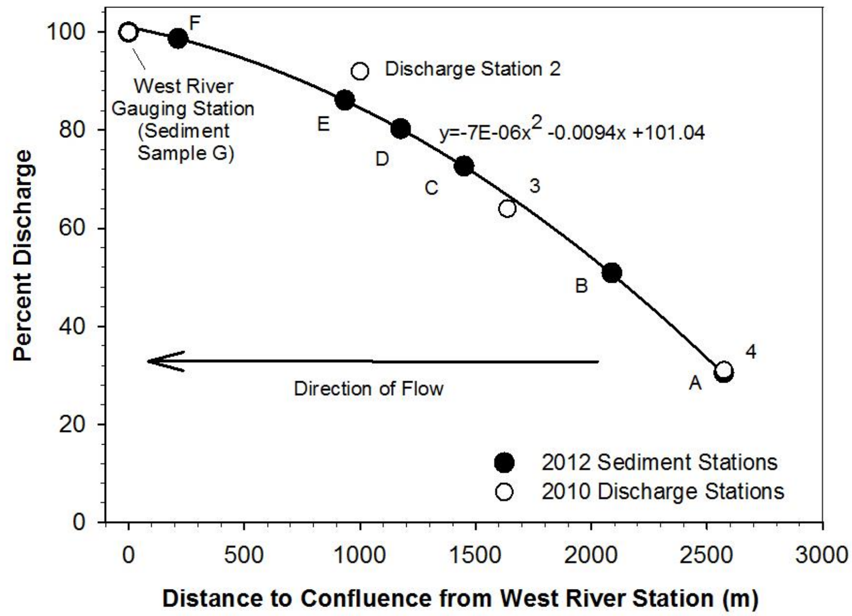


Figure 3.2 Polynomial curve fitted to 2010 discharge data to determine 2012 discharge at synoptic sampling locations.

3.4.4 Suspended Sediment Sampling

A sediment budget approach was undertaken for the West River in 2012 by manually collecting water samples from six fixed locations along the length of the channel (Appendix B). Additionally, suspended sediment samples were collected at 3 hour intervals with an ISCO 3700C pump sampler at the WRGS. Manual samples were also taken at the gauging station twice daily (for redundancy in case of pump sampler failure) at the approximate low and high daily flow (approximately 1000 and 1600h, respectively) during the nival period and following precipitation events, and once daily at approximate peak flow thereafter until the end of the season.

All samples were vacuum filtered volumetrically through pre-weighed 1 µm glass fiber filters, subsequently freeze-dried and weighed to determine suspended sediment concentration (SSC). An hourly seasonal SSC record for the West River was generated using a robust cubic spline to infill hourly point samples from 3-hour data. Seasonal sediment yield for the West River was calculated by the summation of hourly sediment yield, which was determined by multiplying mean hourly discharge and SSC.

Upstream SSC samples were processed with the same methods and used in conjunction with estimated relative discharge to estimate daily sediment flux at each sample location (see previous section). Sediment fluxes were calculated by multiplying SSC and the estimated relative discharges for the six sampling locations along the reach of the river (Figure 3.2). Given the uncertainties in this approach, all fluxes are considered to be inferred rather than precise estimates. Individual fluxes were used in the calculation of net results for each reach, however, reach net fluxes less than $\pm 2 kg \cdot day^{-1}$ were assumed to be not significantly different from zero. Similarly, a minimum SSC concentration of $0.01\ mg \cdot L^{-1}$ was applied to prevent division errors in calculations (in 11 instances).

3.4.5 Suspended Sediment-Discharge Hysteresis

Suspended sediment-discharge hysteresis was used to determine the direction and magnitude of diurnal, event, and seasonal hysteretic patterns and follows previous work on the West River (Macdonald and Lamoureux, 2009; Veillette et al., submitted). Lawler et al. (2006) developed a hysteresis index ($HI_{mid,}$ reported as HI in following sections) in order to quantify the hysteretic relationship between the dynamic responses of sediment mobilization to flow changes in discharge events. By measuring the width of the hysteresis loop at the discharge midpoint of the event, Q_{mid}, the index is used to quantify the magnitude and direction of the concentration-discharge relationship. Q_{mid} is determined by:

$$Q_{mid} = k\,(Q_{max} - Q_{min}) + Q_{min} \tag{3.1}$$

where Q_{max} and Q_{min} are the maximum and minimum discharge values reached during an event and k is the position at which the loop breadth is assessed relative to the flow range. The center of the hysteresis loop is defined by either k=0.5 and k=0.75, depending upon which value more closely represents the center of the hysteresis loop due to the inherent irregularities of the data. Once located on the hysteresis plots, Q_{mid} values are used to extract SSC on the rising limbs and falling limbs (SSC_{RL} and SSC_{FL}, respectively) for the loop. HI_{mid} for clockwise hysteresis is calculated by:

$$HI_{mid} = (SSC_{RL} / SSC_{FL}) - 1 \tag{3.2}$$

while HI_{mid} for counter-clockwise hysteresis is calculated by:

$$HI_{mid} = (-1/ (SSC_{RL} / SSC_{FL})) + 1 \tag{3.3}$$

Hence, positive (negative) HI values indicate clockwise (counterclockwise) hysteresis, and values range from zero (no hysteresis) to larger HI values (±) for increasing hysteresis for the period of investigation (Lawler et al., 2006). HI values were determined for daily periods, using the 1000-1000h hydrological day coinciding with the daily minimum flow and used by previous workers at this location (Macdonald and Lamoureux, 2009).

3.5 Results

3.5.1 Meteorology

The 2012 season was typified by relatively warm and dry conditions. The earliest occurrence of first day of flow in the West River (June 6th) since 2003 was recorded in 2012, and represents nearly a one week advancement of flow from 2010 and three weeks from 2003 (See Table 3.1 in section 3.6.3). The catchment received 68% of the seasonal total of precipitation during two rainfall events in July (July 9 and 24) with the remaining rainfall occurring as low magnitude events during the rest of the season (Figure 3.3). As a result, the catchment experienced dry conditions for the majority of the field season, particularly late June to early July.

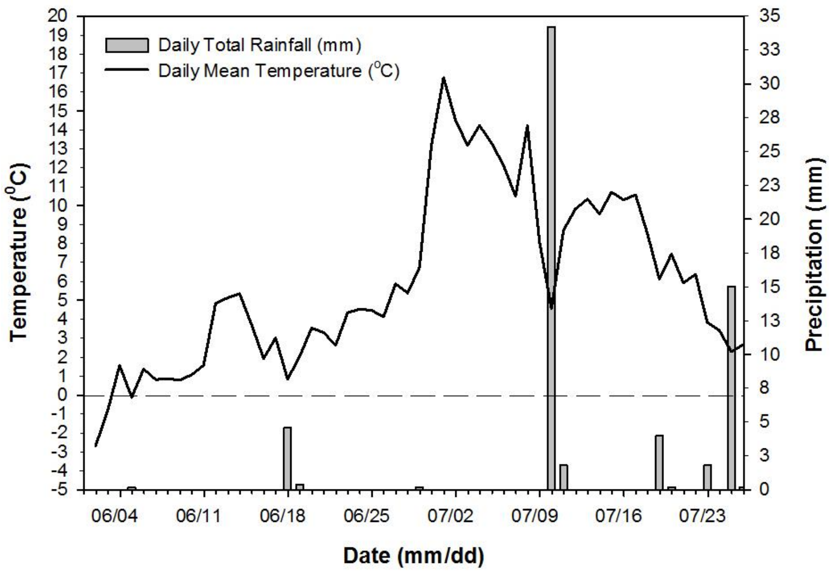


Figure 3.3 Daily mean temperature and daily total rainfall for the West Watershed in 2012, recorded at MainMet.

3.5.2 Seasonal Discharge and Suspended Sediment Characteristics

The 2012 season was typical of an Arctic nival regime, with strong control over discharge being exerted by the presence of in-channel snow (Figure 3.4). The nival melt began on June 3rd, with flow beginning on June 6th. Peak discharge of 1.8 m^3/s occurred on June 8th (Figure 3.4a) but it is most likely due to the rapid release of ponded water just upstream of the gauging station. Subsequent open-flow peak discharge of 1.4 m^3/s was reached on June 12th (Figure 3.4b). During the nival and recession periods (June 3-20), 98% of suspended sediment yield occurred. Recession and baseflow conditions rapidly followed the nival melt, and were only minimally interrupted during two major rainfall events (July 9th and July 23rd), which mobilized the remaining 2% of suspended sediment. Both events resulted in especially low discharge responses and minimal sediment transport (see Chapter 4). Total seasonal runoff for the West River was 75.1mm.

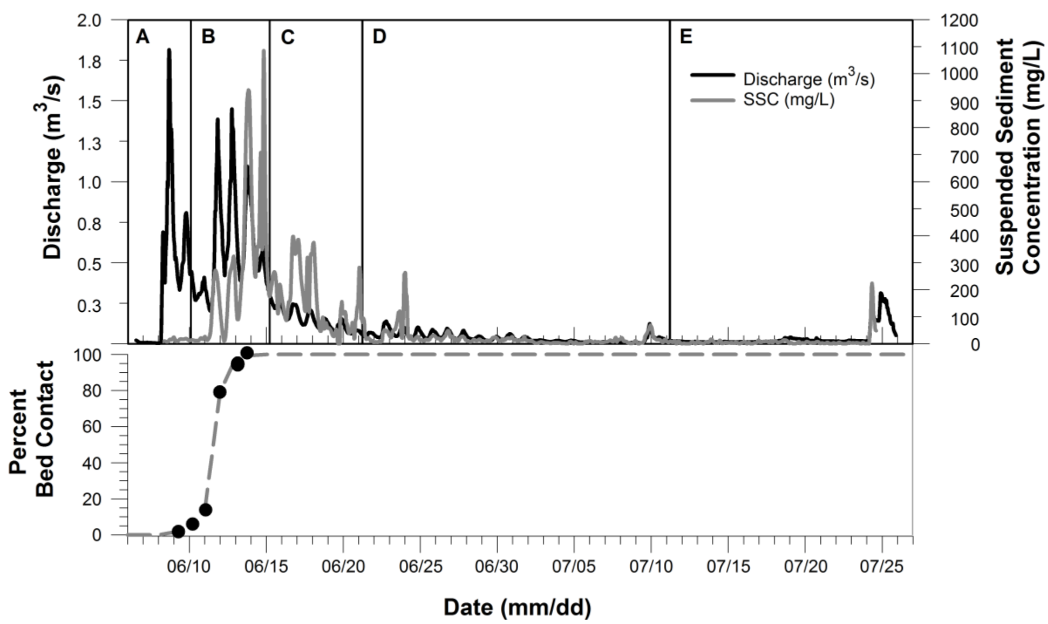


Figure 3.4 West River hydrograph and period delineations: A) Pre-melt; B) nival melt; C) recession flow; D) baseflow; E) baseflow following rainfall, as well as percent bed contact for the 2012 hydrological season.

Suspended delivery during the initial flow and nival melt periods were asynchronous with discharge. Maximum SSC (1085 mg·L^{-1}) occurred on June 14th, following the establishment of hydrological connectivity at the narrowing of the West River, immediately upstream of the West River gauging station (Figure 3.4 and 3.5). After this time, sediment transport became relatively synchronous with discharge during periods of recession and baseflow due to complete channel connectivity and the limited influence of in-channel snow. Compared to previous years (2003-10), 2012 was characterized by low flow and minimal suspended sediment transport.

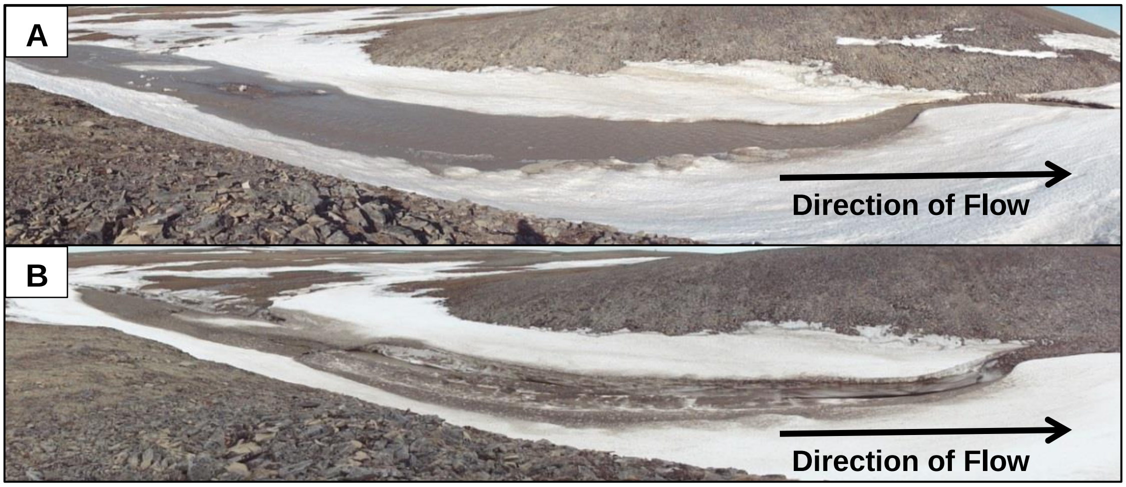
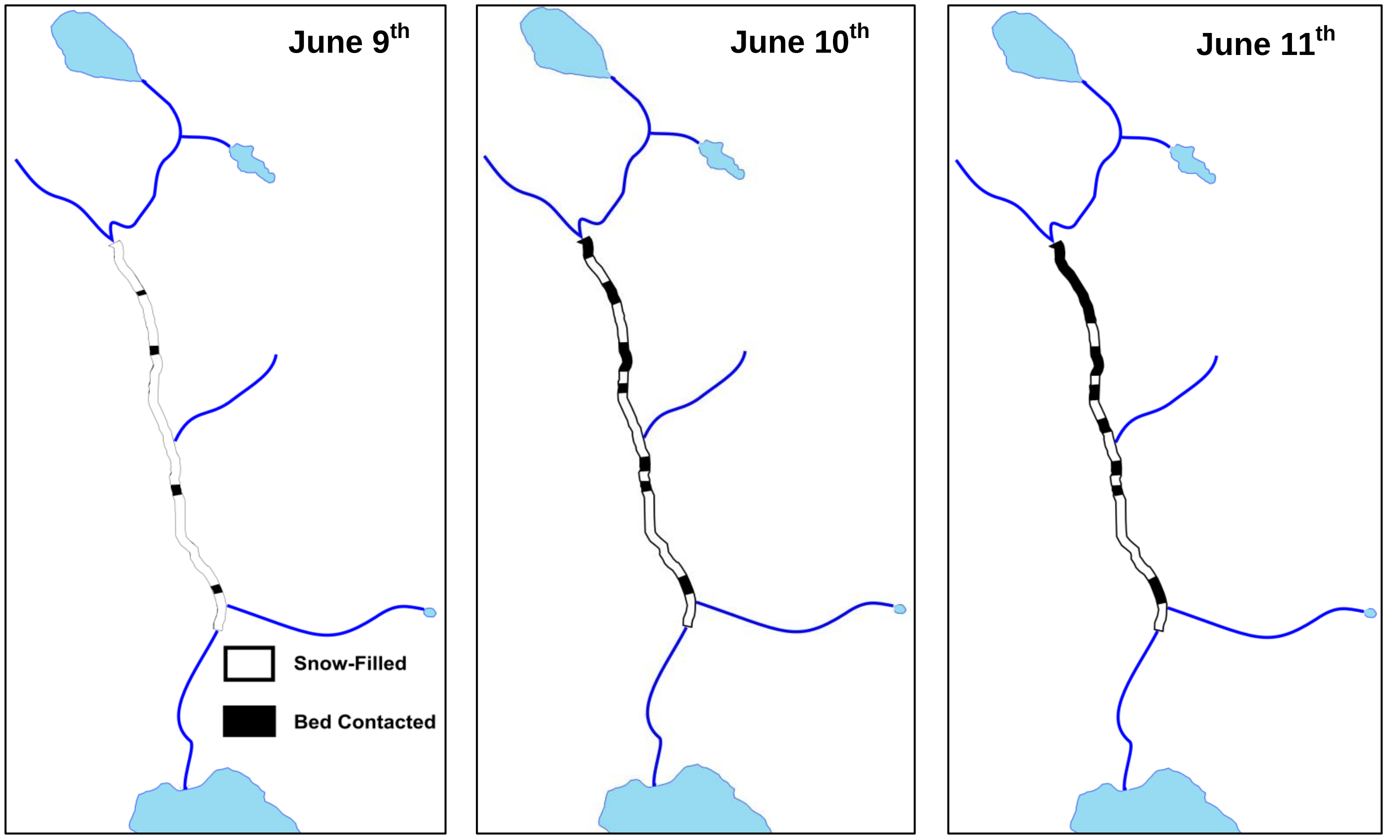


Figure 3.5 Hydrologic connectivity at the narrowing of the West River. A) The influence of snow on channel connectivity as ponded water accumulates at the narrowing of the river on June 12th. B) Release of ponded water on June 14th coincides with the highest hourly SSC values of the 2012 hydrological season.

3.5.3 Flow Bed-Contact Timing

Due to extensive redistribution of snow from the surrounding terrain, areas of the West River can accumulate nearly 5 m of snow in some reaches of the channel (McDonald and Lamoureux, 2009), while others may accumulate less than 1 m. Despite highly variable snow depths, 2012 mapping of flow contact with the bed during the nival flood shows rapid changes during the most energetic time of the melt season.

Through rapid thermal melting of the in-channel snowpack, the channel progressed from 100% bed isolation to complete contact over a six day period (Figures 3.4 and 3.6). During this period, a small channel less than 1 m wide provided the initial points of contact. Channelization of the flow grew from these small finger-like channels to their river-width size (4-8 m) over the course of the nival period. Bed contact occurred primarily in the upper reaches of the river first and progressed downstream with local anomalies due to thick drifts and variations in the channel formed in the snow. Full river length bed contact was not reached until June 14th, when flow broke through the thick snowpack at the narrowing of the river (Figure 3.5). This breeching of the snow dam facilitated rapid sediment and water transport to the downstream gauging station, which recorded season-high SSC as 1085 $mg \cdot L^{-1}$. Following this event, discharge receded and baseflow was established shortly thereafter.


