HYDROLOGIC CONTROL ON PROGLACIAL SUSPENDED SEDIMENT DYNAMICS

By

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Abstract

Measuring suspended sediment concentration (SSC) is both costly and labour intensive. Temporal records of SSC are, however, of paramount importance in elucidating issues relating to geomorphology, ecology and water quality. Rating curves, that relate SSC and discharge by a simple linear regression function, are frequently employed by workers to address the problems of recording SSC. Such functions, however, rarely account for more than 50% of the variability in observed SSC. The aim of this thesis is to formulate sub-seasonal predictive SSC models and to investigate hydrologic controls on proglacial suspended sediment dynamics using data collected from a glacier-fed stream, Coast Mountains, British Columbia.

In order to model proglacial SSC, the hydrologic season was initially divided into nival, nival-glacial, glacial and autumn recession periods, according to sudden shifts in the ratio of stream discharge between the glacierised and a neighbouring unglacierised catchment of similar size and aspect. Multiple regression functions, to predict SSC, were then developed for each period. These regression models incorporate a suite of easily measured variables and are shown to reduce significantly, initial problems of autocorrelation, heteroskedasticity and non-linearity of the SSC-discharge relationship. Analysis of the significant parameters in the multiple regression models, the hysteretic relationship between SSC and discharge, and downstream changes in SSC reveal that short-term, within channel, storage of fine sediment may be an important control on proglacial suspended sediment dynamics in this complex glaciofluvial lacustrine system.

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Chapter 1
Introduction

Temporal variations in suspended sediment transport have received considerable attention. Such studies have traditionally been spurred by geomorphic interests in, for example, global sediment yield to oceanic basins (Milliman and Syvitsky, 1992), estimates of landscape denudation rates (Collins, 1998), models of sediment transport (Syvitski *et al.*, 2000; Picouet *et al.* 2001) and relative rates of glacial and non-glacial erosion (Hicks *et al.*, 1990; Harbor and Warburton, 1993; Hallet *et al.* 1996). Suspended sediment is, however, also important from an ecological and water quality perspective because it can alter water chemistry and cause temperature decreases and turbidity increases (Ryan, 1991). In particular, Richardson *et al.* (2001) stressed that high turbidity levels decrease upstream fish migration and thus species' populations.

Most studies of alpine proglacial suspended sediment dynamics have concentrated on glacial erosion processes inferred from measurements of suspended sediment concentration (SSC), discharge (Q) and electrical conductivity (EC) made within close proximity of the glacier terminus. From initial studies of proglacial SSC in the 1950s, when "almost nothing was known of the seasonal variation in sediment concentration of glacial streams" (Matthews, 1956), the literature has grown extensively, incorporating North American, European, Asian and Arctic based studies (e.g. Collins, 1979; Hammer and Smith, 1983; Gurnell and Fenn, 1984; Gurnell *et al.*, 1994; Willis *et al.*, 1996; Collins, 1998). Relatively few investigations, however, have focused directly on downstream transport and storage of glacier-derived sediment. Intuitively, it would seem that the next step is to conduct a study that provides an integral understanding of the temporal and spatial link between glaciers and downstream hydrology and suspended sediment transport. This thesis is an attempt to achieve this link by presenting results of an investigation of temporal and spatial changes in the hydrology and suspended sediment transport of a retreating cirque glacier system in the Coast Mountains, British Columbia. Under conditions of sustained glacier retreat, the delivery of water, sediment and dissolved substances by proglacial stream systems to downstream reaches will undoubtedly change, and will likely have ecological impacts. Thus the study of these processes is of great environmental and academic importance.

Sections 1.1 and 1.2 provide a focused literature review and identify knowledge gaps that this thesis will aim to fill through the objectives stated in Section 1.3. Section 1.1 concentrates on the delivery of water and sediment from alpine headwaters to downstream reaches. Section 1.2 focuses on attempts to model proglacial glacier-derived water and suspended sediment dynamics.

1.1 Alpine hydrology and suspended sediment transport

An appreciation of hydrology is required to understand suspended sediment transport, because sediment input to a stream will occur where hydrologic contributing areas and sediment source areas overlap. In addition, the mode of runoff generation can control the erosion process. For example, the kinetic energy of rainfall on snow-free ground can detach soil particles, rendering them vulnerable to transport, while the presence of snow cover protects the soil surface.

Alpine seasonal hydrographs are typically characterised by spring snowmelt and, where basins are glacierised, late spring and summer glacier melt sources of water.

Throughout the season, flows may also be punctuated by short-term rainfall-driven storm runoff events.

Net radiation and sensible heat transfer provide the dominant mechanisms for snow and ice melt (Hannah and McGregor, 1997). During the nival season, meltwater slowly percolates to the ground through the porous snowpack and then travels as overland or subsurface flow to the stream channel. Discharge typically peaks late in the evening or early in the morning because of routing delays through the snowpack. The rising limb of a diurnal snowmelt hydrograph is thus controlled by melt rates and the falling limb by storage characteristics of the basin (Singh *et al.*, 2000). In mountain catchments, hydrologic contributing areas tend to be dominated by snowmelt in the lower elevation zones at the beginning of the spring. Indeed, the higher zones may experience snowfall while lower zones experience rain and melt. As air temperatures and energy supply increase through the season, the zone of active snowmelt progresses to higher elevation zones. The lower boundary of the active contributing area is dictated by the snowline elevation, which also tends to progress upslope. Thus, the active hydrologic contributing area progresses systematically upslope through the nival melt season. Glaciers tend to be located in the higher elevation zones, and thus become hydrologically active in mid- to late summer. Once most of the non-glacial snowcover has melted, streamflow would be dominated by glacier melt contributions. During the glacial melt season, the daily pattern of discharge is driven by diurnal variations in energy input. Discharge consists of baseflow (subglacial meltwater, water stored in cavities, meltwater percolating through snow and groundwater (Röthlisberger and Lang, 1987)), superimposed by a daily cycle consisting of a rapid subglacial meltwater routing component and a supraglacial component (Benn and Evans, 1998).

The hydrologic effect of rain events may depend on storm characteristics (particularly air temperatures). During cool storms, precipitation may fall as snow at higher elevations, so that only lower elevation bands may generate rainfall runoff. The quantity of rainfall runoff generated will also depend on soil moisture conditions. Where soils are wet (e.g. areas that are experiencing active snowmelt or that have only recently become snow-free), generation of rainfall runoff may be relatively efficient. However, if an area has been snow-free for a period of warm, dry weather, the resulting soil moisture deficit may effectively limit runoff generation. Added to these factors is the fact that precipitation tends to increase with elevation. Thus, the hydrologically active contributing area for rain events may vary in complex ways from storm to storm, as opposed to the seasonally progressive nature of contributing areas for snowmelt.

During the ablation season, fine sediment evacuated from the glacier subsole is transported as suspended load in proglacial melt streams. Several studies have also highlighted the significance of the bed (Østrem, 1975; Hammer and Smith, 1983; Gurnell *et al.*, 1999) and dissolved (Barsch and Caine, 1984) components of sediment load in high mountain rivers, but these components of sediment load were not measured in this thesis and the focus will be on suspended sediment. Temporal variability of proglacial SSC is frequently claimed to result from the interaction between discharge fluctuations and accumulation of sediment at the glacier base, as the subglacial drainage system develops through the season (Collins, 1998). Proglacial lakes are, however, also important because they act both as sediment traps and buffers to daily SSC fluctuations. Weirich (1985), for example, formulated a sediment budget for a high-energy glacial lake in southeastern British Columbia. The study stressed that SSC was much lower and varied less in the outlet than inlet stream. Several anomalous spikes of SSC were, however, recorded and concluded to be the product of overflow events.