June 9th
June 10th
June 11th
Snow-Filled
Bed Contacted

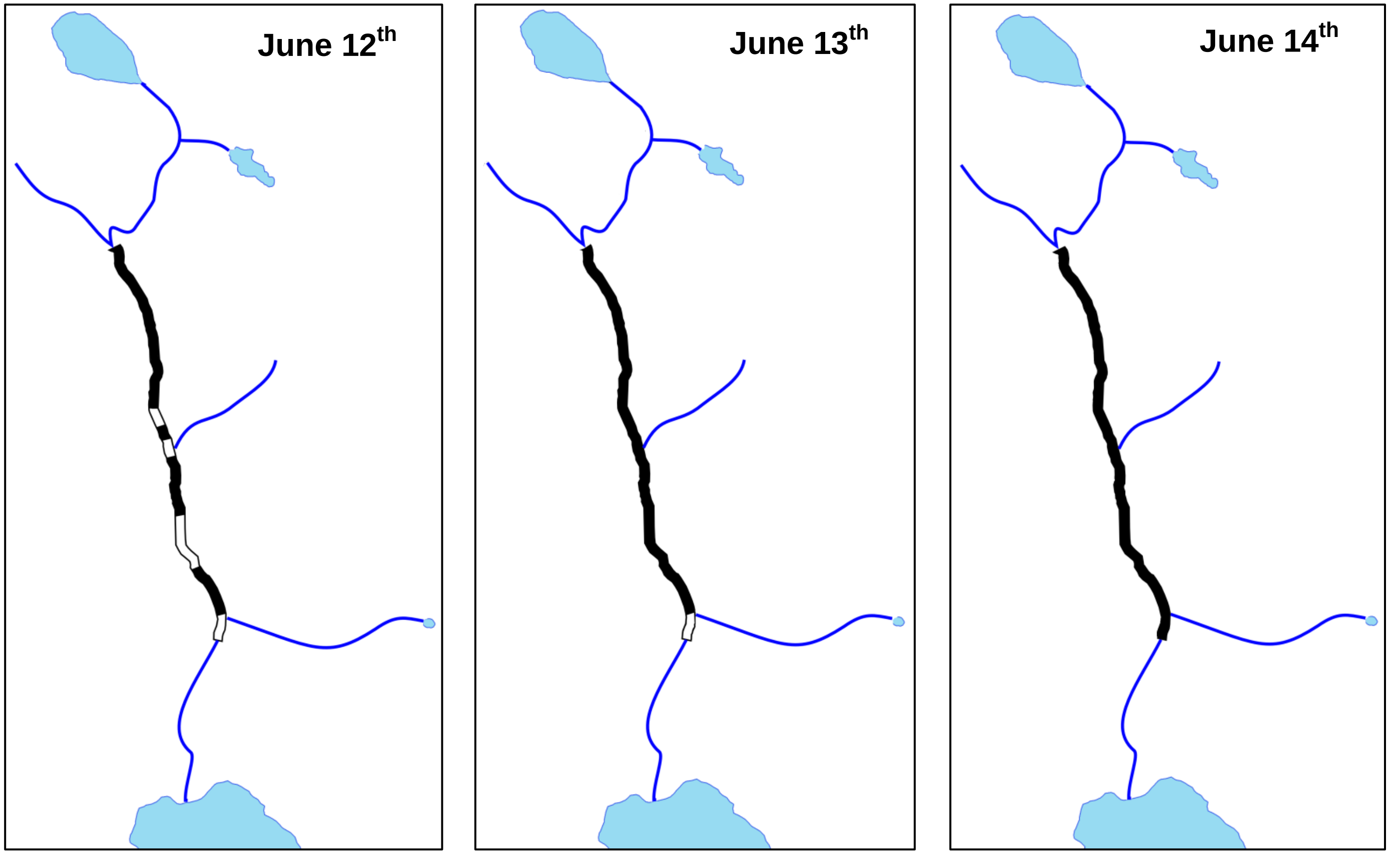


Figure 3.6 Mapped bed contact in the West River during the early 2012 flow period, from the confluence to the narrowing of the river to the West River gauging station. Slight visual exaggeration between June 9 and 11 was necessary to indicate areas of the bed which had been contacted by flow, as these reaches often exhibited localized variations that could not be accurately mapped at this catchment scale.

3.5.4 Suspended Sediment Budget

Inferred reach sediment budgets for the West River indicate channel suspended sediment transport changed substantially during the season (Figure 3.7). During the nival melt (June 10-15), the headwaters introduced a substantial amount of suspended sediment to the river, accounting for the seasonal majority of material transport. Reach A-B (Figure 3.1) consistently acted as a major source of sediment with upwards of 50% of the sediment within the reach originating in the upper headwaters of the river (Figure 3.8). As the nival melt progressed into the recession period (June 15-20), the magnitude of sediment delivered diminished downstream, nonetheless, during these periods, the West River acted primarily as a source of transportable material.

The start of the recession flow signals a transition for the West River from a channel moving material to one which stores it. The magnitude of sediment storage is often negligible (Figure 3.7a), however, results indicate that the channel does entrain material more effectively than it removes it. This is particularly evident in the storage of materials in the headwaters of the West River, an area which contributes the majority of fine grained material to the channel. As the season progressed, the headwaters began storing material; Reach A-B began to entrain upwards of 70% of the sediment introduced to the channel (Figure 3.8) effectively cutting off the main sediment supply to the lower reaches of the river.

The only reach which acted as a consistent source of material for the channel was C-D (Figure 3.1). This reach is impacted by several large active layer detachments (ALD) and was temporarily dammed along a length of 200 m by slope disturbance in 2007 (Lamoureux and Lafrenière, 2009). Flow through this reach was more channelized than the areas above or below it, and therefore was more effective at entraining sediment and carrying it downstream. Additionally, the channel has continued to undergo substantial alteration in the zone where the blockage occurred in 2007, likely resulting in enhanced sediment availability. However, when sediment reached D-E it was effectively deposited as the river widened and flow competence diminished. The outlet of the West River (Reach F-G) was characterized by a distinct lack of sediment transport over the majority of the season, which is due not only to 2012 being a low discharge year, but a low sediment yield year compared to the 2003-10 period. Overall, upstream sediment storage and low discharge through much of the season resulted in the West River being an effective sink of material.

	A-B	B-C	C-D	D-E	E-F	F-G
06/13/2012	881	780	1303			828
06/14/2012	237	172	225	-44	56	64
06/15/2012	22	4	39	-5.8	33	-29
06/17/2012	3	11	62	-19	42	3
06/18/2012	2	2	13	-6	8	2
06/20/2012	3	2	-5	6	-1	1
06/21/2012	0.1	-0.1	10	-8	-1	-1
06/22/2012	-13	5	6	5	-6	0.4
06/23/2012	-5	-2	3	6	-5	-1
06/25/2012	-17	-6	8	-5	-1	0.2
06/27/2012	-9	-3	3	-4	1	-1
06/29/2012	-4	-2	2	-1	1	-1
07/01/2012	-4	-3	4	-4	-0.5	0.4
07/03/2012	-3	-0.4	-1	-0.3	-1	0.01
07/05/2012	-1	-0.1	-1	-0.3	0.01	-0.3
07/07/2012	-0.5	-0.9	0.3	-0.1	0.3	-0.5
07/09/2012	-5.0	-0.6	3.0	-3.1	0.5	5.2
07/11/2012	-1.2	-1.3	1.0	-1.1	0.1	0.01
07/13/2012	-0.8	-0.5	0.1	0.1	0.01	0.01
07/15/2012	-0.3	-0.1	-0.2	0.4	-0.4	0.01
07/17/2012	-0.3	-0.1	0.1	-0.1	0.1	0.1
07/19/2012	0.1	0.2	-0.2	-0.1	0.1	-0.3
07/21/2012	-0.1	-0.1	0.01	0.01	0.01	0.01
07/23/2012	-0.1	0.01	0.9	-0.3	-0.1	-0.1
07/25/2012	1.5	-0.4	0.8	-2.1	5.8	5.6

	A-B	B-C	C-D	D-E	E-F	F-G
06/13/2012	881	780	1303			828
06/14/2012	237	172	225	-44	56	64
06/15/2012	22	4	39	-6	33	-29
06/17/2012	3	11	62	-19	42	3
06/18/2012	2	2	13	-6	8	2
06/20/2012	3	2	-5	6		
06/21/2012			10	-8		
06/22/2012	-13	4.9	6	5	-6	
06/23/2012	-5	-2	3	6	-5	
06/25/2012	-17	-6	8	-5		
06/27/2012	-9	-3	3	-4		
06/29/2012	-4	-2	2			
07/01/2012	-4	-3	4			
07/03/2012	-3					
07/05/2012						
07/07/2012						
07/09/2012	-5		3	-3		5
07/11/2012						
07/13/2012						
07/15/2012						
07/17/2012						
07/19/2012						
07/21/2012						
07/23/2012						
07/25/2012					6	6

Net Source	Net Sink	Zero Value

Figure 3.7 Estimated reach sediment budgets (in kg) for the West River. Budget (A) contains raw data, including all values less than ±2kgday^{-1}, (B) replaces all values below ±2kgday^{-1} with 0 kg. Missing data are indicated by black cells and represent occasions where sampling conditions were hazardous.

	(B-A)/B	(C-B)/C	(D-C)/D	(E-D)/E	(F-E)/F	(G-F)/G
06/13/2012	0.7	0.4	0.4			0.2
06/14/2012	0.6	0.3	0.3	-0.1	0.1	0.1
06/15/2012	0.5	0.1	0.5	-0.1	0.3	-0.3
06/17/2012	0.1	0.3	0.6	-0.3	0.4	0.1
06/18/2012	0.2	0.2	0.5	-0.3	0.3	0.1
06/20/2012	0.7	0.3	-76.5	1.0		
06/21/2012	0.1	-0.1	0.9	-2.3		
06/22/2012	-1.1	0.3	0.3	0.2	-0.3	
06/23/2012	-0.7	-0.4	0.3	0.4	-0.6	
06/25/2012	-1.2	-0.9	0.5	-0.5		
06/27/2012	-0.9	-0.3	0.2	-0.7		
06/29/2012	-1.2	-1.0	0.5			
07/01/2012	-0.7	-0.9	0.6			
07/03/2012	-1.4					
07/05/2012						
07/07/2012						
07/09/2012	-1.2		0.5	-0.9		0.6
07/11/2012						
07/13/2012						
07/15/2012						
07/17/2012						
07/19/2012						
07/21/2012						
07/23/2012						
07/25/2012					0.6	

Net Source	Net Sink	Zero Value

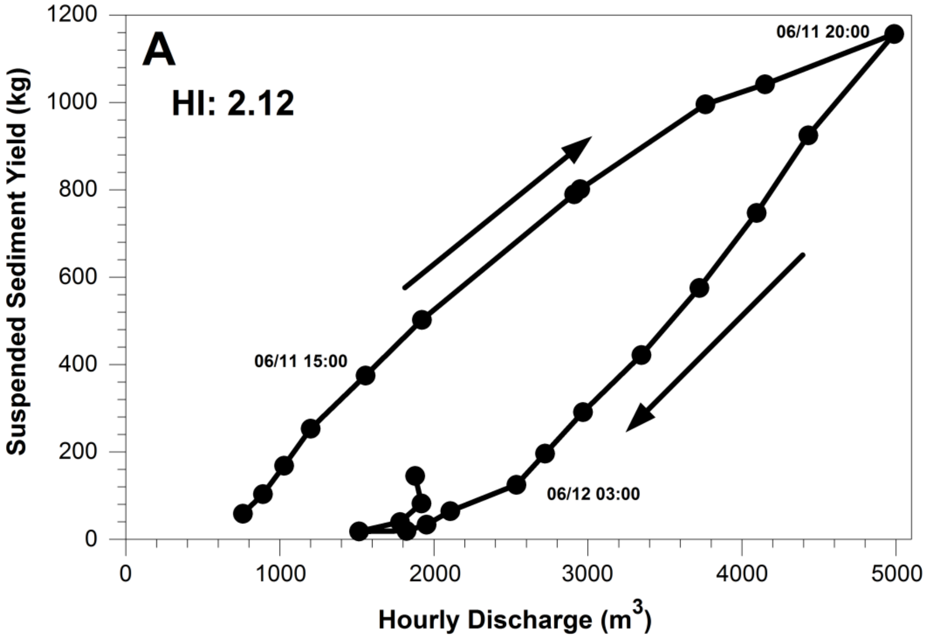
Figure 3.8 Ratio of sediment outflows to inflows by channel reach, indicated as source (positive values) or sink (negative values) in the West River.

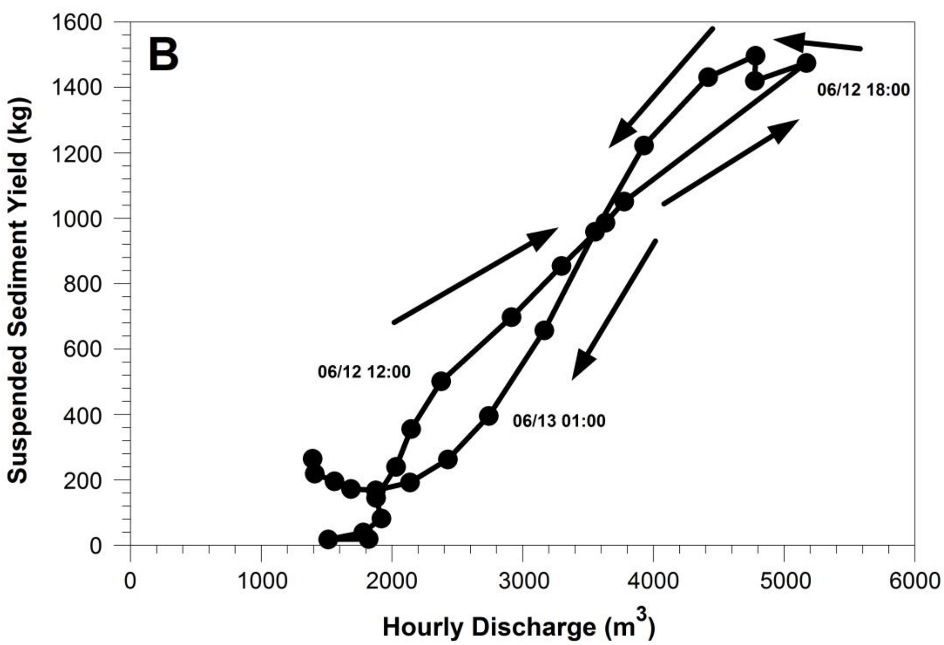
3.5.5 Suspended Sediment-Discharge Hysteresis

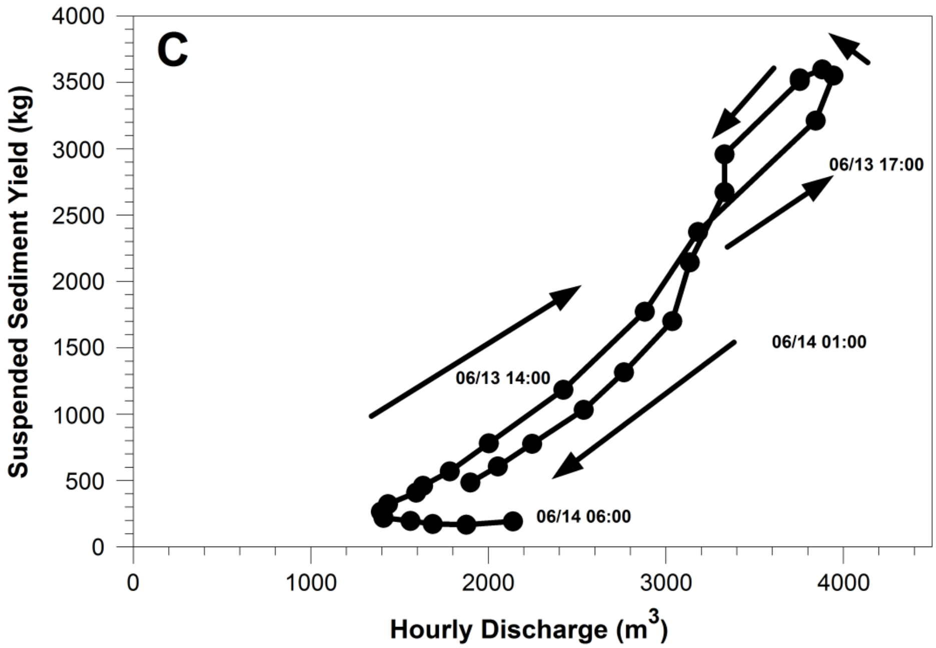
During the nival period, suspended sediment transport peaked three times over five days. Sediment transport for the first peak exhibited strong clockwise hysteresis (k= 0.5, HI= 2.12), while the second and third peaks exhibited complex hysteresis (Figure 3.9a-c, respectively). Multi-day hysteresis encompassing the nival and early recession period for the West River (Figure 3.9d), exhibited counter-clockwise hysteresis (k= 0.5, HI= -0.81). The transition from clockwise to counter-clockwise hysteresis suggests that the available sediment supply was exhausted following the first major discharge event but soon after changed to more complex and proportionate discharge-sediment patterns as the nival period advanced.

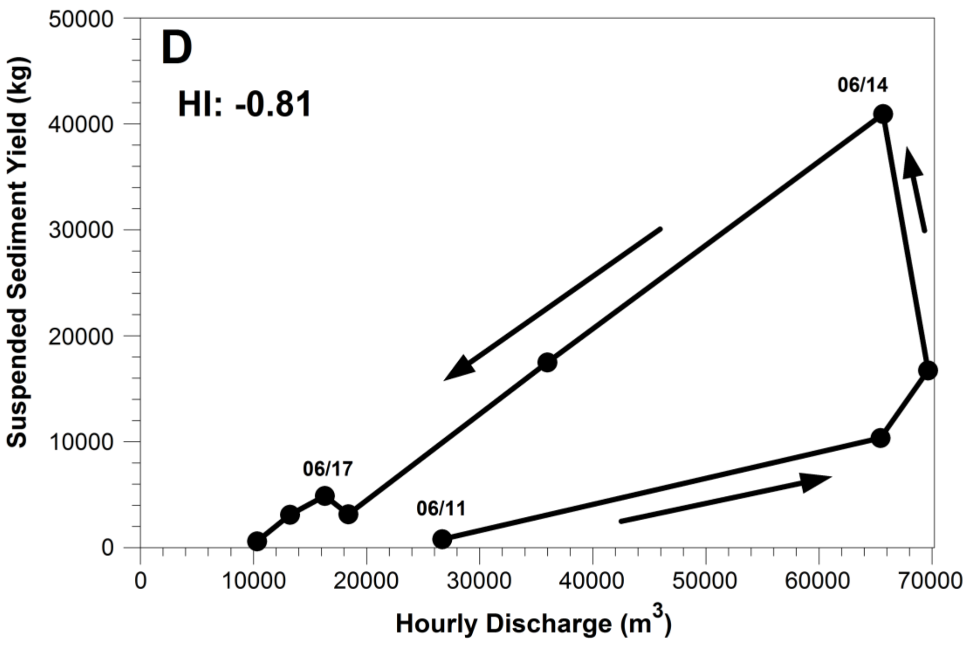
During the majority of the hydrological season, flow preceded sediment delivery, however, there were several diurnal periods which resulted in clockwise or complex hysteresis, and periods where hysteresis resulted in null values (Figure 3.9e). The seasonal record is nearly evenly split between those diurnal periods which exhibited suspended sediment-discharge hysteresis (53%) and those days which did not (46%). Of those days which resulted in hysteresis values, 74% exhibited counter-clockwise relationships (Figure 3.9f).

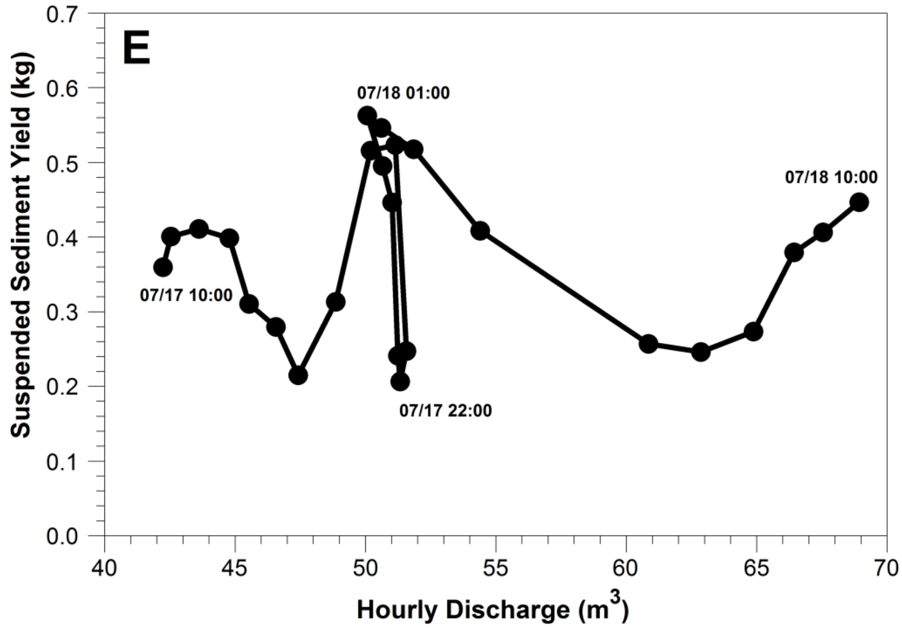
Multi-year diurnal hysteresis relationships have changed from overwhelmingly clockwise (2004-2007, 2010) to counter-clockwise (2008-2009, 2012) (Figure 3.10). This hysteretic shift coincides with the occurrence of permafrost disturbances late in the 2007 season and the overall pattern of suspended sediment storage in the West River.


A
HI: 2.12
06/11 20:00
06/11 15:00
06/12 03:00
Suspended Sediment Yield (kg)
Hourly Discharge (m3)
0
200
400
600
800
1000
1200
0
1000
2000
3000
4000
5000


B
06/12 18:00
06/12 12:00
06/13 01:00
Suspended Sediment Yield (kg)
Hourly Discharge (m3)
0
200
400
600
800
1000
1200
1400
1600
0
1000
2000
3000
4000
5000
6000


C
06/13 17:00
06/14 01:00
06/13 14:00
06/14 06:00
Suspended Sediment Yield (kg)
Hourly Discharge (m3)


D
HI: -0.81
06/14
06/17
06/11
Suspended Sediment Yield (kg)
Hourly Discharge (m3)



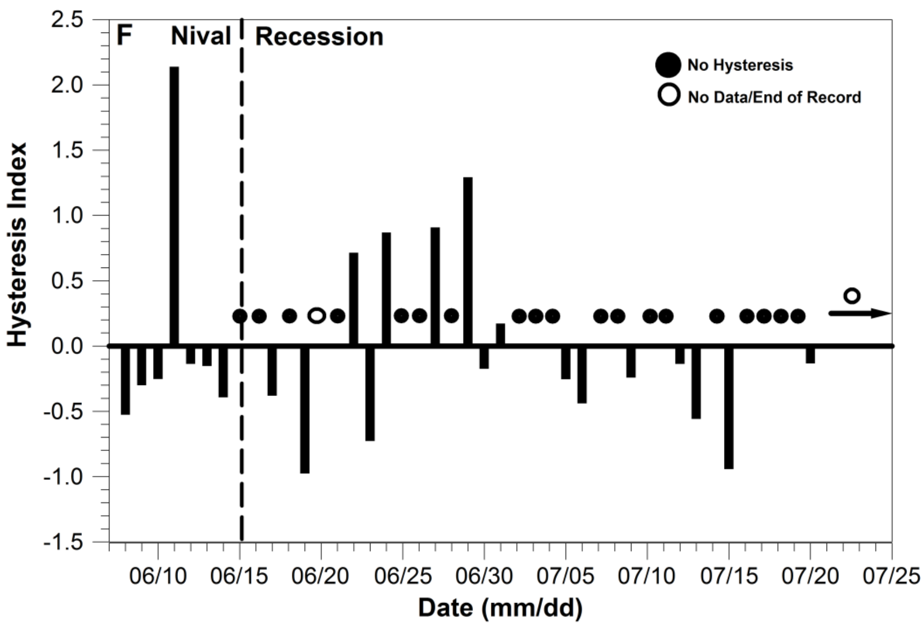


Figure 3.9 Hysteresis patterns during the 2012 season. A) Initial nival peak (Figure 3.4a); B) secondary nival peak (Figure 3.4b); C) tertiary nival peak (Figure 3.4b); D) hysteresis over the nival and recession flow period (June 11-19); E) an example of null hysteresis (July 17-18); F) Seasonal pattern of daily hysteretic relationships for the West River. Positive values denote clockwise hysteresis and negative values denote counter-clockwise hysteresis. Days with no hysteresis represent those days with complex or null hysteresis values from which no hysteresis index could be calculated.

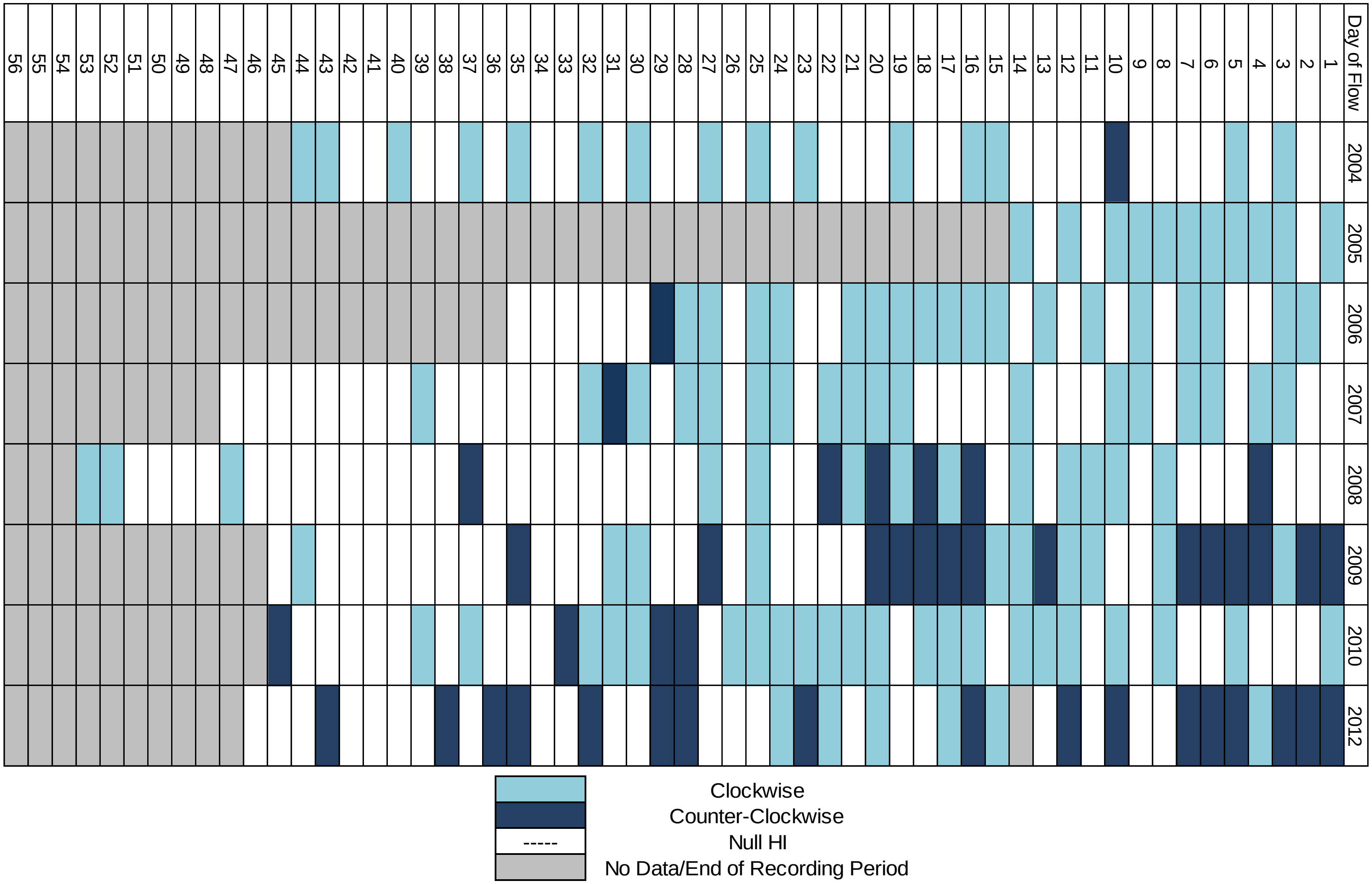


Figure 3.10 Directional hysteresis matrix for 2004-2012 (excluding 2011). Values within individual cells are the HI for the respective diurnal period.

3.6 Discussion

3.6.1 Channel Snowpack and Sediment Load

Many Arctic studies have shown that deep channel snowpack is a major control over early season sediment transport (Woo and Sauriol, 1980; McDonald and Lamoureux, 2009; Woo, 2012) and that residual snow affects sediment availability (Braun et al., 2000). Early in the melt season, flow access to sediment is limited until channel snowpack begins to ablate or when contact is made with the channel bed by flow (McDonald and Lamoureux, 2009). Snowpack variability also exerts substantial control on the timing and magnitude of sediment release, and therefore nival-generated suspended sediment transport. The morphology of snow accumulation in the High Arctic is characterized by redistribution by wind leading to accumulation in areas more conducive to snow accumulation (Woo and Sauriol, 1980; McDonald and Lamoureux, 2009). In the West Watershed, low surface roughness and strong winds lead to extensive snow accumulation in lee slopes, depressions, gullies, and the river channel (Lewis et al., 2011). The dynamic interaction between channel snowpack, sediment buffering by snow, and the magnitude of the nival melt, affects the amount of suspended sediment transported during the most energetic hydrological periods of the melt season.

Results from the bed-contact survey demonstrate the rapidity of flow-bed connectivity, which was established over a six day period in 2012 (Figure 3.5), highlighting the complex spatial pattern of flow contact within the channel. Early bed contact within the West River was limited to sub-meter width channelization. Areas of channelized flow within a given reach varied between years depending upon a number of complex factors. These include the temperature of the snowpack and the direction of the prevailing winds, the latter of which influences the amount and degree of compaction of in-channel snowpack (Woo and Sauriol, 1980). Regardless of these factors, rapid bed contact was the primary factor necessary for high sediment loads in 2012.

Following the establishment of bed contact at the narrowing of the West River on June 14th (Figure 3.5), the seasonal peak SSC was recorded (Figure 3.4b), and over the nival period, 98% of the 2012 seasonal sediment yield was delivered from the catchment. Overall, these findings suggest the magnitude and timing of nival-driven sediment discharge is strongly influenced by the quality and quantity of the in-channel snowpack (McDonald and Lamoureux, 2009), and the establishment of flow-bed and hydrological connectivity.

3.6.2 Evidence of Sediment Slugs and Inferred Sediment Sources

The seasonal decline in suspended sediment yield, sediment budget work, and analysis of hysteresis relationships between discharge and SSC all supports the conclusion of a sediment slug in the upper reaches of the West River.

A substantial amount of sediment was introduced into the channel in 2007 as a result of ground ice melt and channel disturbance in the headwaters, along with a number of active layer detachments adjacent to the river channel. These disturbances initiated due to persistent exceptionally warm temperatures and late season rain ultimately impacting the West River (Lamoureux and Lafrenière, 2009). However, the propensity for sediment storage in the channel has inhibited the downstream transport of sediment and has contributed to a decrease in sediment yields generated by the nival melt (see Table 3.1 in section 3.4.3) and seasonally over the recording period (Appendix A).

Sediment budget analysis completed in 2010 concluded that sediment released from the headwaters is extensively stored in the upper reaches of the channel (Veillette et al., submitted), a conclusion verified by the 2012 budget results. The preferential storage of material at the upper catchment and its subsequent delayed advancement downstream is due to decreased discharge during the recession and baseflow periods. Decreased discharge during these periods reduced stream power and the wetted perimeter of the river, leading to decreased suspended sediment transport during the majority of the hydrological season. This slow progression of substantial amounts of material in the upper catchment is referred to as a sediment slug (James, 1989; Nicholas et al., 1995; Benda and Dunne, 1997; Lamoureux, 2002; Fryirs et al., 2007).

The relationship between discharge and SSC has been used in both temperate (Brasington and Richards, 2000; Seeger et al., 2004; Nistor and Church, 2005; Beel et al., 2011) and Arctic studies (Lewkowicz and Wolfe, 1994; Forbes and Lamoureux, 2005; Dugan et al., 2009; McDonald and Lamoureux, 2009) to identify and explain the controls over sediment accessibility and transport. Prior to permafrost disturbances in 2007, hysteretic patterns were predominantly clockwise; however, in 2012, the predominant daily hysteresis pattern was counter-clockwise. The latter occurs when sediment is sourced from an area some distance away from the outlet, or when sediment availability within the channel system is delayed relative to discharge (Klein, 1984; Brasington and Richards, 2000; Nistor and Church, 2005; McDonald and Lamoureux, 2009). As flow diminished, the delivery of sediment in the upper catchment to the outlet of the river was delayed by the storage of material in the upper reaches of the river, a conclusion supported by 2010 and 2012 sediment budgets. These results indicate that the sediment slug generated from sediment released by permafrost disturbances is having a measurable effect on hysteresis patterns in the West River.

It is difficult to predict how long the sediment slug is likely to impact the West River, as the factors dictating the geomorphic adjustments to fluvial systems are complex (Lamoureux, 2002). Research from both temperate and Arctic settings suggest catchment disturbances can lead to persistent downstream effects on suspended sediment transport (James, 1989; Lamoureux, 2002). Hydraulic mining in the 1880's resulted in substantial amounts of sediment being transported through the Bear River, California, which is still working its way through the channel system over a century later (James, 1989). Contrarily, in the High Arctic, an analysis of a 487-

year varved sediment record from Nicolay Lake, Cornwall Island, revealed that it took this system approximately 17 years to return to pre-event sediment yields following catchment disturbance brought about by major rainstorm events (Lamoureux, 2002). Both of these studies are in agreement with recent modeling of stochastic delivery of debris-flow sediment, suggesting that the transport of sediment as pulses or waves through river channels could last decades to centuries (Benda and Dunne, 1997).

3.6.3 Long Term Sediment Transport Response to Catchment Disturbances and Climate Change

To our knowledge, the suspended sediment and discharge record at Cape Bounty is the longest of its kind in the North American Arctic and, as such, presents a unique opportunity to assess changes to suspended sediment transport over longer timescales. Assessment of sediment and discharge data from 2004-2012 using the analytical methods described in this study provides insights into the changing pattern of sediment mobilization processes in this setting and also builds upon similar methods used by McDonald and Lamoureux (2009) and Veillette et al. (submitted) for portions of the longer record. With future climate change expected to be amplified over the Arctic, resulting in non-linear changes to climate (ACIA, 2005; IPCC, 2007; AMAP, 2012), predicting the responses of systems to increased sediment and discharge perturbations is difficult. Studies that document seasonal patterns of sediment dynamics are therefore important to undertake in order to constrain our understanding of how rivers will respond to change.

Prior to catchment disturbances, daily SSC-Q hysteresis in 2004, 2005 and 2006 predominantly exhibited clockwise loops (McDonald and Lamoureux, 2009), although discernible daily hysteresis was not apparent during most of the nival period in 2004 (Figure 3.10). During the nival period each year, when much of the bed is armored by snow and/or ice, the material available to be mobilized was exhausted on the rising limb of the hydrograph, resulting in clockwise hysteresis. As the season progressed, sediment available for mobilization was exhausted and resulted in weak diurnal clockwise hysteresis, indicating that during these hydrological seasons, sediment was mobilized from readily available sources within the channel system, and the primary limiting factor for suspended sediment transport was discharge and stream power (McDonald and Lamoureux, 2009).