The spatial variability of SSC beyond glacier margins has, however, not been studied greatly. Gurnell (1982) investigated downstream changes in SSC in order to highlight the importance of sampling location, but the study focused on tributary sediment sources. More recently, Lenzi and Marchi (2000) argued that, during flood events in a steep alpine stream, within-channel suspended sediment sources provided a significant proportion of sediment loads during storms. No data were provided to substantiate this claim and the study was only located at one downstream sampling site. There is a need, therefore, for more intense seasonal monitoring programmes at both up and downstream SSC sampling locations.

Attempts to link alpine runoff sources to suspended sediment transport in mountain streams have been made in the literature. In a Norwegian study comparing suspended sediment transport during glacial melt and rainfall-dominated runoff, Richards (1984) concluded by proposing that different hydrologic source areas determined the dynamics of sediment quantities and particle sizes. Chikita (1993) examined seasonal changes in SSC in a snowmelt fed river in western Hokkaido, Japan. In that study it was discovered that as the snowmelt season progressed, SSC decreased for a given value of discharge because of an upslope decrease in the supply of bank sediment. Finally, Lenzi and Marchi (2000) suggested that for unglaciated alpine basins, suspended sediment transport takes place at low discharge during snowmelt because erosion processes consist of the removal of loose, fine-grained material from slopes by surface runoff. Except for large floods when bank failure may contribute much sediment to the channel, low discharges during summer and autumn rainfall storms were seldom found to transport suspended sediment because of snowmelt depletion of sediment loosened during the previous winter. If diurnal through to seasonal scale downstream SSC dynamics are to be understood, further investigations of the link between suspended sediment transport and hydrologic source area must be made.

1.2 Modelling proglacial SSC

High values of SSC can occur under the following conditions: (1) at the start of the ablation season, when there is an extensive supply of glacially eroded basal sediment that has accumulated over the winter; (2) during large melt events when the capacity of the subglacial drainage system to transport sediment increases; and (3) during rain-induced events (Richards, 1984). Periods of relatively low SSC are caused by exhaustion of suspended sediment supply on diurnal (Collins, 1979), synoptic (Gurnell, 1987) and seasonal timescales (e.g. Østrem, 1975). In order to predict SSC these factors must be accounted for.

Stream SSC is both a labour intensive and time-consuming variable to measure. In the absence of a continuous (hourly) sampling programme, the simplest and most widespread procedure adopted is to construct a suspended sediment rating curve derived from observations of SSC and Q. A rating curve consists of a graph relating SSC and Q. From the equation of the resulting curve, which is typically a power function, SSC can be calculated from a continuous record of Q. In this way rating curves can be used to interpolate and extrapolate measured SSC time series.

Applicability and accuracy of suspended sediment rating curves are, however, highly questionable. Although errors may stem from inaccurate field and laboratory procedures, much of the scatter in the SSC-Q rating plot can be explained by: (1) seasonal variations in sediment availability, associated with early season flushing and late season exhaustion of sediment supply (Østrem, 1975), (2) hysteresis effects related to variations in sediment supply on the rising and falling limbs of diurnal flow cycles (Collins, 1979, Bogen, 1980), and (3) sediment supply dynamics associated with rainfall induced flow events (Richards, 1984, Stott and Grove, 2001).

Various methods used to overcome problems with suspended sediment rating curves have been adopted extensively in the literature. Principally, these problems are autocorrelation in the residual series and the non-normal distribution of error terms. Gurnell and Fenn (1984) and Fenn (1989) accounted for the former by using univariate AutoRegressive Integrated Moving Average (ARIMA) stochastic time series models of Q and SSC. Although predictions based on ARIMA models were superior to the original rating functions, ARIMA modelling has not been adopted extensively in the literature because a detailed series of uniformly spaced observations is needed. In order to normalise the error distribution, logarithmic transformation of the Q and SSC series is common. Ferguson (1986, 1987), however, stressed that such transformations, when back-transformed to a rating curve, lead to underestimation of SSC, by up to 10 to 50% (Asselman, 2000), because the residual term is additive in a power function non-linear regression model and multiplicative in a log-transformed model. One of the properties of a regression function is that it must pass through the arithmetic and geometric means for non-linear and log-transformed models, respectively. Because geometric means are systematically lower than arithmetic means, the log-transformed equation underestimates true values of SSC because of the bias afforded to lower values of SSC (Walling, 1977; Jansson, 1985). Miller (1984) proposed a bias correction factor to reduce the transformation bias that arises when regressions of natural logarithms are detransformed.

Separate rating curves can also be fitted to different ablation seasons, for specific sub-periods within ablation seasons and for conditions of rising and falling discharge only (e.g. Fenn *et al.*, 1985; Gurnell *et al.*, 1992a). This approach allows for changing sediment availability and supply dynamics to be partly accounted for. Methods used to sub-divide seasonal discharge hydrographs are, however, subjective and have been a result of 'hydrological judgement' (Hannah *et al.*, 2000). Hodgkins (1996), for example, described his method of division as "arbitary" and provided no quantitative justification. In another case, Hodson *et al.* (1998) based their sub-seasonal divisions on changes in the amount of energy delivered to the basin and on the position of the transient snowline. Hannah *et al.* (2000) attempted a more statistical approach to the classification of the shape and magnitude of diurnal hydrographs using a combination of principal components analysis and cluster analysis. Nine different classes of hydrograph classes were developed using these techniques, but the division of discharge series into their relevant class was subjective.

Recently, workers have developed multivariate rating equations that incorporate additional explanatory variables such as the rate of change of discharge, cumulative discharge and hourly precipitation (e.g. Hodgkins, 1999; Hodson and Ferguson, 1999). Generally, though, such complex rating equations contain variables derived from measured SSC (e.g. lagged values of SSC) and so independent model validation is uncommon because of the time and cost involved in measuring the predictor variables.

1.3 Objectives

Drawing from the knowledge gaps identified in the preceding literature review, the objectives of this thesis are: (1) to investigate whether and how the SSC-Q relation varies with changing hydrologic conditions in a glacier-fed mountain catchment, (2) to evaluate the use of multiple regression models for predicting SSC, and (3) to investigate the significance of channel storage on the downstream delivery of suspended sediment. Data from a glacier-fed stream in the Coast Mountains, British Columbia, Canada, will be used to fulfil these objectives. A neighbouring creek draining an unglacierised basin will be used as a reference basin with which to aid interpretation of discharge and SSC series in the glacierised basin.

1.4 Thesis outline

Details of the study area and methods are presented in Chapter 2. In Chapter 3 the results of the investigation are presented. Firstly, discharge and SSC time series for both basins are analysed over the 2000 season and then attention is drawn to the glacierised basin. The seasonal hydrograph is separated and for each sub-season, multiple regression models are developed to predict SSC. Hysteresis in the SSC-Q relation is examined on diurnal, synoptic and seasonal timescales. Finally an upstream-downstream comparison of SSC is undertaken for two diurnal data series. Chapter 4 discusses the hydrologic control on SSC within Place Creek on diurnal, synoptic and seasonal scales, and addresses the importance of adopting an integrated approach to such timescales. Multiple regression models for predicting SSC are then assessed. Chapter 5 summarises the key findings of the thesis and makes suggestions for future research.

Chapter 2
Study Area and Methods

2.1 Regional context

2.1.1 Climate

The winter climate of coastal British Columbia is dominated by successions of midlatitude cyclones which move onshore from the Pacific Ocean. Associated frontal activity provides over 60% of annual precipitation from November-March in the south coastal region (Moore and McKendry, 1996). Mean annual precipitation averages more than 3500 mm at high elevations within the Coast Mountains, but in the valleys ranges from 1500 to 2500 mm. The study basins in this investigation are, however, located within a transitional zone from a strong maritime to dry interior influence, where annual precipitation ranges from 750 to 1000 mm at valley sites. In the study area, mean monthly air temperature ranges from 0 to –5 °C in January and from 18 to 20 °C in July (Farley, 1979).

2.1.2 Geology

The Coast Mountains lie along a northwest band of Cretaceous and Tertiary plutonic and metamorphic geology. The topography is dominated by glacial landforms. The study basins lie on granodiorite and dacite-pyroclastic rocks, and so are typical of the regional geology.

2.1.3 Vegetation

From the coast to the study area, the dominant vegetation changes from Coastal Douglas Fir to Coastal Western Hemlock in the valleys and from Subalpine Mountain Hemlock to Subalpine Engelmann Spruce at higher elevations. Within the Coast Mountains the tree-line ranges from 1500 to 2000 m (Ryder and Thomson, 1986).

2.1.4 *Glacial influences on hydrology*

The majority of glaciers within the Coast Mountains reached their maximum Holocene extent during the 1800s and have since experienced overall recession punctuated by short periods of advance (Ryder and Thomson, 1986). Few studies have examined the contribution of glaciers to streamflow in the Coast Mountains. Moore (1993), however, used a conceptual model to estimate that for the Lillooet River in the southern Coast Mountains, over 50% of total basin runoff in August is derived from glacial melt. The glacial cover of the Lillooet River basin is approximately 17%.

2.2 Study basins

Figures 2.2 to 2.4 illustrate the topography, vegetation and geology of both study basins.

2.2.1 *Place Creek*

Place Creek (PC) is located approximately 140 km north of Vancouver in the southern Coast Mountains, British Columbia, Canada (Figure 2.1). Its basin faces northwest and has an area of 13 km^2 (Figure 2.2). In 1965 Place Glacier had an area of 3.98 km^2, when a mass balance study was instigated as part of the International Hydrological Decade. In 1987 the glacier was 3.4 km^2. Evidence from air photographs indicates that from 1982 to present, a series of three proglacial lakes has formed within 200 m of the glacier terminus. Place Creek originates at the outlet of the largest of these lakes (Figure 2.5), Place Lake, and flows along a steep channel for 4 km to the valley below. Large boulders dominate the bed morphology of Place Creek, except over a short braided section about halfway down the creek where the channel gradient declines. Channel width ranges from approximately 4 to 5 m (Figure 2.6) at the gauging site.

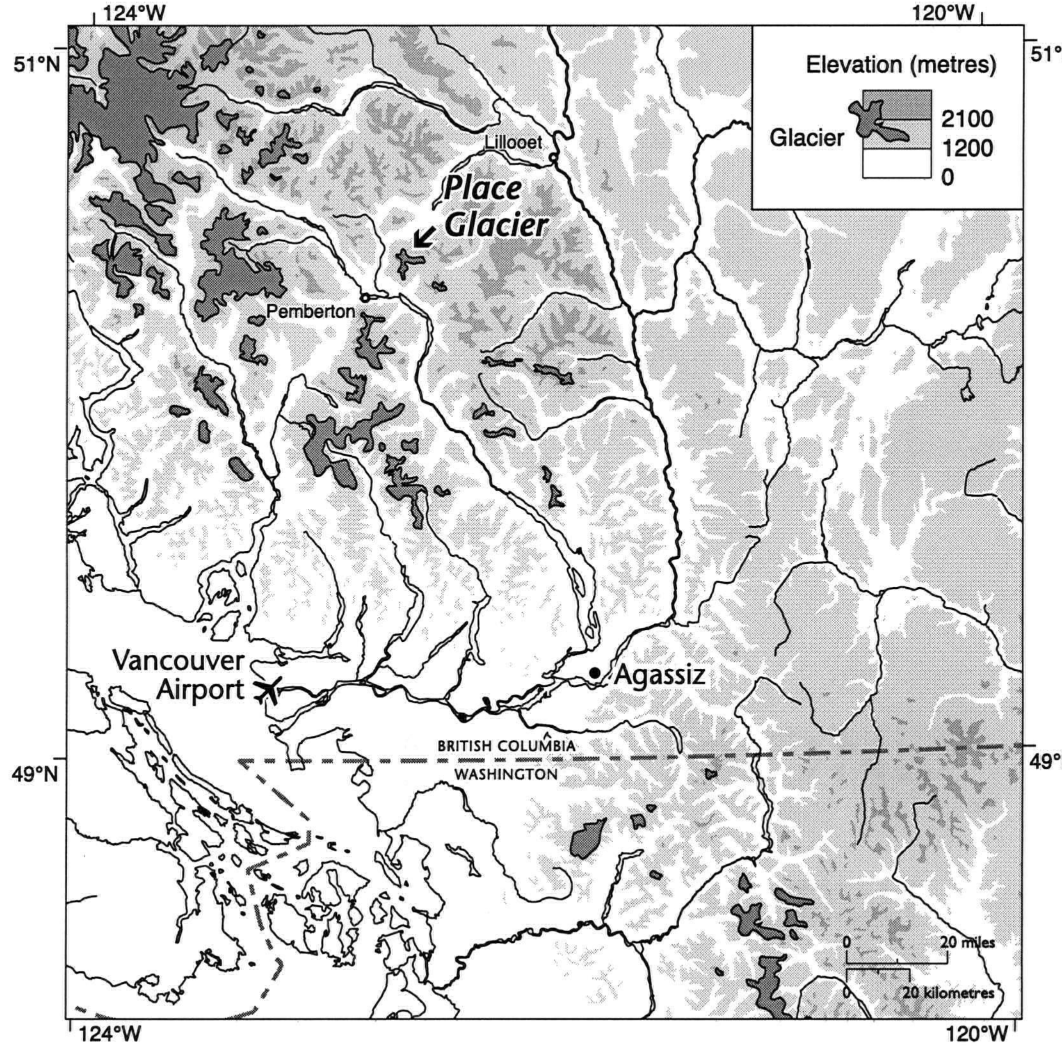


Figure 2.1: Location map of study area (provided courtesy of E. Leinberger, Department of Geography, University of British Columbia).