The channel response to permafrost disturbances in the headwaters and adjacent to the river in 2007 (Lamoureux and Lafrenière, 2009), was to limit the downstream delivery of sediment. Two years of sediment budget work suggests the river is now an effective sink of material (Figure 3.7 for 2012, Veillete (2011) for 2010), the cause of which can be linked back to the headwater disturbance which introduced substantial amounts of sediment into the West River. Lewis et al. (2011) also noted that, over catchment scales, the influence of permafrost on sediment yields is attenuated by the propensity for substantial sediment storage in the channel system, which inhibits the downstream transport of sediment. In 2008, instances of counter-clockwise hysteresis became more common in the record, with 2012 being characterized predominantly by counter-clockwise patterns (Figure 3.10). During these years, suspended sediment was available following the discharge peak, suggesting the material which was transported during these events was sourced from an area of the channel some distance from the outlet. The multi-year shift in hysteretic patterns also signals a change in river storage. Prior to the disturbance, material was readily available to be mobilized, while post disturbance, the river began to effectively store transportable material. This demonstrates that a change to sediment transport with respect to discharge and overall channel storage has occurred as a result of catchment disturbance.

This storage response to perturbation in the West River is broadly similar to fluvial dynamics found in other settings. In the classic study of sediment propagation through the Sierra

Nevada, Gilbert (1917) noted that the extensive hydraulic mining, which began in the mid-1800's, dislodged enormous amounts of sediment from the headwater hillslopes. The sediment migrated downstream to the San Francisco Bay and its associated waterways as a sediment slug which took decades to reach its outlets (James, 1989). In temperate environments, rivers often experience a much lower range of discharge and runoff compared to the Arctic, as the hydrological year is longer as a result of less extreme seasonal climatic changes. This reworking of sediment material in temperate settings occurs over a longer period of the season, a factor which is crucial when disturbances such as deforestation, the building of roads, hydraulic mining, or natural disasters such as mud slides or landslides introduce large stores of sediment to a catchment. For example, Webster et al. (1992) noted that, following logging, accelerated transport of sediment was most often attributed to forest floor disturbances, which included the loss of the top litter layer, compaction of the topsoil resulting in enhanced overland flow, and the loss of vegetation which slowed the loss of sediment from upstream reaches and trapped sediment in downstream areas. Such disturbances are often accompanied by changes in the geomorphology of a region, which in turn affect soil, vegetation, and channel morphology (Webster et al., 1992). The same changes may be seen in Arctic environments when disturbances impact a catchment. However, the ways in which each river responds are dependent upon controls determined by geographic location (James, 1989; Lane et al., 1995; Nichols et al., 1995; Madej and Ozaki, 1996; Bracken and Croke, 2007; Fryirs et al., 2007; Beel et al., 2011; Veillette et al. (submitted)).

While the mechanisms for sediment transport following disturbance are similar in both Arctic and temperate regions, the hydroclimatic environment of the High Arctic differs in some key respects to temperate settings. Most notably, snow plays a dominant role in this region, both in terms of generating runoff, as well as altering access to sediment during high flow periods. Numerous studies have shown that the nival flood in snowmelt dominated systems represents the prominant mechanism for sediment transport during the short hydrological season (Woo and

Sauriol, 1980; McDonald and Lamoureux, 2009; Woo, 2012). During the nival melt, when instantaneous discharge is often highest of the season, in-channel snow leads to discontinuous contact from the bed and sediment isolation from the flow. A decline in nival-generated runoff and subsequent suspended sediment yield (SSY), which has historically mobilized the majority of sediment in a season, could affect downstream aquatic and coastal marine ecosystems which rely on the influx of water and sediment for nutrients. In the West River, there has been a recorded decline in snowmelt-driven runoff and associated SSY over the past several years (Table 3.1), coincident with an advancement in the first day of flow, which occurred three weeks earlier in 2012 compared to 2003. Additionally, the influence of snow diminishes as the season progresses, leading to a reduction in the intensity of discharge in the baseflow period, which constitutes the majority of the hydrological season. As flow wanes, stream competence and wetted perimeter decreases, resulting in less effective sediment mobilization (McDonald and Lamoureux, 2009; Veillette, 2011). This often means, in the absence of sediment transport brought about by summer rainfall runoff, the dominant sediment mechanism during the recession and baseflow periods is storage.

Over the past decade, there has been an overall decline of seasonal discharge and SSY at Cape Bounty (Appendix A). The 2012 hydrological season recorded low seasonal runoff, which has coincided with the highest mean June and second highest mean July temperatures on record. This increase in summer temperatures and decrease in runoff has also coincided with a seasonal decrease in suspended sediment yield, which is consistent with recent budget work suggesting that storage is the dominant mechanism in the river (Figure 3.11b) (Appendix A).

Table 3.1 Cumulative nival suspended sediment yield, West River, Cape Bounty

Year	Nival Runoff (mm)	Nival Suspended Sediment Yield (Mg)	First Day of Flow
2004	75.6	381	June 25
2005*	19.3	64.5	June 10
2006	79.3	315	June 21
2007	51.6	65	June 13
2008	77.4	168	June 14
2009	50.3	60	June 13
2010	46.0	125	June 13
2012	49.6	88	June 6

*Note: Data collection in 2005 ended on June 26th. There was no hydrological data collection in 2011.

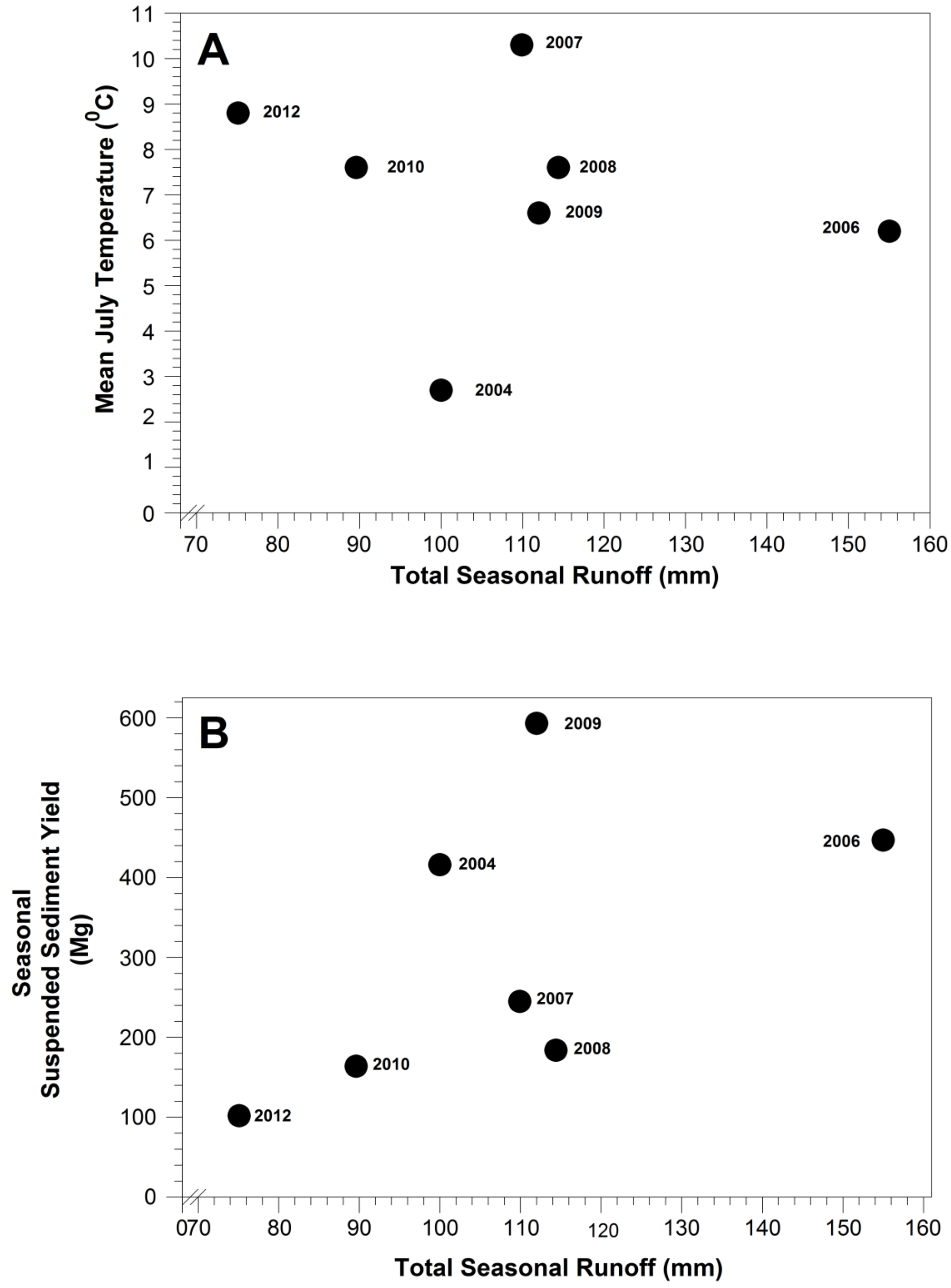


Figure 3.11 Temperature induced changes to established hydrologic regimes. A) Mean July temperature increases with decreasing seasonal runoff; and B) Seasonal SSY and runoff decreases.

The West River catchment, which is likely indicative of similar nival-dominated catchments elsewhere in the Arctic, has been slow to respond to the increased sediment load resulting from permafrost disturbances. The demonstrated propensity for sediment storage has been recognized through the diurnal seasonal hysteresis analysis (Figure 3.10) as well as through the use of sediment budgets in 2010 (Veillette, 2011) and 2012 (Figure 3.7). Results demonstrate that this river has buffered the yield of sediment introduced by permafrost disturbances through channel dynamics and net storage along most of the main reach. Climatic-induced changes to the established hydrological regime, along with early season channel snowpack, further serve to contribute to decreasing suspended sediment yield over the past decade.

Since 2004, the West River has transitioned from a system in which sediment was generally widely available and effectively transported downstream, to a river in which sediment is stored, especially in the upper reaches of the channel, and is released as a slow moving slug. Hence, this geomorphic response, combined with climatically-induced hydrological changes has substantively subdued the sediment yield response to disturbance.

Further long-term studies are needed to accurately constrain the pattern of downstream sediment movement following the introduction of large amounts of sediment from disturbances. However, these results suggest that while the Arctic region is considered sensitive to changes in climate, and therefore prone to disturbances caused by increasing temperatures, the river systems appear to have the capacity to mitigate the impacts of localized channel and catchment disturbance. Climate and fluvial processes such as the storage and release of sediment materials all generate complex diurnal, seasonal, and inter-annual responses to perturbations and disturbances in High Arctic catchments.

Chapter 4

Antecedent Controls on Late Season Sediment Delivery in a High Arctic Catchment

4.1 Abstract

In the High Arctic, late summer precipitation events have the potential to transport substantial amounts of sediment. Past studies have suggested that, with heavy rainfall, suspended sediment will be discharged in large quantities. These studies have either failed to recognize the importance of antecedent catchment conditions prior to a major rainfall event (that event which exceeds some catchment storage threshold, which varies spatially and temporally), or, a more likely scenario is that changes in temperature have led to a new sedimentological discharge regime resulting from drier antecedent periods and deepened active layers. In 2012, discharge and suspended sediment were studied in detail in a small watershed at Cape Bounty, Melville Island, Nunavut. Fluvial and sedimentological responses to late season major rainfall events (MREs) were quantified. Two MREs on July 9 and July 23, totaling 35.4 and 10.6 mm, respectively, resulted in negligible responses in discharge and suspended sediment mobilization. The magnitude and intensity of the MREs were not unusual in this area, but the lack of response was substantial when compared to past events of similar magnitudes. The two-week antecedent period leading up to the July 9th rainfall was characterized by exceptional temperatures and high solar radiation, decreasing soil moisture and increasing infiltration potential. This significantly diminished the effect of rainfall on runoff and suspended sediment transport. These results indicate that should projected model predictions of enhanced summer precipitation be realized, antecedent catchment conditions may substantially attenuate suspended sediment transport responses to MREs and decrease runoff ratios. These results highlight the importance of

antecedent soil moisture conditions during the antecedent period to the runoff and sediment transport response to late season rainfall events.

4.2 Introduction

Extensive documentation has identified the Arctic as being acutely sensitive to climatic changes. The hydrological system will respond not only to increases in temperature, but also to available moisture (ACIA, 2005). In addition to a longer melt season, the thawing of permafrost, and increases in active layer thickness, increased temperatures will alter the frequency of precipitation, both in winter as snow accumulation decreases, and in summer as rainfall increases (ACIA, 2005; IPCC, 2007; Frey and McLelland, 2009; Lewis et al., 2012).

Summer rainfall events have been identified as important agents of change in northern environments (Woo and McCann, 1994). Studies of High Arctic watersheds spanning nearly 50 years have suggested that summer rainfall has the potential to mobilize considerable quantities of materials, despite their variable return periods (e.g. Cook, 1967; Woo & Sauriol, 1980; Woo, 1983; Lamoureux, 2000; Dugan et al., 2009; Lewis et al., 2012). Summary model projections (ACIA, IPCC, AMAP) suggest that the frequency and magnitude of summer precipitation events will increase as the climate warms, which is forecasted to have substantial impacts on seasonal sediment yields (Lewis et al., 2012). Woo (2012) suggests that the antecedent conditions in the catchment, most notably soil moisture, can be a major contributing factor to the availability of sediment following a precipitation event. As temperatures rise, Arctic basins are expected to dry out, thereby leaving the storage capacity of soil in the active layer receptive to inputs of moisture from rainfall events. This soil storage dictates the amount of runoff a basin experiences, along with the mobilization of sediment. Under wet or saturated conditions, the amount of infiltration into the soil decreases as the hydraulic conductivity of the soil increases, resulting in higher runoff ratios (RR) as sediment is entrained and mobilized as water flows off the surface as saturated overland flow (Macrae et al., 2010). The mechanisms for predicting the timing and magnitude of downstream suspended sediment fluxes are generally well understood, however, researchers have suggested that a shift in the delivery of sediment, which acts as a substrate for nutrients and contaminants, could result in considerable biological pressure being placed on downstream marine and aquatic ecosystems (Lyons & Finlay, 2008; McKnight et al., 2008).

Despite the suggested relative importance of rainfall events to Arctic sediment transport and yields, comparably little research into their relationship has been undertaken. The goal of this research is to assess the importance of summer rainfall to runoff generation and the magnitude of sediment delivery to the West River (unofficially name) at the Cape Bounty Arctic Watershed Observatory (CBAWO), Melville Island, where hydrology and sediment transport has been monitored since 2003. This paper evaluates the response to major rainfall events in 2012 and compares these results with similar records from 2007-2009 to explain the interactions between rainfall and sediment mobilization with analysis of soil moisture, drying trends, and synoptic scale atmospheric patterns.

4.3 Study Site

Research was carried out at the Cape Bounty Arctic Watershed Observatory (CBAWO), located on the south-central coast of Melville Island, Nunavut, in the Canadian Archipelago (74°55’ N, 109°35’ W) (Figure 4.1). As part of larger multidisciplinary research efforts, monitoring of the paired West and East watersheds (unofficially named) commenced in 2003 and has produced datasets pertaining to hydrological, meteorological, sedimentological, limnological, permafrost, and biogeochemical processes. The focus of this study is the unofficially named West River located in a nonglacial 8.0 km^2 watershed. The terrain is underlain by continuous permafrost (Lewis et al., 2012) and forms an active layer that can reach 0.7-0.9 m in by late July (Rudy et al., 2013).

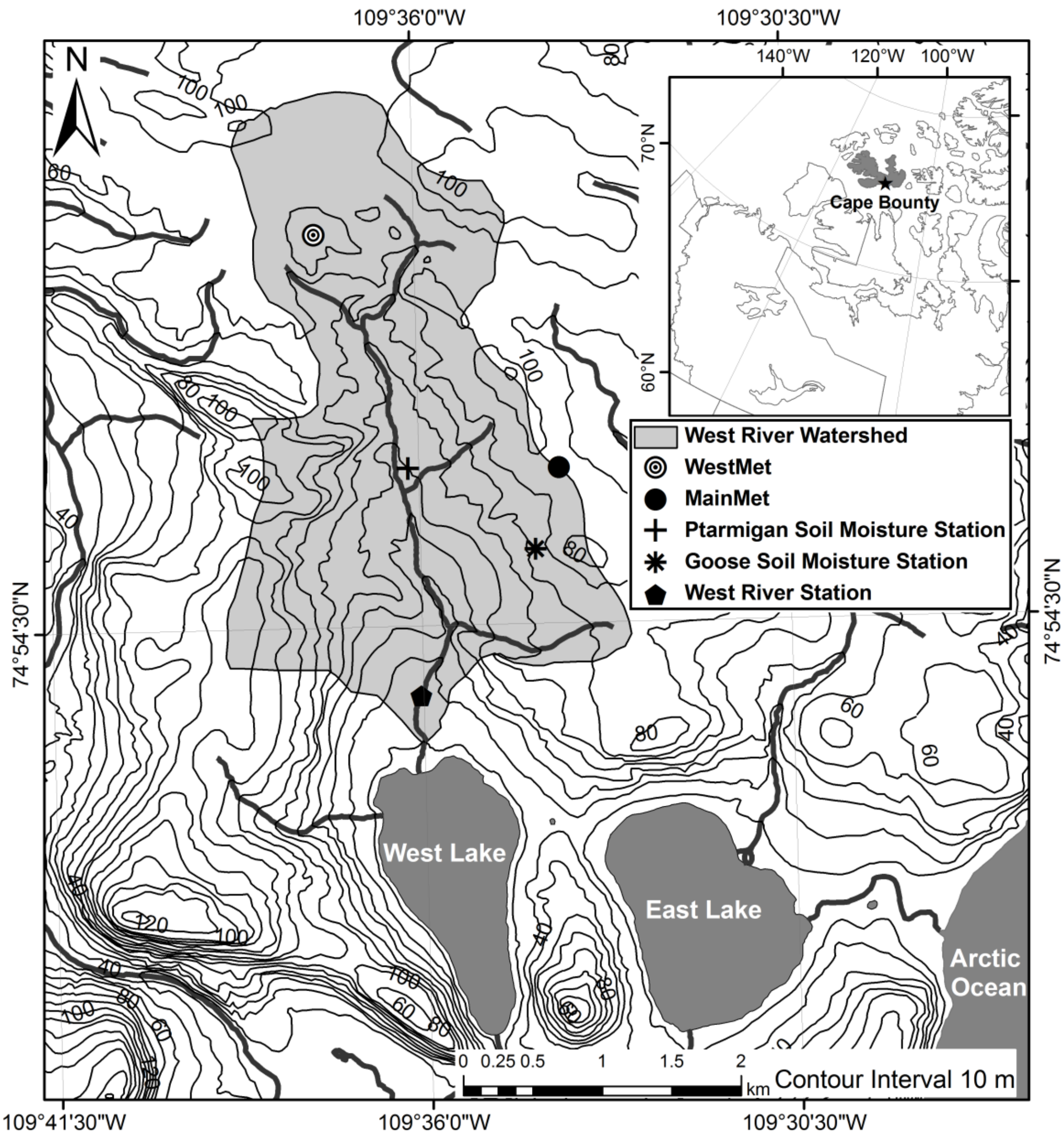


Figure 4.1 Cape Bounty Arctic Watershed Observatory (CBAWO) study site with West Catchment, meteorological, and soil moisture stations. Inset map is location of CBAWO in the Canadian High Arctic.