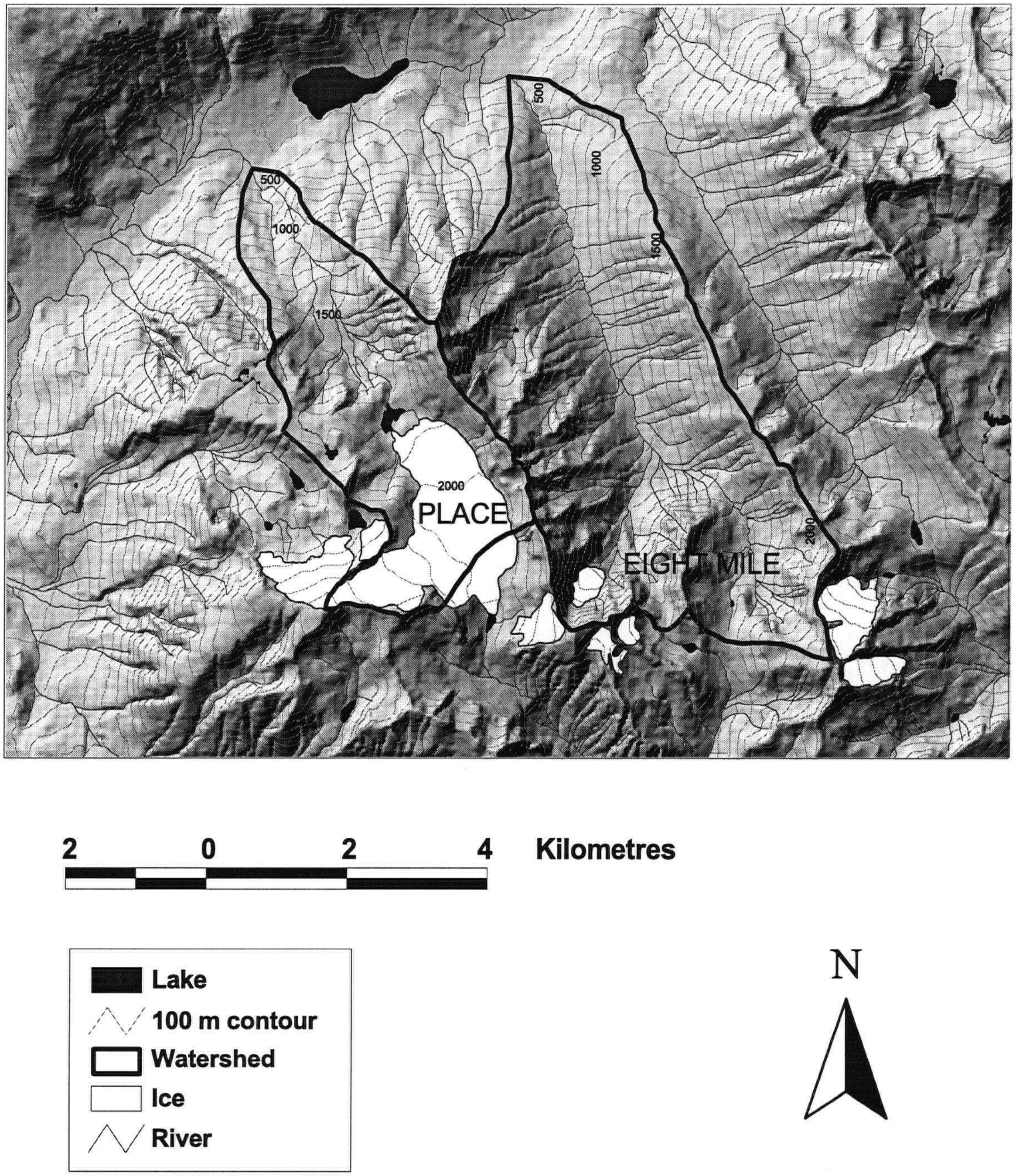


Figure 2.2: Map showing drainage areas (based on data from 1987) for Place and Eight Mile Creeks.

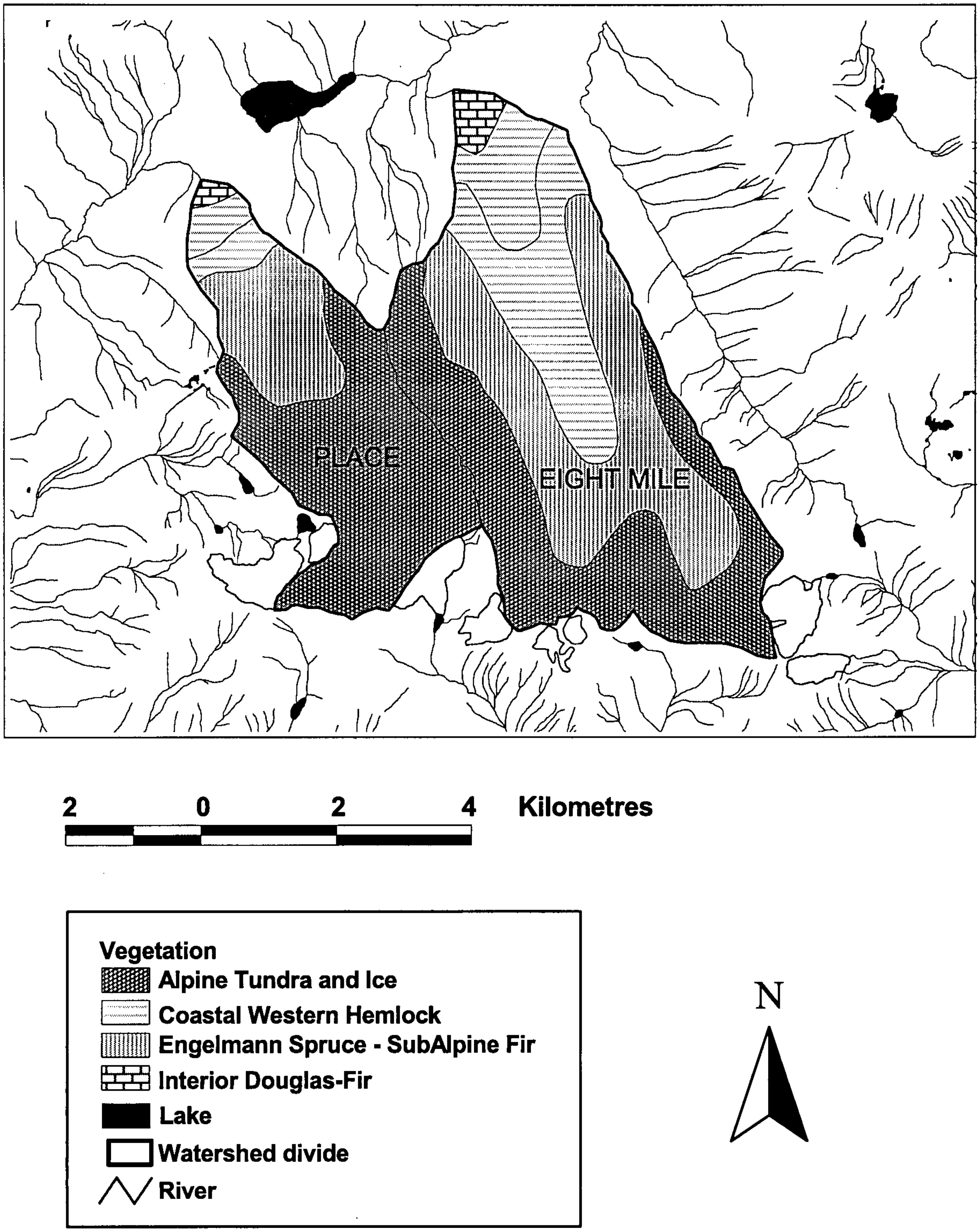


Figure 2.3: Vegetation in drainage basins for Place and Eight Mile Creeks (based on 2001 data from Ministry of Forests, Government of British Columbia).