The climate at Cape Bounty is that of a polar desert, typified by long cold winters (September to May), short melt seasons (June to August), and relatively dry conditions, punctuated by low frequency high intensity summer rainfall events. The mean annual temperature at the nearest long-term weather station, Mould Bay, Prince Patrick Island, is -17.5°C, while monthly mean temperatures above freezing are recorded for May, June, July, and August. Prevailing precipitation is snow, which is subject to extensive redistribution in the catchment by wind, preferentially depositing on leeward slopes, low-lying areas, and within gullies and river channels (McDonald and Lamoureux, 2009; Woo, 2012). Initial flow in the West River typically begins in early to mid-June, with peak discharge occurring only a few days later (McDonald and Lamoureux, 2009; Lewis and Lamoureux, 2010). The subsequent baseflow period is intermittently interrupted by streamflow responses to late season precipitation events. The West River remains at baseflow until freeze up in early September (Lamoureux & Lafrenière, 2009).

4.4 Methods

While the West watershed has been studied since 2003 (Cockburn & Lamoureux, 2008; Lewis et al., 2012), only data between 2007-2009, and 2012 is reported in this study, as these years have both discharge and suspended sediment transport records and recorded major rainfall events ($\geq$ 6 mm of rainfall with no more than 6 hours between rainfall inputs) (Cook, 1967; Dugan et al., 2009).

4.4.1 Meteorology

Two meteorological stations were established within the boundaries of the West watershed (Figure 4.1). The primary station, MainMet, located on the boundary of the two catchments at approximately 80 m a.s.l, is equipped to record precipitation, temperature, wind speed and direction, relative humidity, and solar and net radiation. A secondary meteorological station, WestMet, was located in the headwaters of the West River at approximately 90 m a.s.l.

For the purposes of this study, hourly precipitation, air temperature and incoming solar radiation data will be presented, with MainMet data being utilized unless otherwise stated. At MainMet, air temperature was recorded 1.5 m above the ground with an Onset Temperature/RH smart sensor (± 0.21°C temperature, ±2.5% relative humidity) and logged with an Onset U30 station. Prior to 2011, MainMet air temperature was recorded with a shielded Humirel HTM2500 sensor (0.2°C and 3% accuracy) logged with a Unidata Prologger. Incoming solar radiation was measured with a Davis sensor (3% accuracy). WestMet air temperature was measured with an Onset H8 logger (± 0.7 °C accuracy). Precipitation at both stations was measured using a Davis Industrial Tipping Bucket (0.2 mm tip). Meteorological data from previous years used in this study is presented in MacDonald and Lamoureux (2009) and Lewis et al. (2012).

4.4.2 Hydrology and Suspended Sediment

Hydrology and suspended sediment data were collected at the West River gauging station (Figure 4.1) throughout June and July. Stage was recorded with a Unidata capacitive water depth probe logged with an Onset Flexsmart logger. During the nival period, West River sensors recorded data at 15 second intervals (June 7^{th}-June 20^{th}). Owing to the taxing power consumption and subsequent failure of some instruments towards the end of this period, recording was changed to one minute intervals for the remainder of the season (June 20^{th}-July 26^{th}). Discharge was calculated from stage measurements using a rating curve derived from manual point velocity-area measurements (Veillette, 2011). For periods of extremely low flow, the polynomial rating curve overestimated discharge from stage measurements less than or equal to 0.06 m; a linear extrapolation was used for all stage measurements less than 0.06m (34% of the record).

Suspended sediment was collected at the West River gauging station utilizing both manual and automatic sampling techniques. Automatic sampling of the river occurred every three hours using an ISCO automatic pump sampler. Manual sampling at the gauging station occurred twice daily at base and peak flows during the nival period and following precipitation events, and once daily at peak flow thereafter until the end of the season for pump sampler redundancy. Sampling was increased to twice daily following precipitation events. In the field, samples were vacuum filtered volumetrically through pre-weighed 1 μm glass fiber filters and subsequently freeze-dried to determine suspended sediment concentration (SSC). A robust cubic spline was used to calculate missing hourly point samples to create an hourly SSC record for the West River. The annual sediment yield for the West River was calculated by the summation of hourly sediment yield, which was determined by multiplying hourly discharge and SSC. Sampling protocols for hydrology and suspended sediment in the West River between 2007-2009 are outlined in Lewis et al. (2012).

Hydrograph separations based on the subjective method (Singh, 1992) were used to separate baseflow from event flow during periods of rainfall. The return to baseflow following an event was estimated based on inflection points on the falling limb of the event hydrograph. A sensitivity analysis was conducted on several different inflection points and it was concluded that the difference between these points were not substantial enough to cause a difference in event discharge and SSC determinations.

4.4.3 Soil Moisture

Volumetric soil moisture at 0-10 cm depth was recorded during the 2007-2009 field seasons at the Ptarmigan soil station and in the upper reaches of the Goose subcatchment in 2012 (Figure 4.1). Decagon ECH$_2$O water probes, logged with Onset U12 loggers were used at both stations. The manufacturer's calibration equation,

$$q = 11.9 \times 10^{-4} \times V - 0.401 \tag{4.1}$$

where q is the volumetric water content and V is the output from the probe (mV), was used to convert the data output to volumetric soil moisture units (m^3/m^3).

4.5 Results

4.5.1 Meteorology

Climate conditions for the 2012 melt season were warm and generally dry (Figure 4.2). Above freezing daily average temperatures began on June 4th, which is the earliest date of consistent positive temperatures recorded at Cape Bounty. First day of flow for the West River was recorded on June 6th, the earliest day since 2003 and a one week advancement from the earliest previous discharge period in 2010 (Veillette, 2011).

Despite over 57 mm of rain falling in July, the summer months were relatively dry as the majority of this rain (68% of the seasonal total) was delivered in two major rainfall events (herein referred to as MRE). MRE_1 began at 0900h on July 9th and resulted in 35.4mm of rainfall at MainMet over 26 hours, achieving a maximum intensity of 4.4 mm/h. MRE_2 began at 0000h on July 24th and resulted in 10.6 mm of rainfall over 9 hours, with a maximum intensity of 2.8 mm/h.

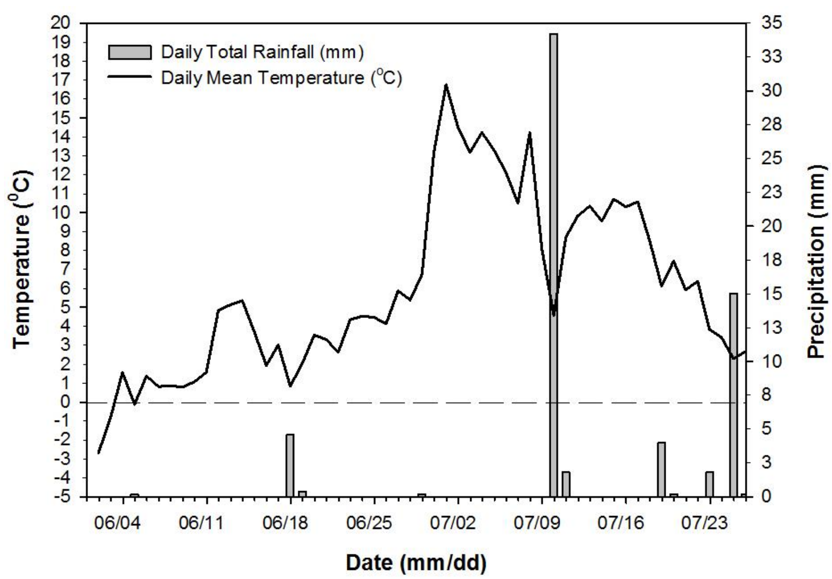


Figure 4.2 Mean daily temperature and daily total rainfall in 2012 recorded at MainMet.

When compared against the instrumental climate record at Cape Bounty, 2012 was a warmer year than average (Table 4.1). Additionally, an analysis of total summer rainfall over the instrumental recording period did reveal that similar major rainfall events (≥ 6 mm of rainfall with no more than 6 hours between rainfall inputs) occurred between 2007-2009 and 2012, with similar rainfall amounts recorded in 2012 and 2009 (Table 4.1).

Table 4.1 The instrumental climate record for the CBAWO Lamoureux, personal communication; Dugan et al., 2009; McDonald and Lamoureux, 2009; Veillette, 2011). Bold font indicates years with major rainfall events.

Year	Mean June Temperature (°C)	Mean June Rainfall (mm)	Mean July Temperature (°C)	Mean July Rainfall (mm)	Cumulative Melting Degree Days (MDD)†
2003	-0.8[1]	0.1	3.6	5.4	121.1
2004	-0.1[1]	0.5	2.7	2.5	81.3
2005[2]	2.0	5.4	3.1	32.6	--
2006	1.1	18.0	6.2	4.8	195.1
2007	**2.9**	**16.2***	**10.3**	**13.4***	**376.1**
2008	**3.5**	**4.6**	**7.6**	**27.4**	**309.2**
2009	**3.1**	**0.0**	**6.6**	**66.8**	**268.5**
2010	3.3	6.6	7.6	12.6	293.1
2011	**2.6**	**21.4**	**9.0**	**4.0**	**333.0**
2012	**3.5**	**5.4**	**8.8**	**57.2[3]**	**336.0**

[1] Records begin June 8, 2003 and June 6, 2004, respectively. Results are biased warmer
[2] Record ends early on June 26th
[3] Record ends July 26th, 2012
*Precipitation data collected from WestMet, due to instrumentation failure at MainMet
† Calculations for 2003-2006 started at the beginning of their climate records. All records end on July 26th, except for 2005.

4.5.2 Discharge and Suspended Sediment

The 2012 hydrological season was typical of a nival-dominated runoff regime, and the resulting hydrograph includes five hydrological periods (Figure 4.3). The nival flood began on June 3rd, with flow beginning on June 6th. On June 8th, a peak discharge of 1.8 m^3/s was recorded (Figure 4.3a), but is most likely due to the rapid release of ponded water just upstream of the gauging station; open-flow peak discharge, 1.4 m^3/s, was recorded on June 12th (Figure 4.3b). Recession and baseflow conditions followed the nival melt, and were only interrupted during two major rainfall events (July 9th and July 23rd). Total seasonal runoff for the West River was 75.1 mm. During the nival and recession flow periods, 98% of the total suspended sediment yield (SSY) for the season was mobilized. The remaining 2% was mobilized following rainfall events in July, with negligible sediment being mobilized during the recession and baseflow periods.

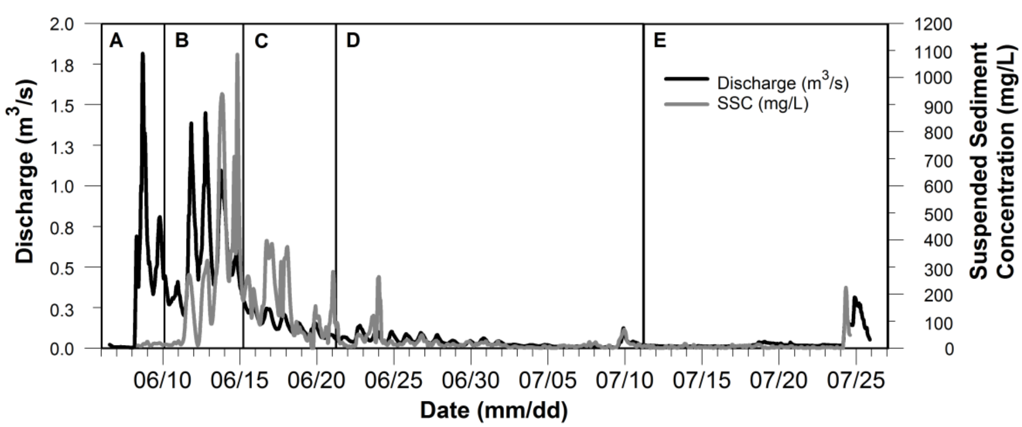


Figure 4.3 Discharge (m^3/s) and SSC ($mg \cdot L^{-1}$) for the West River during the 2012 hydrological season at the CBAWO. A) Pre-melt; B) nival melt; C) recession flow; D) baseflow; E) baseflow following rainfall.

4.5.2.1 Discharge and Suspended Sediment Delivery during Major Rainfall Events

Between 2007-2009 and in 2012, ten major rainfall events were recorded at the CBAWO, and each resulted in substantial interannual variability in catchment sediment delivery (Table 4.2).

Table 4.2 Multi-year rainfall-runoff-sediment mobilization for the West River, CBAWO.

Year and Event (MRE: Rainfall Event)	Total Rainfall (mm)	Total Event Discharge (mm)	Runoff Ratio	Total Suspended Sediment Yield (Mg)
2007_{MRE1}	9.2	6.7	0.73	31.4
2007_{MRE2}	10.8	8.0	0.74	44.1
2008_{MRE1}	7.6	0.1	0.01	0.1
2008_{MRE2}	13.2	0.4	0.03	4.4
2008_{MRE3}	7.6	0.9	0.12	6.4
2008_{MRE4}	7.0	2.4	0.34	11.1
2009_{MRE1}	37.4	16.2	0.43	291.1
2009_{MRE2}	14.2	11.9	0.84	235.6
2012_{MRE1}	35.4	0.23	0.001	0.2
2012_{MRE2}	10.6	0.7	0.07	0.8*

*Sediment recorded until July 24th, 2012

Observed differences between rainfall runoff ratios within the same year and when compared to similar events in other years cannot be explained on the basis of rainfall amount or total event discharge alone. This is evidenced by each of the first events in 2009 and 2012 which received similar rainfall inputs but resulted in substantially different sediment yields and runoff ratios (Figure 4.4).

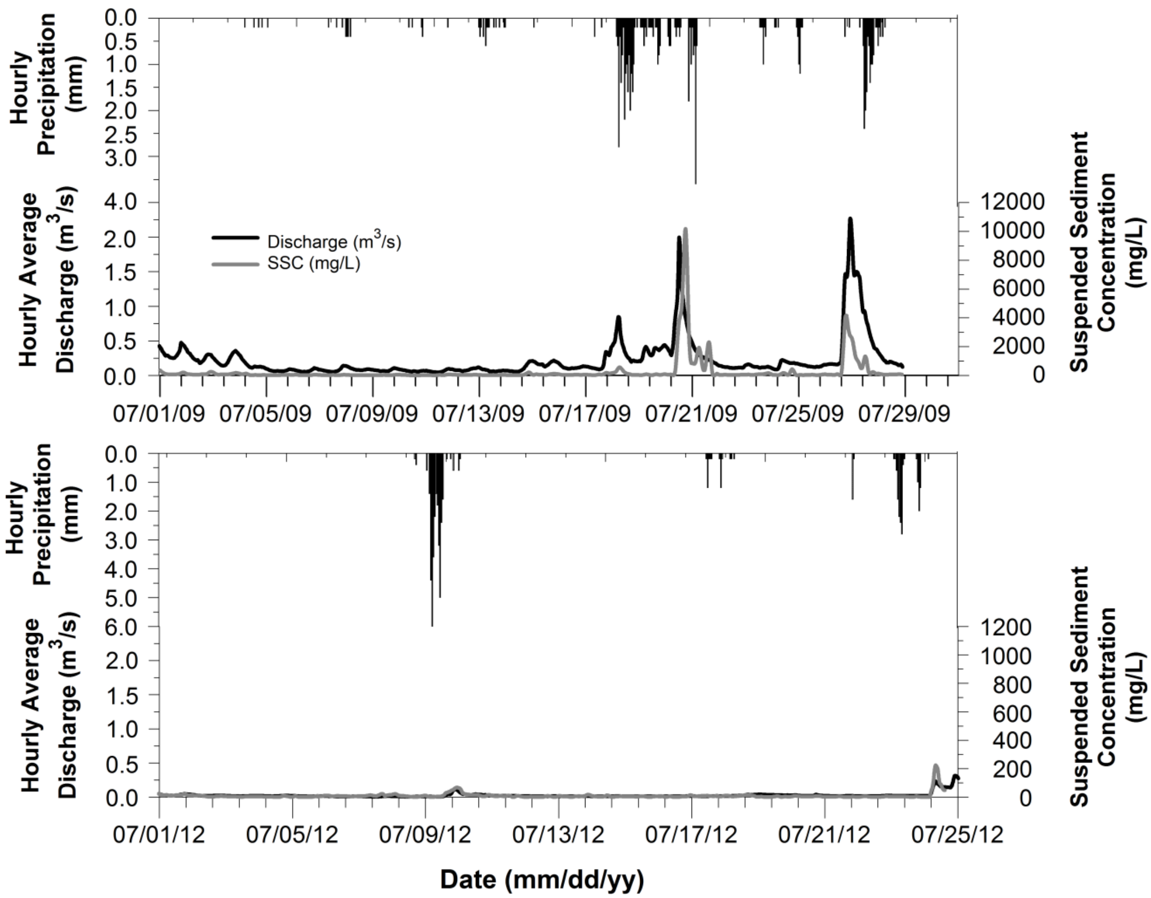


Figure 4.4 Comparison of 2009 and 2012 precipitation and discharge and corresponding sediment transport, beginning on July 1st of each year.

Baseflow separations for MRE_1 and MRE_2 in 2009 estimated event discharge as 16.2 and 11.8 mm, with runoff ratios of 0.43 and 0.84, respectively. During these events, 526.6 Mg (tonnes) of sediment were mobilized, representing 89% of the seasonal annual yield (Lewis et al., 2012). On a seasonal basis, these events generated the dominant peaks in discharge and suspended sediment concentration and load. Similar magnitude rainfall events impacted the catchment in 2012, but did not dominate either the sediment graph or hydrograph. Baseflow separations for MRE_1 and MRE_2 in 2012 estimated event discharge as 0.23 and 0.7 mm, with runoff ratios of 0.001 and 0.07, respectively. These events contributed a total of 0.98 Mg of sediment, accounting for only 2% of the annual sediment yield and resulted from a disproportionately low hydrograph and sediment response. This is most likely a slight underestimation of suspended sediment yield in 2012, and especially for MRE_2, as the SSC record ended two days before the discharge record, and immediately following a rainfall event, due to lost samples. However, the SSC data suggests sediment load was declining steadily prior to the end of the available record.

4.5.3 Soil Moisture and Rainfall Events

An analysis of soil moisture from the four years with major rainfall events illustrates that variations in suspended sediment yield corresponds broadly to the antecedent soil water content of the soil prior to rainfall input. While 2007 and 2008 broadly show this relationship, similar rainfall amounts for MRE_1 and MRE_2 in 2009 and 2012 allow for comparisons of resulting suspended sediment mobilization. In particular, the variations in runoff responses to rainfall, and subsequent sediment delivery downstream, are linked to the antecedent conditions that develop in the weeks prior to the initial MRE.

In 2012, soil moisture measurements were carried out near the upper boundary of the Goose subcatchment, a departure from previous year's soil moisture stations in the Ptarmigan subcatchment due to destruction of the latter (unofficial subcatchment names) (Figure 4.1). Both stations are located on dry level sites, proximal to ephemeral water tracks.

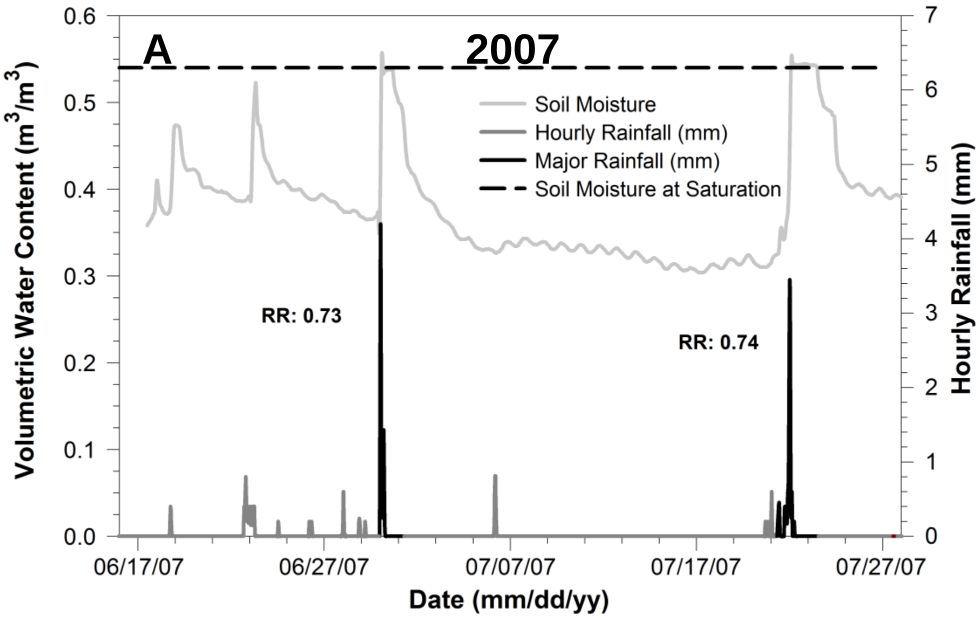
Above average temperatures and a lack of rainfall caused prolonged drying within the soil in 2012 prior to MRE_1 on July 9th (Figure 4.5d). The soil began to dry out following the nival melt from peak volumetric water content (VWC) of 0.37 m^3/m^3 to a low of 0.24 m^3/m^3. This drying trend began two weeks prior to the antecedent period leading up to MRE_1. A rapid increase in soil moisture accompanied the initiation of rainfall. Following cessation of rainfall, the ground did not achieve saturation, and immediately began to dry. The low runoff ratios for

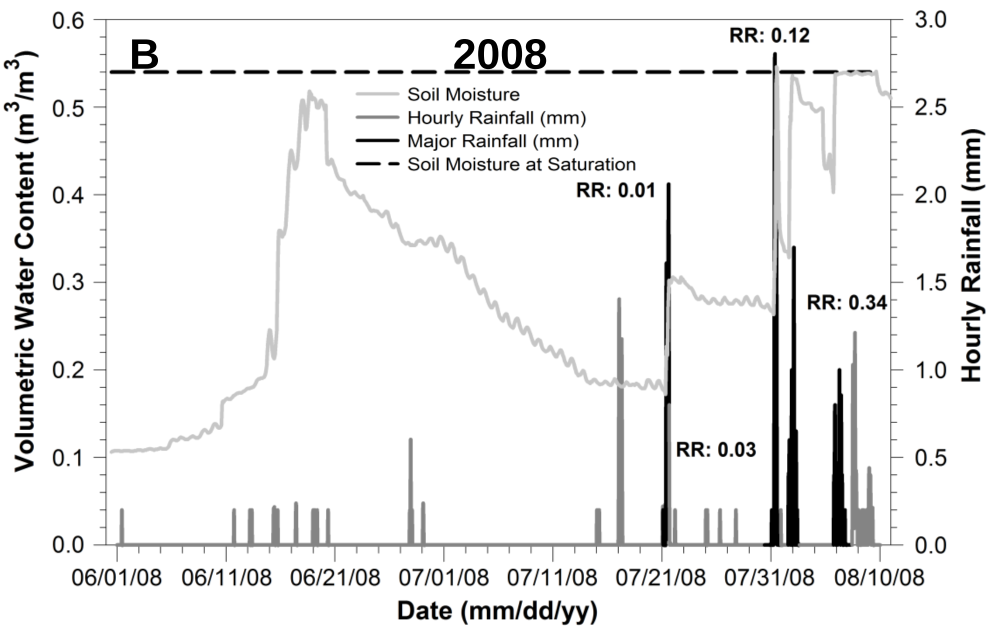
$MRE_1$and MRE_2 suggest the majority of rainfall infiltrated the soil and did not exceed soil water holding capacity, resulting in negligible increases to river discharge and therefore limited suspended sediment mobilization.

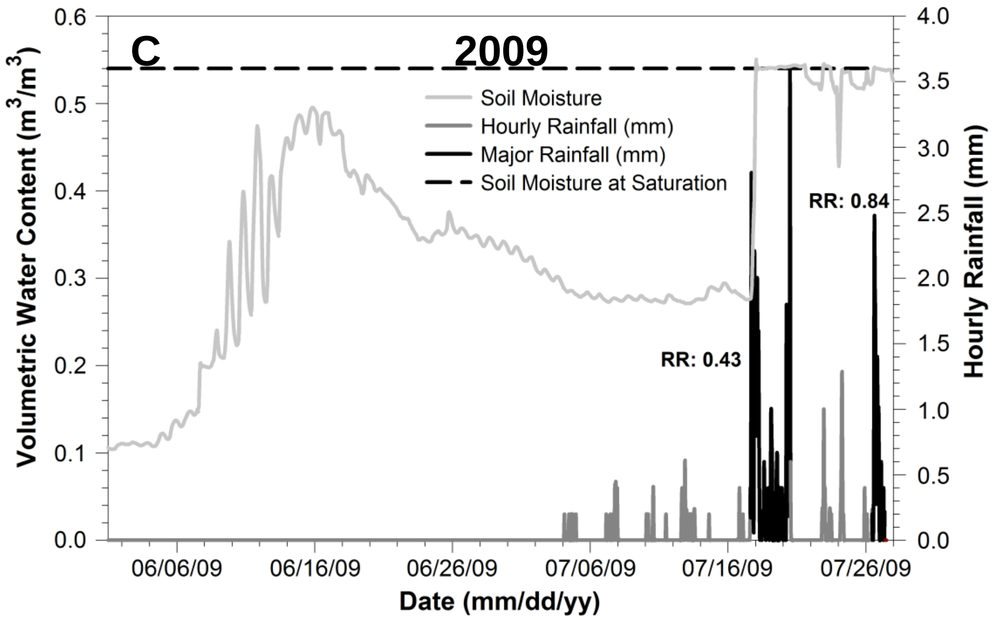
Between 2007 and 2009, a more punctuated drying trend was observed at the Ptarmigan soil site resulting from multiday rainfall (Figure 4.5a-c). In 2007 and 2009, all MREs caused a period of soil saturation from sporadic rainfall inputs, which halted drying of the soil, and in some cases reversed the established drying trend. Rainfall in 2008 also caused soil saturation, but not until MRE_2 and MRE_3. Runoff ratios for these events (Table 4.2) are considerably higher than observed with MREs in 2012, which sustained runoff to effect the catchment leading to substantial suspended sediment mobilization.

During all four years, volumetric water content (VWC) did not return to seasonal lows following rainfall. If soil did begin to dry out again following rainfall, as is the case in 2007, 2008, and 2012, it did so starting from a higher VWC than the period before the rainfall. In 2007, the average soil moisture was 0.32 prior to and 0.40 m^3/m^3 following MRE_2. 2008 saw a similar pattern, with VWC prior to MRE_1 (which occurred later in the season than 2007 MRE_1) recorded as 0.18 and 0.28 m^3/m^3 before and after MRE_1, respectively. The difference between pre- and post VWC following rainfall was less pronounced in 2012: a difference of 0.05 m^3/m^3 was recorded between the lowest recorded VWC and the stable period following rainfall. By contrast in 2009, soil saturated at 0.54 m^3/m^3 following an average VWC of 0.27 m^3/m^3 prior to MRE_1, and, save minor drying intervals later in the end of the season, remained saturated. These trends in higher VWC towards the end of July is seen in 2008 when the record extends into early August and remains high for the remainder of the season.

In 2009, soil moisture began to dry following the nival melt (June 15th) and continued to dry until July 3rd, when the catchment began to receive low magnitude rainfall inputs. These inputs, totaling 5.3 mm over the two week antecedent period prior to MRE_1, reversed the drying trend of the soil just prior to MRE_1. In 2012, the soil also began to dry following the nival melt, but began to do so on June 7th, a week prior to 2009. Soil moisture drying over the antecedent period leading up to MRE_1 in 2012 did not reverse, as it had in 2009, due to limited rainfall input (0.8 mm). Over the two week antecedent period, fewer melting degree days (MDD) were recorded for 2009 (66 MDD) then 2012 (137 MDD), suggesting that the rain was accompanied by overall cooler temperatures in 2009.


A
2007
Soil Moisture
Hourly Rainfall (mm)
Major Rainfall (mm)
Soil Moisture at Saturation
RR: 0.73
RR: 0.74
Volumetric Water Content (m3/m3)
Hourly Rainfall (mm)
Date (mm/dd/yy)
06/17/07
06/27/07
07/07/07
07/17/07
07/27/07


B
2008
Soil Moisture
Hourly Rainfall (mm)
Major Rainfall (mm)
Soil Moisture at Saturation
RR: 0.12
RR: 0.01
RR: 0.34
RR: 0.03
Volumetric Water Content (m3/m3)
Hourly Rainfall (mm)
Date (mm/dd/yy)
06/01/08
06/11/08
06/21/08
07/01/08
07/11/08
07/21/08
07/31/08
08/10/08



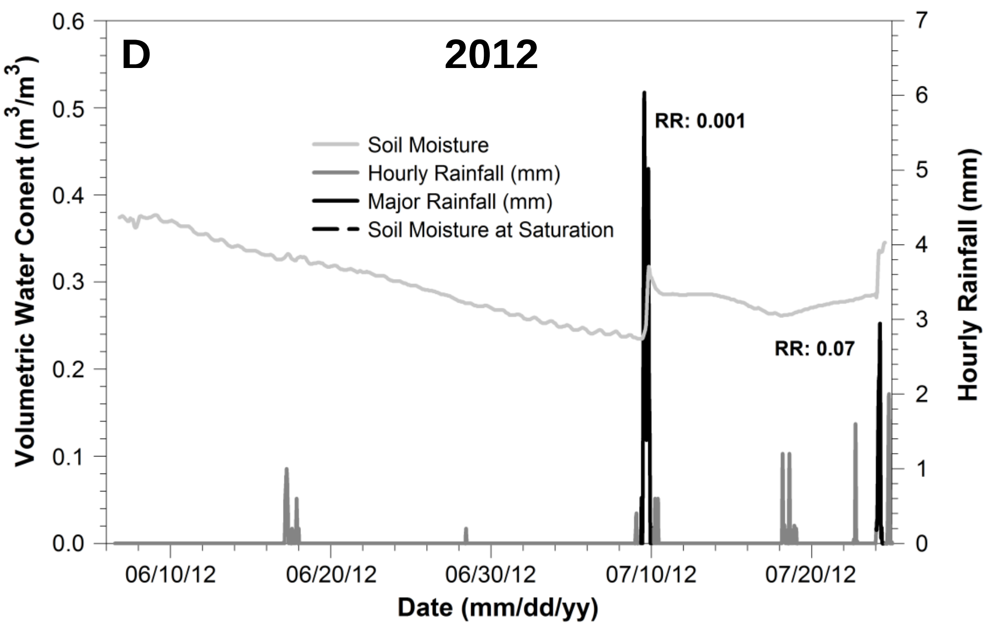


Figure 4.5 Soil moisture at Ptarmigan (2007-2009; A-C) and Upper Goose (2012; D) and precipitation recorded at MainMet, CBAWO. Runoff ratios are denoted as RR.

4.5.3.1 Synoptic Climate

Polar stereographic near surface pressure maps at 925 mb for the region (60°- 85° N and 140°- 80° W) were generated using NCEP reanalysis data (NOAA/OAR/ESRL PSD, Boulder, CO, www.esrl.noaa.gov/psd).

Near surface (925 mb) mean pressure maps for the region over Cape Bounty and surrounding Queen Elizabeth Islands, indicate the synoptic controls influencing climate and precipitation and hence antecedent soil drying and resulting precipitation-induced runoff and suspended sediment yields. Four mean pressure maps were generated for two week antecedent periods for 2009 and 2012 (July 2nd to 16th and June 24th to July 8th, respectively), and mean July pressure for 2009 and 2012 (Figure 4.6). Regional low pressure conditions for 2009 resulted in cooler conditions and prolonged rainfall inputs, while a ridge of high pressure in 2012 during the antecedent period is consistent with warmer and drier conditions conducive to extensive soil moisture drying and limited rainfall. The pressure anomalies indicate departures from the climate normal (1981-2010) and occurred in both 2009 and 2012, manifesting themselves as low and high pressure systems, respectively.

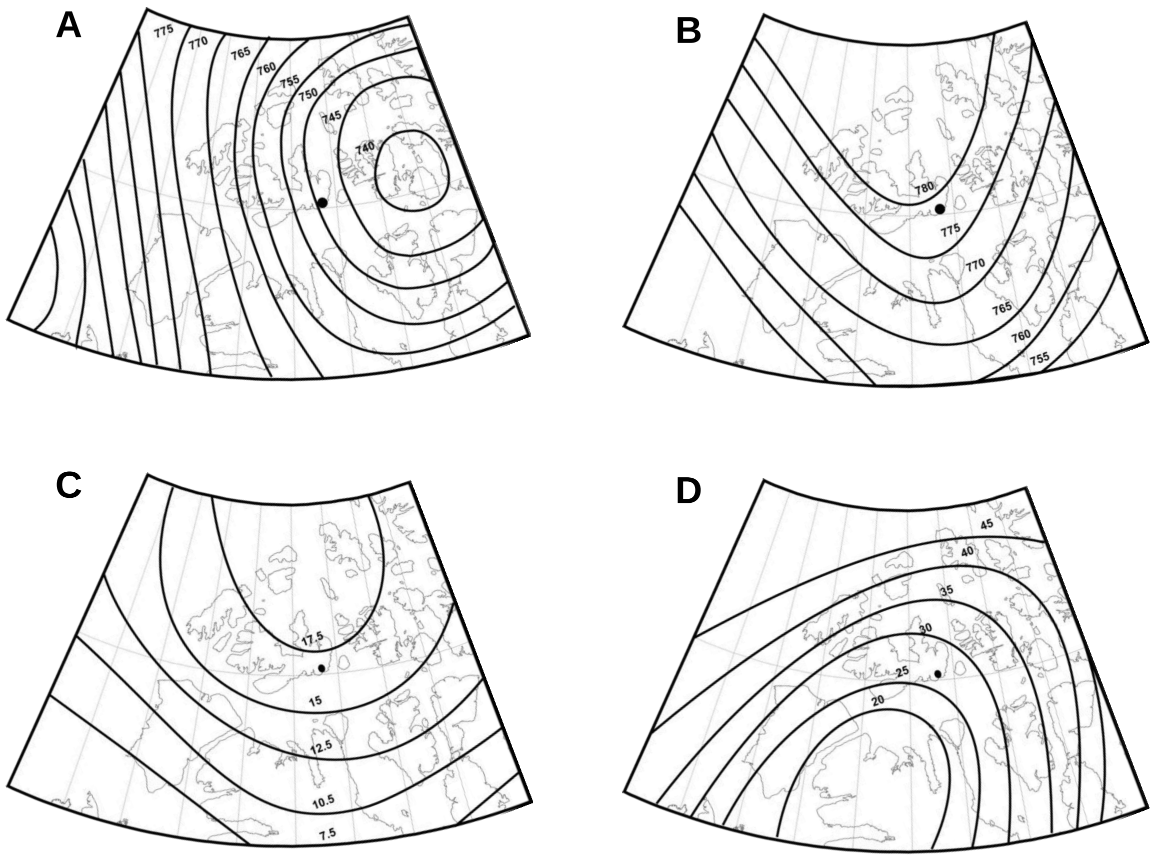


Figure 4.6 Atmospheric 925 mb surfaces for the area surrounding Melville Island during the two week antecedent period prior to MRE: (A) July 2-16, 2009 and (B) June 24 –July 8, 2012. July composite 925 mb pressure anomaly for (C) 2009 and (D) 2012. (www.esrl.noaa.gov/psd).