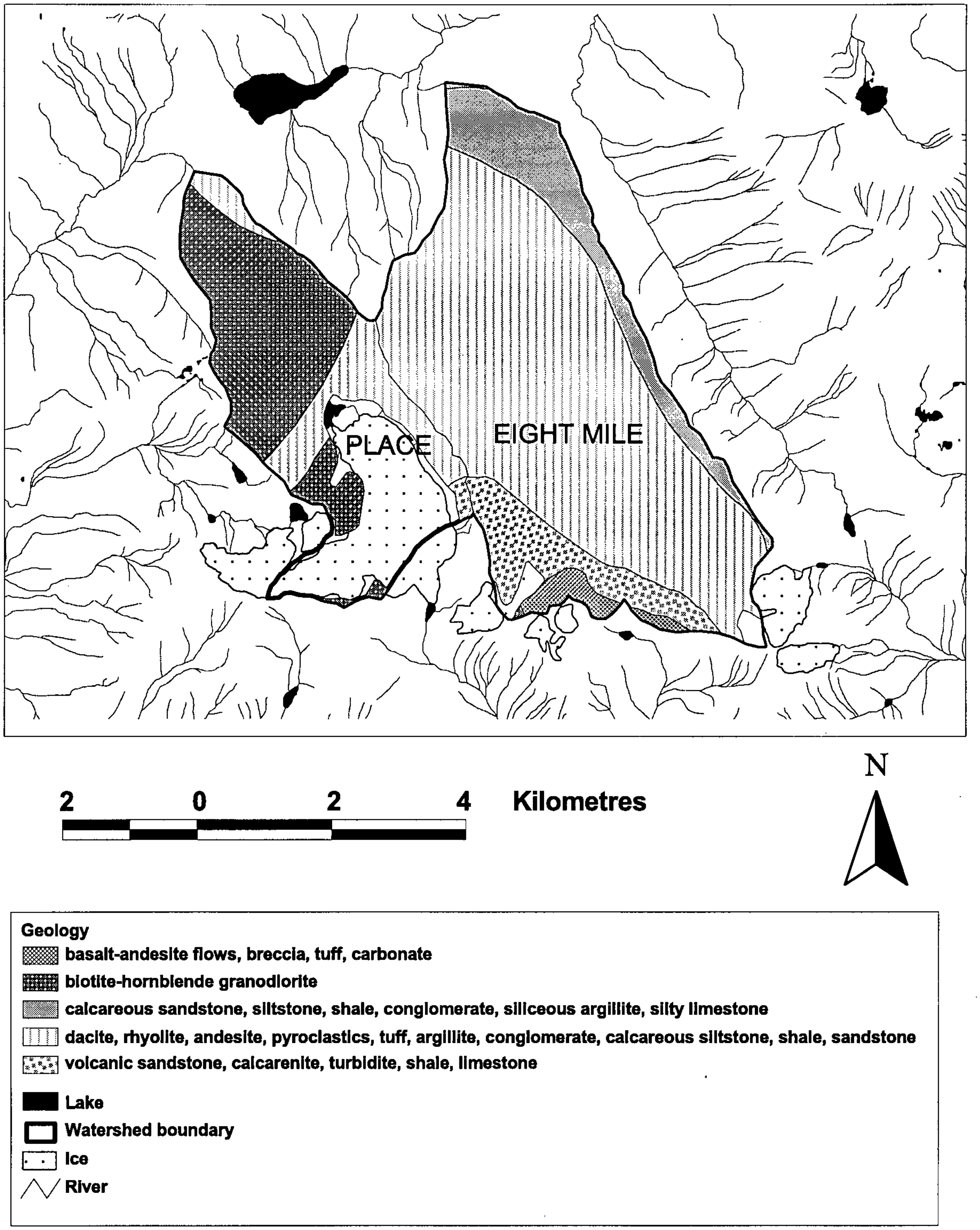


Figure 2.4: Geology of Place and Eight Mile basins (based on data courtesy of Dr. Journey, Geological Survey of Canada).

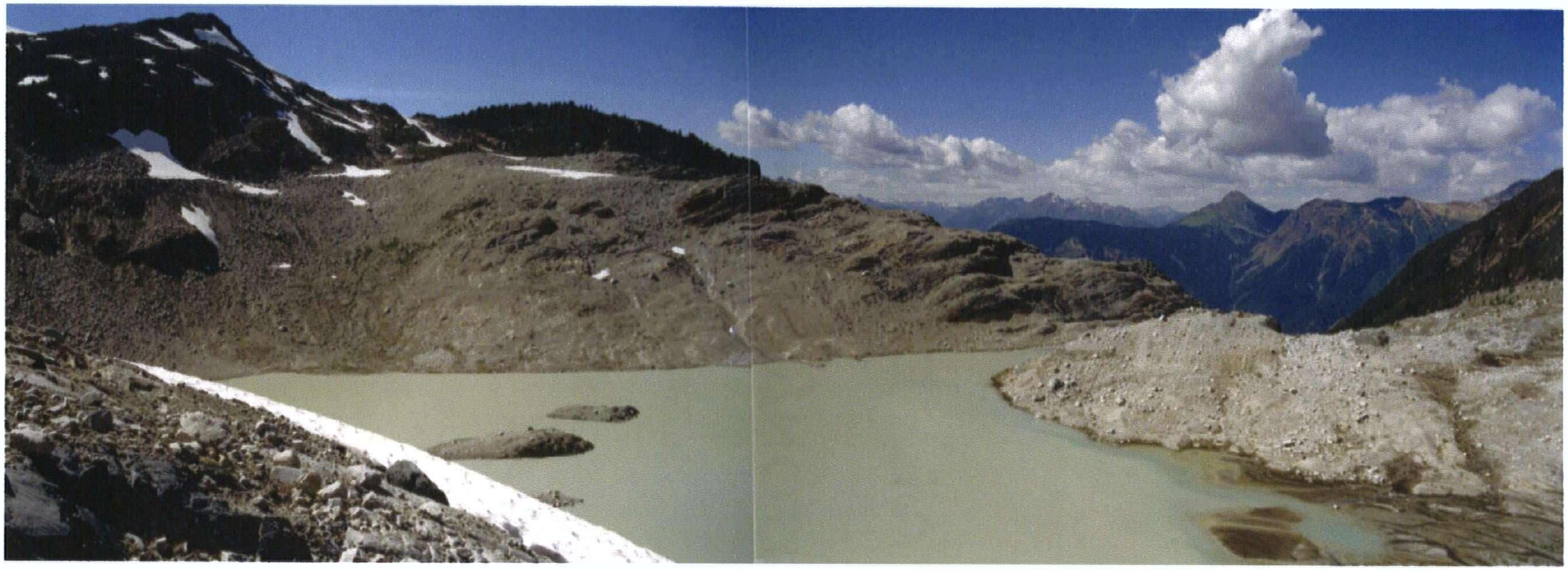


Figure 2.5: Place Lake. A braided stream flows from a small lake at the terminus of Place Glacier into the Place Lake on the right side. Place Lake outlet is on the far side.

Figure 2.6: Place Creek in the valley bottom during spring snowmelt.

The tree-line within the basin is at approximately 1800 m, above which Alpine Tundra vegetation dominates. Below the tree-line, land is forested with Engelmann Spruce and Sub-Alpine Fir from 1000 to 1800 m, Coastal Western Hemlock from 700 to 1000 m and Douglas Fir below 700 m (Figure 2.3).