4.6 Discussion

Major rainfall events in the High Arctic, while infrequent, have the potential to substantially impact catchments through rapid runoff response and enhanced suspended sediment transport (Cogley and McCann, 1976; Lewkowicz and Wolfe, 1994; Lamoureux, 2000; Braun et al., 2000; Dugan et al., 2009; Lewis et al., 2012). The nature of the relationship between rainfall and sediment yield has been difficult to quantify given the lack of the necessary hydroclimatic data (Kuchment et al., 2000). Hence, little work has been carried out to understand the role antecedent catchment conditions have on rainfall runoff and sediment mobilization.

McDonald and Lamoureux (2009), among others (Woo, 2012), recognized nival melt as being the most energetic runoff period in nival systems. Upwards of 90% of seasonal discharge and sediment transport occurs during the annual nival flood. Following from that, and under normal circumstances, major late season precipitation would not produce substantial sediment transport due to increased soil storage capacity and catchment drying following the nival period (Woo, 2012). However, if conditions prior to rainfall contributed to limited soil water storage capacity, effectively reversing the drying trend, rainfall can generate overland flow and mobilize substantial sediment. For example, Dugan et al. (2009) reported that runoff from two moderate rainfall events in 2007 (9.2 and 10.8 mm total respectively) collectively mobilized more sediment (35% of the seasonal annual sediment yield) than the nival runoff (29%). Further observations at Cape Bounty revealed this dynamic again in 2009, where the overwhelming majority of seasonal annual sediment yield (88%) was transported as a consequence of a late summer rainfall event (Lewis et al., 2012).

Despite the heavy rainfall of similar magnitude and intensity in 2012, the resultant runoff was characterized by low discharge that mobilized only 2% of the seasonal sediment load. The differential response between years to similar rainfall events can be attributed to differing antecedent conditions, which yielded substantial difference in sediment export during the MREs in 2009 and 2012 (Table 4.3).

Table 4.3 Runoff and suspended sediment discharge (SSQ) characteristics from rainfall events in 2009 and 2012.

Year	Major Rainfall Event (duration in hours)	Total event Rainfall (mm)	Runoff generated from rainfall (mm)*	Runoff Ratio	SSQ (Mg)*	Specific Yield (Mg/km^2)	Specific Yield per Unit Runoff ($Mg/mm/km^2$)
2009	MRE_1(71)	37.4	5.4	0.43	291	36.4	2.2
	MRE_2 (23)	14.2	4.5	0.84	236	29.8	2.5
2012	MRE_1 (26)	35.4	0.2	0.001	0.2	0.02	0.1
	*MRE_2 (9)	10.6	0.6	0.07	0.1	0.1	0.2

*Runoff and SSQ are calculated for the period when both discharge and SSC records are available. Runoff generated from rainfall is a measure of the discharge at the West River after baseflow separations were calculated, and could represent a potential underestimation of runoff.

During the antecedent period prior to MRE_1 in 2009, both temperature and precipitation reflected the regional synoptic climate conditions. A decrease in measured air temperature and incoming solar radiation (Figure 4.7) coincided with the growth of a low pressure system off the east coast of Melville Island (section 4.4.3.1). This resulted in cooler temperatures (74 MDD) and intermittent low level precipitation (5.4 mm) over the 14 days prior to MRE_1 (Figure 4.5). This antecedent period increased soil moisture and effectively reduced potential soil water storage, leading to rapid soil saturation during the initial hours of MRE_1. Although evaporative losses during this period were not quantified, it is assumed that reduced incoming solar radiation and relatively low temperatures would reduce drying during this time. These antecedent conditions, coupled with nearly three days of continuous rainfall input during MRE_1 resulted in substantial runoff (RR: 0.43) and suspended sediment mobilization (Table 4.3).

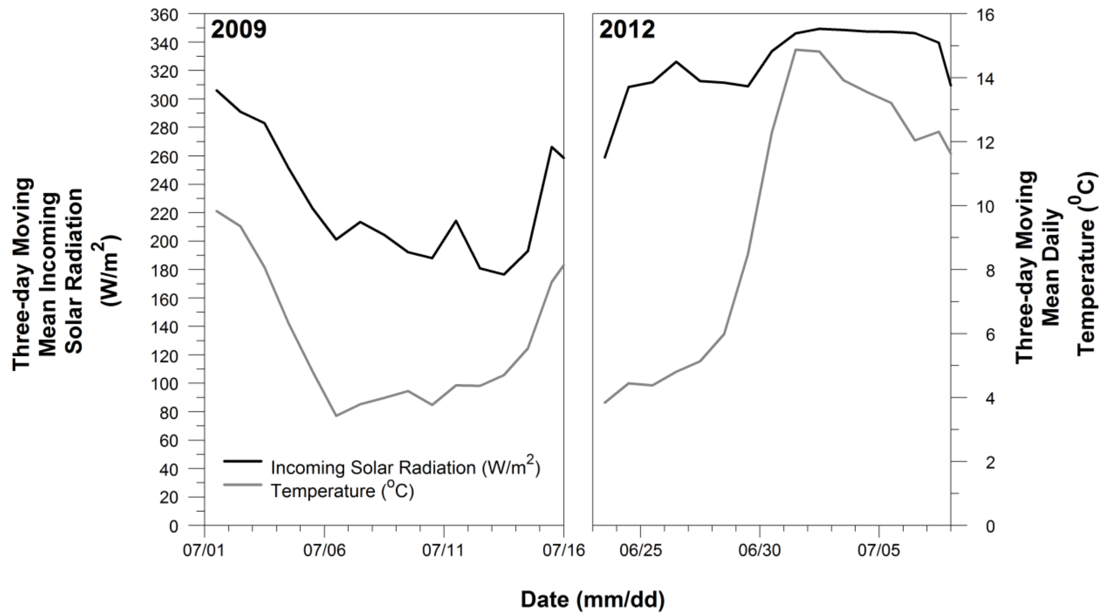


Figure 4.7 Three-day moving mean of temperature and incoming solar radiation for 2009 and 2012 during the period prior to the first MRE. The drop in temperature and solar radiation in 2009 coincides with the establishment of a regional low pressure system, while a regional high pressure system in 2012 (see text) coincides in increasing temperature and solar radiation conditions.

Runoff and suspended sediment transport from the second rainfall in 2009 was conditioned by soil saturation following MRE_1 (Figure 4.5c) and resulted in the highest runoff ratio (0.84) and specific sediment yield (Table 4.3) of the four rainfall events. Disregarding climatic factors, MRE_2 was able to mobilize large amounts of sediment due to the increase in stream flow resulting from precipitation (Figure 4.4) and the reduced infiltration potential of the soil prior to MRE_2 (Figure 4.5c). Both 2009 rainfall runoff events generated increased discharge and wetted perimeter of the river that accessed channel bed and bank sediments and from slope tributaries. This resulted in substantial sediment transport in total and in specific-yield terms (Table 4.3).

Discharge and suspended sediment yield in 2012 did not record a substantial response to rainfall, despite similar rainfall amounts and intensities that occurred in 2009. The 2012 river response to rainfall was negligible for MRE_1, the result of substantial soil moisture losses during the antecedent period characterized by sustained high levels of incoming solar radiation (Figure 4.7b) due to the presence of a ridge of high pressure in the region (Figure 4.6b). Warmer than average temperatures during the antecedent period (144 MDD in 14 days) and only trace amounts of rainfall (0.8 mm) resulted in sustained reduction of soil moisture (Figure 4.5d). Following these prolonged drying conditions, the catchment minimally responded to MRE_1 and generated specific sediment yield of 0.1 $Mg/mm/km^2$, indicating that the majority of rainfall infiltrated and leaving little rainfall for runoff and sediment transport. Despite an observed small increase in soil moisture prior to MRE_2, negligible runoff and suspended sediment transport occurred during this event.

Establishing baseline suspended sediment yield conditions in the Arctic is critical to recognizing catchment responses to hydroclimatic change (Lamoureux, 2000). The magnitude response of sediment transport to rainfall in the Canadian High Arctic varies; however, the mechanisms remain similar. Broadly speaking, rainfall which impacts the catchment following the nival flood and the melt of the majority of the snowpack infiltrates the soil matrix, and following saturation, results in enhanced discharge, which facilitates sediment erosion and downstream transport from bed and bank sources.

The magnitude of the transported material depends on the runoff response from the rainfall event, and in some cases, can represent the majority of the seasonal suspended sediment yield (Dugan et al., 2009). However, despite this system response, comparatively few Arctic studies have assessed sediment transfer response to rainfall. Cogley and McCann (1976) noted an exceptional storm event at Vendom Fiord on Ellsemere Island resulting from low synoptic level pressure over the area. They also concluded that heavy summer precipitation was an important seasonal control for surface erosion processes in that setting. Similar responses were recorded on Melville Island (Dugan et al., 2009; Lewis et al., 2012), Ellesmere Island (Lewkowicz and Wolfe, 1994), and Cornwallis Island (Braun et al., 2000), suggesting that rainfall induced runoff affects a wide range of High Arctic locations. Hence, the results in this study are widely applicable to other High Arctic areas.

More broadly, studies in a number of settings have noted the importance of antecedent catchment conditions and water content of the soil as contributing factors to the magnitude of catchment runoff and suspended sediment transport (e.g., Lamoureux, 2000; Lenzi and Marchi, 2000; Seeger et al., 2004; Dugan et al., 2009). However, few Arctic studies have investigated this complex relationship. In one of only a few studies to do so, Lamoureux (2000) compared sedimentary structures in a downstream lake and the meteorological record and noted the varying presence of sedimentary rhythmites in response to major multi-day rainfall events. The largest of these rhythmites occurred in two years when meteorological results from the nearest weather station recorded the two largest rainfall events of the 30-year record. However, the author noted that antecedent soil moisture (as inferred by temperature and MDD metrics) and the timing of rainfall (whether the rain fell on snow or following the snowmelt period) complicate the interpretation of the sedimentary record, as catchment conditions could have mitigated suspended sediment discharge. While this study interpreted rainfall response and the role of antecedent conditions indirectly (through a lake sedimentary record), the results are consistent with those found in this study.

In all four years with major rainfall events at Cape Bounty (Figure 4.5), the tendency for soil moisture to dry during June and up until mid- to late July commonly occurred. Even after a MRE (such as in 2007), the catchment responds by further drying to achieve moisture contents lower than prior to rainfall. This trend continues into late July when a general shift occurs from soils drying to becoming progressively wetter. In three of those years where the soil became saturated (2007-2009) (Figure 4.5a-c), enhanced baseflow runoff occurred following rainfall events. Hence, these records indicate that antecedent soil moisture plays a pivotal role in determining the runoff response and magnitude of sediment transport following rainfall events. Additionally, it is clear that both antecedent soil moisture levels determine whether or not soil saturation will occur in response to a MRE, and also determines the magnitude of discharge response and associated sediment transport. In 2012, when soil saturation did not occur, runoff was minimal and far less sediment was transported compared to previous years. Hence, these results indicate the need to detail the complex relationship between soil moisture, discharge and resultant sediment transport.

Evaluating the variable discharge and sediment yield response from a top-down standpoint, we can conclude that synoptic-level pressure and the resulting climatic patterns have a major influence in defining the nature of the antecedent period. In this Arctic setting, persistent high pressure generated reduced cloud cover, increased solar radiation, generated warmer temperatures, and resulted in limited rainfall. These conditions facilitated soil drying which resulted in high capacity potential for infiltration during rainfall events. By contrast, regional low pressure reduced incoming solar radiation, cooled temperatures and generated more frequent low intensity rainfall. These conditions can result in earlier soil saturation during subsequent major rainfall events, greater runoff response, and higher sediment transport. These results suggest that synoptic controls play an important role in conditioning the overall rainfall-runoff response in the Arctic, particularly through soil moisture. Further, these results provide important data to constrain modeling efforts to more accurately represent these systems, and echo earlier concerns noted by Lamoureux (2000) and Braun et al. (2000) that antecedent conditions are critical to understanding sediment transport responses to rainfall. Moreover, these results are of particular importance given evidence that Arctic environments appear to be becoming drier in the summer, as evidenced by lower water levels and drying of ponds (Smol and Douglas, 2007).

4.6.1 Modeling of Future Arctic Rainfall-Runoff

A large body of research has suggested that, given the anticipated warming in the Arctic as a result of anthropogenic climate change, hydrological regime changes are also expected and likely to occur in tandem (ACIA, 2005; AMAP, 2012). Global climate models (GCM) as well as regionally statistically downscaled predictions for specific areas in the High Arctic (e.g. Lewis and Lamoureux, 2010), suggest that moisture availability under warmer scenarios is likely to increase precipitation, as well as temperatures.

IPCC (2007) has noted that, over the 20th century, global climate warming has coincided with changes to important facets of the hydrological cycle. Modeled projections into the 21st century from the IPCC, the Arctic Climate Impact Assessment (ACIA) and the Snow, Water, Ice and Permafrost in the Arctic (SWIPA) suggest that a 10-30% increase in Arctic runoff can be expected, along with an increase in summer precipitation (IPCC, 2007; AMAP, 2012). A consequence of these higher temperatures is enhanced atmospheric transport of moisture to high latitudes leading to an increase in precipitation over the Arctic Ocean and terrestrial Arctic regions. Further, permafrost degradation is expected to increase the seasonal thaw depth substantially (AMAP, 2012), which can facilitate additional changes to soil water and related hydrological responses (Couture and Pollard, 2007). These changes ultimately create new hydrological pathways and potential stores that are able to redirect seasonal precipitation and impact soil moisture and river discharge. However, projecting the changes to Arctic hydrological regimes is difficult owing to strong seasonal variability and coarse spatial precipitation patterns among individual GCM.

Generally modeled discharge and suspended sediment transport as a result of warming for Cape Bounty are in agreement with both Arctic (ACIA, AMAP) and global (IPCC) model predictions. Lewis and Lamoureux (2010) assessed the impact of projected changes on the hydrological system to 2100 at Cape Bounty from a warming of 3°C in the A1B scenario and 5°C in the A2 scenario. They determined that summer temperatures, annual river discharge, seasonal runoff, precipitation, and evaporation are expected to substantially increase as the century progresses. Downscaled climate projections resulted in increased thawing days and suggest deeper seasonal thaw and an increase in water-holding capacity as the soils dry out. As Cape Bounty is classed as a nival runoff setting, the increase in precipitation is substantial, doubling and tripling for A1B and A2 scenarios, respectively. However, the model results for Cape Bounty, especially those pertaining to summer rainfall, are limited by the lack of direct precipitation measurements in the Arctic Archipelago and in the modelling process itself. For example, daily averaged discharge data outputted by the model smooth the intensity of rainfall events and diminish the effect of high intensity rainfall events, infiltration, and runoff (Lewis and Lamoureux, 2010). Models such as these often suffer from apparent linearity which is often an artifact of the analysis. Beven (2001) highlights this problem when modellers describe the relationship between effective rainfall inputs and river discharge without recognizing the influence antecedent conditions, rainfall magnitude, and the interaction between the surface and subsurface have on runoff generation. The recognition of this limitation is especially relevant to this study, as rainfall has been shown to produce variable sediment yield responses based on antecedent soil moisture conditions

Overall, current climate models suffer from a lack of spatially resolved precipitation resolution which in turn affects the assumptions that can be made of catchment-level soil moisture. Future models must be robust enough to capture the antecedent soil moisture state in order to accurately predict the suspended sediment mobilization response to major rainfall events. These types of predictions will become increasingly important to model as GCMs suggest not only temperature increases are to come in the coming decades, but also the frequency and magnitude of summer rainfall in the High Arctic (Dugan et al., 2009; Lamoureux, 2000; Lewis and Lamoureux, 2010).

4.7 Conclusions

The results from this study demonstrate the importance of antecedent factors, particularly soil moisture conditions, in determining the runoff and sediment transport response to major summer rainfall events in a small Arctic river. While major rainfall events can generate substantial runoff and sediment transport and have been documented elsewhere, results from this study exemplify the role of antecedent soil moisture conditions to significantly reduce rainfall runoff. Hydrological modelling for this region suggests a future increase in soil moisture and runoff that could have a substantial impact on runoff and the mobilization of sediment in these settings. Continued studies into the contribution of runoff and suspended sediment as a result of rainfall would benefit from closer integration of antecedent soil water conditions to capture the complex rainfall-runoff response.

Chapter 5

Conclusion

In the summer of 2012, a bed-contact survey and suspended sediment sampling program was undertaken at the Cape Bounty Arctic Watershed Observatory, Melville Island, Nunavut. The purpose of the research was to map the transition of the West River (unofficial name) from the onset of the nival melt through to full bed contact to quantify the amount of suspended sediment transported from the West watershed during this period and throughout the remainder of the season. Following the nival melt, an inferred sediment budget was generated for the main channel to identify sediment net source and sink areas of the river. From this work, it was also possible to evaluate the fluvial and suspended sediment mobilization response to major rainfall events, while identifying the factors controlling the magnitude of sediment transport. To support this work, a multi-year analysis of diurnal hysteresis patterns was undertaken to evaluate the long-term changes to suspended sediment transport in the West River.

Three major conclusions can be drawn from this research:

1. Early in the melt season, channel snowpack isolates sources of transportable sediment while flow makes discontinuous contact with the bed. Despite this initial limitation on sediment transport, the rapid establishment of hydrologic connectivity in the river channel mobilized 98% of the seasonal sediment yield in 2012. As the flow wanes into the recession and baseflow, stream competence and wetted perimeter decrease, limiting the amount of sediment mobilized from the catchment. It is therefore a combination of early season snow and late season waning discharge which exert considerable control over sediment transport in the West River through much of the season.