The geology of the basin is dominated by a dacite-pyroclastic complex above 2000 m and granodiorite below 2000 m (Figure 2.4). Most of the sediment produced from glacial erosion is thus derived from the former, while down-basin sediment sources originate from the latter, more resistant rock.

2.2.2 Eight Mile Creek

The basin containing Eight Mile Creek (EM) neighbours Place and also faces northwest (Figure 2.2). It has an area of 25 km^2 and is essentially unglacierised, except for a small portion of residual ice (0.18 km^2) in the southwestern corner (Figure 2.2). Figure 2.2 was constructed using TRIM data from 1987 and it is probable that the area of ice cover is currently even smaller. Therefore, this ice likely has an insignificant hydrological influence at present.

From its headwaters to the valley below, Eight Mile Creek also flows along a high gradient boulder-dominated channel that contains frequent large woody debris jams. Near the gauging station the channel width varies from 4 to 6 m (Figure 2.7). The basin is actively logged at present and a 5 km logging road that has three minor tributary roads stretches from the mouth to approximately half way along the length of the basin. The effect of logging on streamflow characteristics was not, however, investigated. Below the measurement site, the

Figure 2.7: Eight Mile Creek at low flow

creek joins Gates Creek, which flows northeast from Gates Lake. Vegetation for the basin is as described in Sub-section 2.2.1.

The geology of Eight Mile is approximately 75% dacite-pyroclastics. The lowest portion of the basin is a less-resistant and more permeable sandstone and conglomerate, while the highest portion is mostly tuff and volcanic sandstone (Figure 2.4). Thus, although Place and Eight Mile are neighbouring basins, their dominant geology is different.

2.3 Streamflow measurement

2.3.1 Stage measurement

Stage was recorded at stable gauging sites (established at Place Creek by RD Moore in 1999 and at Eight Mile Creek by RD Moore and the author in 2000) with a Campbell Scientific CR10X datalogger attached to a submerged Keller PSI pressure transducer that was housed in a stilling well secured firmly in the stream. Stage was measured every 10 seconds and averaged every 10 minutes. Stage was also measured manually, from the top of the stilling well to the water level within it. An insulated wire attached along the length of a ruled steel rod was connected to a multi-meter and stage was recorded by eye when resistance changed from an off-scale reading as the exposed end of the wire touched the water and completed the circuit. These measurements provided a check on the stability of the data logger-transducer system.

2.3.2 Discharge measurement

For small creeks with steep channel gradients and boulder-bed morphologies, salt dilution gauging has become the preferred gauging technique over the traditional velocity-area method (Elder *et al.*, 1990). For Place Creek and Eight Mile Creek, 5 L of salt solution, approximately 100 g/L, was injected as a "slug." Stream electrical conductivity was measured approximately 75 m downstream from the injection point to allow complete mixing of the solution. From measurement of the conductivity wave as it travelled downstream, and background conductivity, discharge was calculated from

$$Q = \frac{fV_s}{(EC_{ave} - EC_b)D}, \tag{2.1}$$

where Q is stream discharge, f is the slope of the relation between EC and relative concentration, determined by field calibration, V_s is the volume of the injected salt solution, EC_{ave} is the average conductivity during the salt wave passage, EC_b is the background conductivity and D is the duration of the salt wave at the measurement point.

2.3.3 Rating curves

Stage-discharge rating curves were established for Place Creek (Equation 2.2) using 20 salt dilution gauges from 2000 and 5 from 1999 and for Eight Mile Creek using 19 salt dilution gauges from 2000. A shift in the Eight Mile rating curve required two rating relations to be established (Equation 2.3a for the original relation and 2.3b for the adjusted relation). All rating curves were fitted using the power function non-linear trendline tool in Excel2000.

$$Q = 1.383S^{1.856} \tag{2.2}$$

$$Q = 0.284S^{2.485} \tag{2.3a}$$

$$Q = 0.688S^{1.878}, \tag{2.3b}$$

where Q is discharge (m^3/s) and S is stage (mV). The rating relation scatter plots are shown in Figure 2.8.

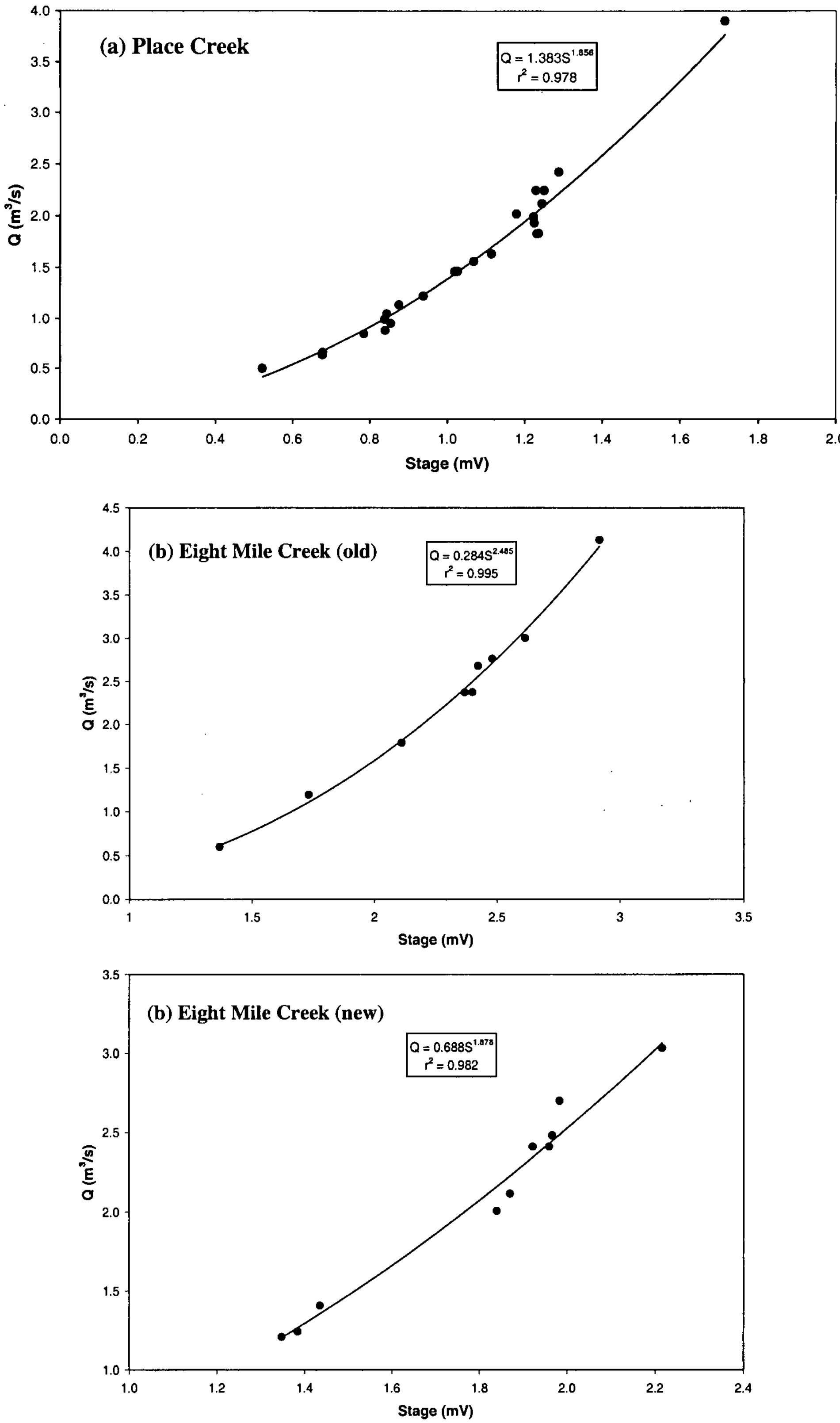


Figure 2.8: (a) Place Creek and (b) Eight Mile Creek stage-discharge rating relations. Eight Mile has two plots (old and new) because of a shift in the original rating curve resulting from movement of the stilling well during high flows in early July 2000.

2.4 Suspended sediment concentration

The objectives of this thesis did not require sampling SSC at a fixed interval. Rather, a range of sample intervals, over a number of field campaigns from mid-May through to the beginning of October, was employed to capture a variety of hydrologic conditions. Sample intervals thus ranged from 1 to 12 hr, during various periods of the field season. Stream water samples of 150 to 200 mL were collected at the gauging sites, at Place Creek and Eight Mile Creek, using an ISCO (model 2900) automatic pumping water sampler which was located on the channel bank. The intake of the 7.6 m of Teflon1 ISCO hose was fixed in the stream cross-section, approximately 1 m from the bank. Sample volumes were measured to ±1 mL using a 250 mL cylinder before being vacuum filtered by a hand pump through individually pre-weighed numbered 0.7 μm glass-fiber filters. Care was taken to ensure that no sediment remained in either the cylinder or sample bottle by rinsing both with the filtrate and re-filtering using the same filter. Sediment-laden filters were stored in individually marked sample bags. Filters were oven-dried in the laboratory at 105°C for 1.5 hr, both before and after being used in the field. Mass of dry sediment was obtained using an electronic balance, by subtraction of the original mass from that of the dried sediment laden filter.

Organic proportions of SSC were determined by ashing the dry sediment laden filters at 550°C for 1.5 hr and subtracting the mass of the ashed from the pre-ashed filter. Adjustment for loss in water of hydration when ashing filters at 550°C was calculated from the average loss in mass of 30 randomly selected ashed sample filters, from each site, that had been used in the field and recorded a SSC of 0 mg/L.

It is noted widely in the literature that proglacial streams are highly turbulent and that fine suspended sediment is, therefore, well-mixed in the vertical and horizontal water profiles (Gurnell *et al.*, 1992b; Wren *et al.*, 2000). Such claims support the use of fixed depth sampling in this thesis. To substantiate such inferences, 32 DH48 depth-integrated samples were taken at various times within the season on either side of the cross-section of Place Creek in which the ISCO intake hose was fixed. From the right bank, 24 samples were taken, but only eight were taken from the left bank because of difficulties in crossing the stream at high flows. All filtering and laboratory procedures followed those described earlier in this section.

Samples from the outlet of Place Lake were taken using an improvised depth-integrated grab technique, where 500 mL polyethylene bottles were lowered and raised by hand, at an arm's length, through approximately 80% of the water depth with the bottle neck facing upstream. Sample volumes were approximately 300 mL. Again, subsequent filtering procedures were conducted as described for Place Creek.

2.5 Water chemistry

2.5.1 Electrical conductivity

Electrical conductivity (EC) of the ISCO water samples was measured using a WTW LF 340 EC probe, which corrected EC to 25°C using a non-linear function. The EC of sampled stream water containing fine sediment may, however, continue to change because of solute acquisition from water-rock flour chemical reactions (Brown *et al.*, 1994; Brown *et al.*, 1996). Periodic spot measurements of stream EC were thus conducted at the same time as samples were being collected by the ISCO sampler. The relation between EC of the ISCO samples and stream water followed the functions

$$EC_{PC} = (1.015 \cdot EC_{ISCO_{PC}}) - 0.438 \qquad (r^2 = 0.996, \text{SEE} = 0.3, n = 17) \qquad (2.4)$$

$$EC_{EM} = (1.056 \cdot EC_{ISCO_{EM}}) - 4.563 \qquad (r^2 = 0.992, \text{SEE} = 0.5, n = 6), \qquad (2.5)$$

where EC_{PC} and EC_{EM}, and $EC_{ISCO_{PC}}$ and $EC_{ISCO_{EM}}$ are the EC of Place Creek and Eight Mile Creek, and of the ISCO samples at Place and Eight Mile Creek, respectively. Although time between ISCO stream sampling and EC_{ISCO} measurement varied from 5 minutes to 1 week, Equations 2.4 and 2.5 provide calibration factors to adjust for any post-sampling geochemical reactions.

2.5.2 Cations and anions

Stream samples for chemical analyses were taken throughout the season at Place and Eight Mile Creek. Sampling was conducted as close as possible to maximum and minimum daily flows, to capture chemical conditions close to high and low flows. In total, 66 samples were taken at these two sites.

All 125 mL polyethylene sample bottles had been soaked in warm soapy water and were pre-washed with a 30% hydrochloric acid solution and then with distilled water, before being taken into the field. Having rinsed all filtering equipment with stream water, approximately 30 mL of water was scooped from the stream into the body of the filterer, swilled around and immediately vacuum filtered by a hand pump through a 0.45 μm cellulose nitrate membrane that had been placed in the filter unit using a clean knife to avoid hand-contamination. The filtrate was used to rinse the inside of the unit and then discarded. This procedure was repeated three times. Approximately 100 mL of stream water was then filtered and part of this filtrate was used to rinse the sample bottle three times before filling the bottle completely, and sealing and labelling it. All samples were kept out of direct sunlight and refrigerated in the dark within 2 hr of collection. Sample storage before analysis ranged from 6 to 9 months.

Samples were analysed by Dr. G. Brown at the Centre for Glaciology, University of Aberystwyth, Wales. Major cation concentrations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}) were determined using Atomic Absorption Spectrophotometry and Inductively Coupled Plasma analysis, and major anion concentrations (Cl^{-}, NO_3^{2-} and SO_4^{2-}) using Flow Injection Analysis. During air and road transportation to Wales, samples would have been exposed to variations in ambient temperature, but this was unavoidable given the distance between sampling and analysis locations.

2.6 Meteorological variables

A tipping bucket rain gauge, attached to a HOBO event recorder, was installed in a clearing opposite the gauging site at Place Creek. The HOBO logger recorded the time of each tip, which represented 0.25 mm rainfall. After downloading the event data, number of tips per hour were calculated using a Fortran programme written by Vincent Kujala, Department of Geography, University of British Columbia. A bulk precipitation gauge was also positioned at the same site and emptied at the beginning of each field campaign in case the tipping-bucket gauge failed. At the end of the season no known problems with the tipping bucket gauge were encountered.

Hourly air temperature data from Phelix Creek, located approximately 30 km northwest of Place and Eight Mile Creeks, was provided by Brian Menounos, Department of Geography, University of British Columbia.

Chapter 3
Results

3.1 Overview of study period

The year 2000 was characterised by near-normal snowpack conditions, based on data from the Tenquille Lake snow course located about 20 km NW of Place Glacier at an elevation of 1680 m (Figure 3.1a). Based on data from Pemberton, located 18 km SW of Place Glacier at an elevation of about 200 m, summer precipitation and summer air temperature conditions were also near-normal in 2000 (Figure 3.1a, b).

3.2 Data quality

3.2.1 Discharge measurement

For Place Creek, the values of r^2 and Root Mean Squared Error (RMSE) for the stage-discharge rating curve (Figure 2.8a) were 0.978 and 0.11 m^3/s respectively, indicating a reasonable precision. Figure 3.2a also indicates that no shift in the pressure transducer occurred during the season.