2. Hysteretic and inferred sediment budget analysis show a shift in West River channel dynamics from 2004 to 2012. In 2007, permafrost disturbances impacted the catchment amid exceptionally warm temperatures and late season rainfall and in the headwaters of the catchment, ground-ice exposure and related sediment disturbance released substantial amounts of sediment into the river channel. Multi-year analysis of hysteretic patterns reveals a general shift from clockwise to counter-clockwise diurnal hysteresis, suggesting the river is now mobilizing sediment from a source further upstream of the outlet of the river compared to previous years. These results are consistent with sediment budget results from 2010 and 2012 that reveal the propensity of storage throughout most of the river channel, particularly in upstream reaches close to the large ground ice disturbance. The findings of these analyses indicate the sediment released in the headwaters of West River is likely progressing downstream as a sediment slug and sediment release is dampened by storage and progressive release over 5+ years.
3. Antecedent catchment conditions are important factors over the magnitude of runoff and suspended sediment discharge following late season major rainfall events (MREs). Synoptic level pressure patterns prior to an MRE influence soil drying through incoming solar radiation (and therefore air temperature) and evaporation in the West River catchment. Additionally, should the soil become saturated during an MRE, there is the potential for higher discharge and substantial transport of sediment. However, if the soil does not reach saturation then comparatively little sediment is mobilized, as was the case in 2012.

These research results have contributed to a better understanding of how disturbance, rainfall, and antecedent catchment conditions impact sediment transport in Arctic river systems.

Future work should focus on constraining suspended sediment and discharge during the nival period, inasmuch as this period, which is the most energetic in the short hydrologic season, is often difficult to investigate due to difficult field conditions, particularly challenges to accurately gauge discharge during this period (Veillette, 2011). Moreover, suspended sediment sampling is often difficult during this period, as the flow occurs beneath deep snowpack. Sediment transport during the waning and baseflow periods may benefit from more frequent and extensive suspended sediment sampling in which the spatial sampling distance is substantially reduced. In this way, the resulting change in discharge will be insignificant, thus eliminating the need for extensive discharge monitoring over the length of the river, or for estimated relative discharge calculations.

References

ACIA. (2005). Arctic Climate Impact Assessment. Cambridge University Press, 1042.

AMAP. (2012). Arctic Climate Issues 2011: Changes in Arctic Snow, Water, Ice and Permafrost, SWIPA 2011 Overview Report.

Beel, C.R., Orwin, J.F., & Holland, P.G. (2011). Controls on slope-to-channel fine sediment connectivity in a largely ice-free valley, Hoophorn Stream, Southern Alps, New Zealand. *Earth Surface Processes and Landforms, 36,* 981-994.

Benda, L. & Dunne, T. (1997). Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research, 33,* 2865-2880.

Beven, K. (2001). How far can we go in distributed hydrological modelling? *Hydrology and Earth System Sciences, 5,* 1-12.

Bowden, W.B., Gooseff, M.N., Balser, A., Green, A., Peterson, B.J., & Bradford, J. (2008). Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. *Journal of Geophysical Research, 113,* G02026.

Bracken, L.J. & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes, 21,* 1749-1763.

Brasington, J. & Richards, K. (2000). Turbidity and suspended sediment dynamics in small catchments in the Nepal Middle Hills. *Hydrological Processes, 14,* 2559-2574.

Braun, C., Hardy, D.R., Bradley, R.S., & Retelle, M.J. (2000). Streamflow and suspended sediment transfer to Lake Sophia, Cornwallis Island, Nunavut, Canada. *Arctic, Antarctic, and Alpine Research, 32,* 456-465.

Clifford, N.J., Richards, K.S., Brown, R.A., & Lane, S.N. (1995). Scales of variation of suspended sediment concentration and turbidity in a glacial meltwater stream. *Geografiska Annaler. Series A, Physical Geography, 77,* 45-65.

Cockburn, J.M.H., & Lamoureux, S.F. (2008). Hydroclimate controls over seasonal sediment yield in two adjacent High Arctic watersheds. *Hydrological Processes, 22*, 2013-2027.

Cogley, J.G. & McCann, S.B. (1976). An exceptional storm and its effects in the Canadian High Arctic. *Arctic and Alpine Research, 8,* 105-110.

Collins, A.L. & Walling, D.E. (2004). Documenting catchment suspended sediment sources: problems, approaches, and prospects. *Progress in Physical Geography, 28,* 159-196.

Cook, F.A. (1967). Fluvial processes in the High Arctic. *Geographical Bulletin, 9,* 262-268.

Couture, N.J. & Pollard, W.H. (2007). Modelling geomorphic responses to climate change. *Climatic Change, 85,* 407-431.

Crowe, C.T., Elger, D.F., & Roberson, J.A. (2005). *Engineering Fluid Mechanics.* New Jersey: Wiley & Sons, Inc.

Davie, T. (2008). *Fundamentals of Hydrology.* New York: Routledge.

DeWalle, D.R. & Rango, A. (2008). *Principles of Snow Hydrology.* New York: Cambridge University Press.

Dingman, S.L. (1994). *Physical Hydrology.* New York: Macmillian Publishing Company.

Dugan, H.A, Lamoureux, S.F., Lafernière, M.J., & Lewis, T. (2009). Hydrological and sediment yield response to summer rainfall in a small high Arctic watershed. *Hydrological Processes, 23,* 1514-1526.

Forbes, A.C. & Lamoureux, S.F. (2005). Climatic controls on streamflow and suspened sediment transport in three large middle Arctic catchments, Boothia Peninsula, Nunavut, Canada. *Arctic, Antarctic, and Alpine Research, 37,* 304-315.

French, H.M. (2007). *The Periglacial Environment.* Hoboken: Wiley.

Frey, K.E. & McClelland, J.W. (2009). Impacts of permafrost degradation on arctic river biogeochemistry. *Hydrological Processes, 23,* 169-182.

Fryirs, K.A., Brierley, G.J., Preston, N.J., & Kasai, M. (2007). Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena, 70,* 49-67.

Gilbert, G.K. (1917). *Hydraulic-Mining Debris in the Sierra Nevada.* U.S. Geological Survey Professional Paper 105. Washingston: Government Printing Office

Gordeev, V.V. (2006). Fluvial sediment flux to the Arctic Ocean. *Geomorphology, 80,* 94-104.

Harvey, A.M. (2002). Effective timescales of coupling within fluvial systems. *Geomorphology, 44,* 175-201.

IPCC (2007). Intergovernmeltal Panel on Climate Change. Cambridge University Press.

James, L.A. (1989). Sustained storage and transport of hydraulic gold mining sediment in the Bear River, California. *Annals of the Association of American Geographers, 79,* 570-592.

Klein, M. (1984). Anticlockwise hysteresis in suspended sediment concentration during individual storms: Holbeck catchment; Yorkshire, England. *Catena, 11,* 251-257.

Kuchment, L.S., Gelfan, A.N., & Demidov, V.N. (2000). A distributed model of runoff generation in the permafrost regions. *Journal of Hydrology, 240,* 1-22.

Lamoureux, S.F. (2000). Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian High Arctic recorded in lacustrine varves. *Water Resources Research, 36,* 309-318.

Lamoureux, S.F. (2002). Temporal patterns of suspended sediment yield following moderate to extreme hydrological events recorded in varved lacustrine sediments. *Earth Surface Processes and Landforms, 27,* 1107-1124.

Lamoureux, S.F., & Lafernière, M.J. (2009). Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. *Arctic, Antarctic, and Alpine Research, 41,* 59-68.

Lane, S.N., Richards, K.S., & Chandler, J.H. (1996). Discharge and sediment supply controls on erosion and deposition in a dynamic alluvial channel. *Geomorphology, 15,* 1-15.

Lantuit, H. & Pollard, W.H. (2008). Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. *Geomorphology, 95,* 84-102.

Lawler, D.M., Petts, G.E., Foster, I.D.L., & Harper, S. (2006). Turbidity dynamics during spring storm events in an urban headwater river system: The Upper Tame, West Midlands, UK. *Science of the Total Environment, 360,* 109-126.

Lenzi, M.A., Mao, L., & Comiti, F. (2000). Effective discharge for sediment transport in a mountain river: Computational approaches and geomorphic effectiveness. *Journal of Hydrology, 326,* 257-276.

Lewis, T., & Lamoureux, S.F. (2010). Twenty-first century discharge and sediment yield predictions in a small high Arctic watershed. *Global and Planetary Change*, *71*, 24-41.

Lewis, T., Lafernière, M.J., Lamoureux, S.F. (2012). Hydrochemical and sedimentary responses of paired High Arctic watersheds to unusual climate and permafrost disturbance, Cape Bounty, Melville Island, Canada. *Hydrological Processes, 26,* 2003-2018.

Lewkowicz, A.G. & Wolfe, P.M. (1994). Sediment transport in Hot Weather Creek, Ellesmere Island, N.W.T., Canada, 1990-1991. *Arctic and Alpine Research*, *26,* 213-226.

Lewkowicz, A.G. & Harris, C. (2005). Frequency and magnitude of active-layer detachment failure in discontinuous and continuous permafrost, Northern Canada. *Permafrost and Periglacial Processes, 16,* 115-130.

Lyons, B.W., & Finlay, J.C. (2008). Biogeocheical processes in high-latitude lakes and rivers. . In W.F Vincent & J. Laybourn-Perry (Ed.), *Polar Lakes and River: limnology of Arctic and Antarctic aquatic ecosystems* (pp. 137-156). Oxford: Oxford University Press

Madej, M.A. & Ozaki, V. (1996). Channel response to sediment wave propogation and movement, Redwood Creek, California, USA. *Earth Surface Process and Landforms*, *21,* 911-927.

Mcrae, M.L., English, M.C., Schiff, S.L., & Stone, M. (2010). Influence of antecedent hydrologic conditions on patterns of hydrochemical export from a first-order agricultural watershed in Southern Ontario. *Journal of Hydrology, 389,* 101-110.

McDonald, D.M., & Lamoureux, S.F. (2009). Hydroclimatic and channel snowpack controls over suspended sediment and grain size transport in a High Arctic catchment. *Earth Surface Processes and Landforms, 34*, 424-436.

McKnight, D.M., Gooseff, M.N., Vincent, W.F., & Peterson, B.J. (2008). High-latitude rivers and streams. In W.F Vincent & J. Laybourn-Perry (Ed.), *Polar Lakes and River: limnology of Arctic and Antarctic aquatic ecosystems* (pp. 83-102). Oxford: Oxford University Press.

Miller, M.C., McCave, I.N., & Komar, P.D. (1977). Threshold of sediment motion under unidirectional currents. *Sedimentology*, *24,* 507-527.

Nicholas, A.P., Ashworth, P.J., Kirkby, M.J., Macklin, M.G., & Murray, T. (1995). Sediment slugs: large-scale fluctuations in fluvial sediment transport rates and storage volumes. *Progress in Physical Geography, 19,* 500-519.

Nistor, C.J., & Church, M. (2005). Suspended sediment transport regimen in a debris-flow gully on Vancouver Island, British Columbia. *Hydrological Processes, 19,* 861-885.

Reid, I. & Frostick, L.E. (1994). Fluvial sediment transport and deposition. In K. Pye (Ed.), *Sediment Trnasport and Depositional Processes* (pp. 89-157). Oxford: Blackwell Scientific Publications.

Rowland, J.C., Jones, C.E., Altmann, G., Bryan, R., Crosby, B.T., Geernaert, G.L, Hinzman, L.D., Kane, D.L., Lawrence, D.M., Mancino, A., Marsh, P., McNamara, J.P., Romanovsky, V.E., Toniolo, H., Travis, B.J., Trochim, E., & Wilson, C.J. (2010). Arctic landscapes in transition. *Eos, 91,* 229-236.

Rudy, A.C.A., Lamoureux, S.F., Treitz, P., Collingwood, A. (2013). Identifying permafrost slope disturbance using multi-temporal optical satellite images and change detection techniques. *Cold Regions Science and Technology, 88,* 37-49

Seeger, M., Errea, M.-P., Begueria, S., Arnaez, J., Marti, C., & Garcia-Ruiz, J.M. (2004). Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees. *Journal of Hydrology, 288*, 299-311.

Singh, V. (1992). *Elemental Hydrology*. New Jersey: Prentice-Hall.

Smol, J.P. & Douglas, M.S.V. (2007). Crossing the final ecological threshold in high Arctic ponds. *PNAS, 104,* 12395-7.

Syvitski, J.P.M. (2002). Sediment discharge variability in Arctic rivers: Implications for a warmer future. *Polar Research, 21,* 232-330.

Veillette, M.A. (2011). *Geomorphic and fluvial response to recent permafrost disturbances in a High Arctic river, Cape Bounty, Nunavut.* Kingston, ON.: Faculty of Graduate Studies, Queen's University.

Veillette, M.A., Lamoureux, S.F., & Orwin, J.F. Seasonal sediment dynamics and budget in a High Arctic river subject to recent permafrost disturbances, Cape Bounty, Nunavut. Submitted to *Earth Surface Processes and Landforms,* March 2013.

Walling, D.E. (1983). The sediment delivery problem. *Journal of Hydrology, 65,* 209-237

Webster, J. R., Golladay, S. W., Benfield, E. F., Meyer, J. L., Swank, W. T., & Wallace, J. B. (1992). Catchment disturbance and stream response: an overview of stream research at Coweeta Hydrologic Laboratory. *River conservation and management*, *15*, 232-253.

Woo, M.K. (1983). Hydrology of a drainage basin in the Canadian High Arctic. *Annals of the Association of American Geographers, 73,* 577-596.

Woo, M.K. (2012). *Permafrost Hydrology.* New York: Springer.

Woo, M.K., Kane, D.L., Carey, S.K., & Yang, D. (2008). Progress in permafrost hydrology in the new millennium. *Permafrost and Periglacial Processes, 19,* 237-254.

Woo, M.K. & McCann, S.B. (1994). Climatic variability, climate change, runoff, and suspended sediment regimes in Northern Canada. *Physical Geography, 15,* 201-226.

Woo, M.K. & Sauriol, J. (1980). Channel development in snow-filled valleys, Resolute, N.W.T., Canada. *Geografiska Annaler. Series A, Physical Geography, 62,* 37-56.

Yalin, M.S. and da Silva, A.M.F. (2001). *Fluvial Processes.* Kingston, On: Queen’s University.

Appendix A

Discharge and Suspended Sediment Yields, Cape Bounty, 2003-2012

Year	Seasonal Discharge (mm)	Suspended Sediment Discharge (Mg)
2003	57.2	134
2004	101.0	413
2005	67.0	62.5
2006	159.0	435
2007	126.0	244
2008	114.0	314
2009	107.0	596
2010	89.6	164
2011	--	--
2012	75.1	102

Sources:

2003: Cockburn, J.M.H, & Lamoureux, S.F. (2008). Hydroclimate controls over seasonal sediment yield in two adjacent High Arctic watersheds. *Hydrological Processes, 22*, 2013-2027.

2004-05: McDonald, D.M., & Lamoureux, S.F. (2009). Hydroclimatic and channel snowpack controls over suspended sediment and grain size transport in a High Arctic catchment. *Earth Surface Processes and Landforms, 34*, 424-436.

2006-09: Lewis, T., Lafernière, M.J., Lamoureux, S.F. (2012). Hydrochemical and sedimentary responses of paired High Arctic watersheds to unusual climate and permafrost disturbance, Cape Bounty, Melville Island, Canada. *Hydrological Processes, 26,* 2003-2018.

2010: Veillette, M.A. (2011). *Geomorphic and fluvial response to recent permafrost disturbances in a High Arctic river, Cape Bounty, Nunavut.* Kingston, ON.: Faculty of Graduate Studies, Queen's University.

Appendix B

Location of Suspended Sediment Sampling Points, 2010 & 2012

Name of Sampling Point (Original Researcher's Name, Year) (Ordered from upstream to downstream)	Geographic Location	UTM (WGS84, Zone 12x) (Easting, Northing)
Station 4 (M. Veillette, 2010)	74°55'41"N, 109°37'8"W	Not Available
Sediment Sample A (E. Favaro, 2012)	74°55'38"N, 109°36'56"W	0540173, 8315993
Sediment Sample B (E. Favaro, 2012)	74°55'31"N, 109°36'42"W	0540302, 8315760
Station 3 (M. Veillette, 2010)	74°55'13"N, 109°36'30"W	Not Available
Sediment Sample C (E. Favaro, 2012)	74°55'7"N, 109°36'30"W	0540501, 8314655
Sediment Sample D (E. Favaro, 2012)	74°54'55"N, 109°36'20"W	0540501, 8314655
Station 2 (M. Veillette, 2010)	74°54'47"N, 109°36'10"W	Not Available
Sediment Sample E (E. Favaro, 2012)	74°54'41"N, 109°36'6"W	0540821, 8313843
Sediment Sample F (E. Favaro, 2012)	74°54'29"N, 109°35'42"W	0540735, 8313711
West River Station (Sample G) (S. Lamoureux, 2003)	74°54'15"N, 109°36'10"W	0540611, 8313261

Appendix C

Glossary

Active Layer Detachments (ALD): A type of permafrost disturbance (see “Permafrost”) characterized by the sudden downslope movement of thawed soil and its vegetation cover.

Discharge: The amount of flow passing through the cross-section of a conduit, such as a water channel, per unit time. Denoted by Q and measured in cumecs, or m^3/s.

Hysteresis: A visual representation of the relationship between suspended sediment concentration and discharge over a discharge event. Hysteretic analysis is useful in investigating the sediment availability and accessibility in a catchment over a discharge event.

Melting Degree Day (MDD): The cumulative sum of positive temperatures for those days which exceed 0°C.

Major Rainfall Event (MRE): Any rainfall event in the Cape Bounty record which records at least 6 mm of rainfall with no more than a 6 hour gap between consecutive rainfall inputs.

Permafrost: Ground material which sustains temperatures at or below 0°C over at least two consecutive years.

Runoff Ratio (RR): The proportion of runoff to inputs from snowmelt and/or rainfall for a given event.

Suspended Sediment Concentration (SSC): The amount of material suspended in a known volume of solution, usually water.