At Eight Mile Creek, high flows during early July induced movement of the stilling well. Although the stilling well was re-fastened to the bank in approximately the same position (indicated by the stability of the manual stage-mV scatter plot (Figure 3.2b)), a shift in the stage-Q rating curve was experienced (r^2 = 0.995 and 0.982, and RMSE = 0.08 and 0.10 m^3/s for old and new rating curves, respectively) (Figure 2.8b).

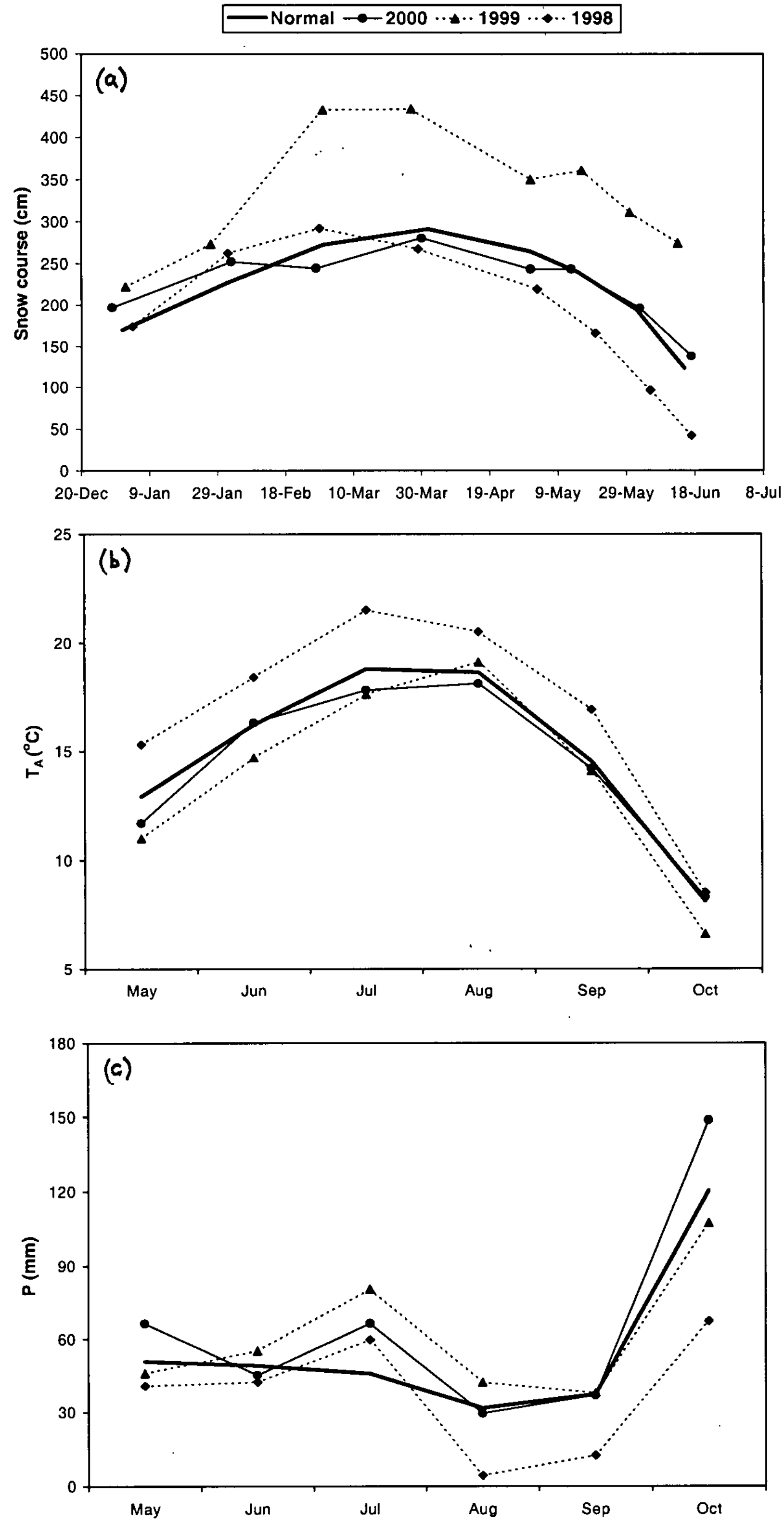
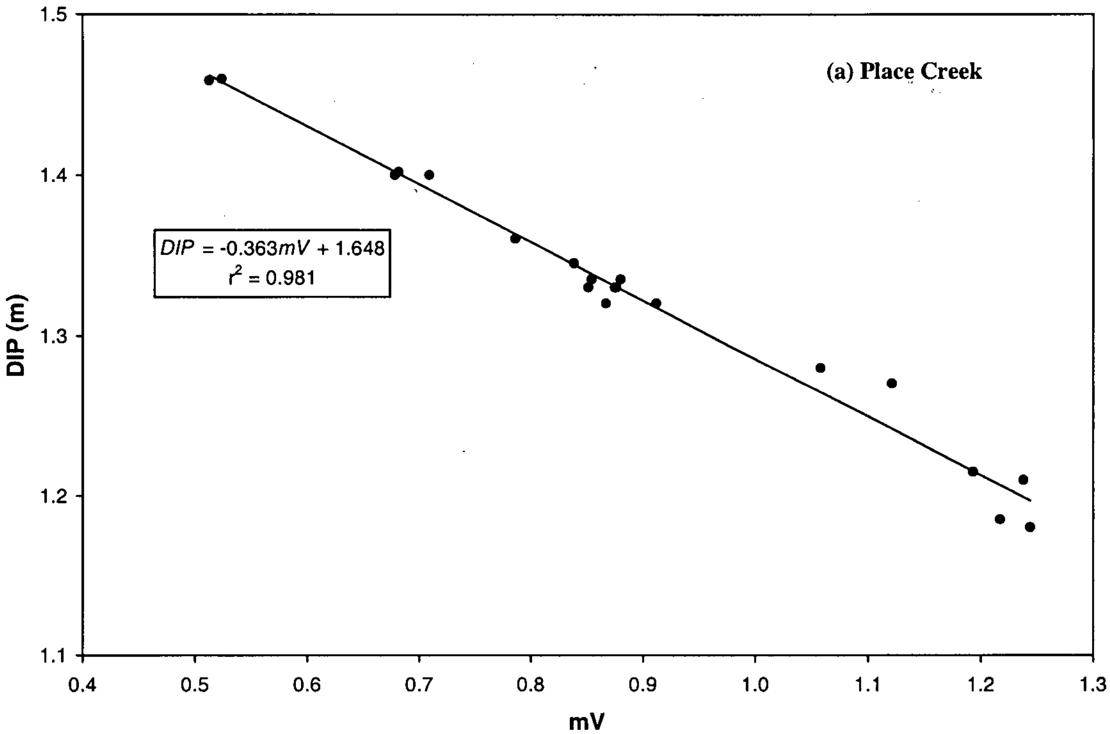


Figure 3.1: Normal (1984 to 2000) versus 1998, 1999 and 2000 (a) monthly snow course, (b) summer monthly air temperature (T_A) and (c) summer monthly precipitation (P). Data provided by (a) B.C. Environment Historical Snow Survey Data and ((b) and (c)) D. Hutchinson, Hydrology Applications Group, Environment Canada.



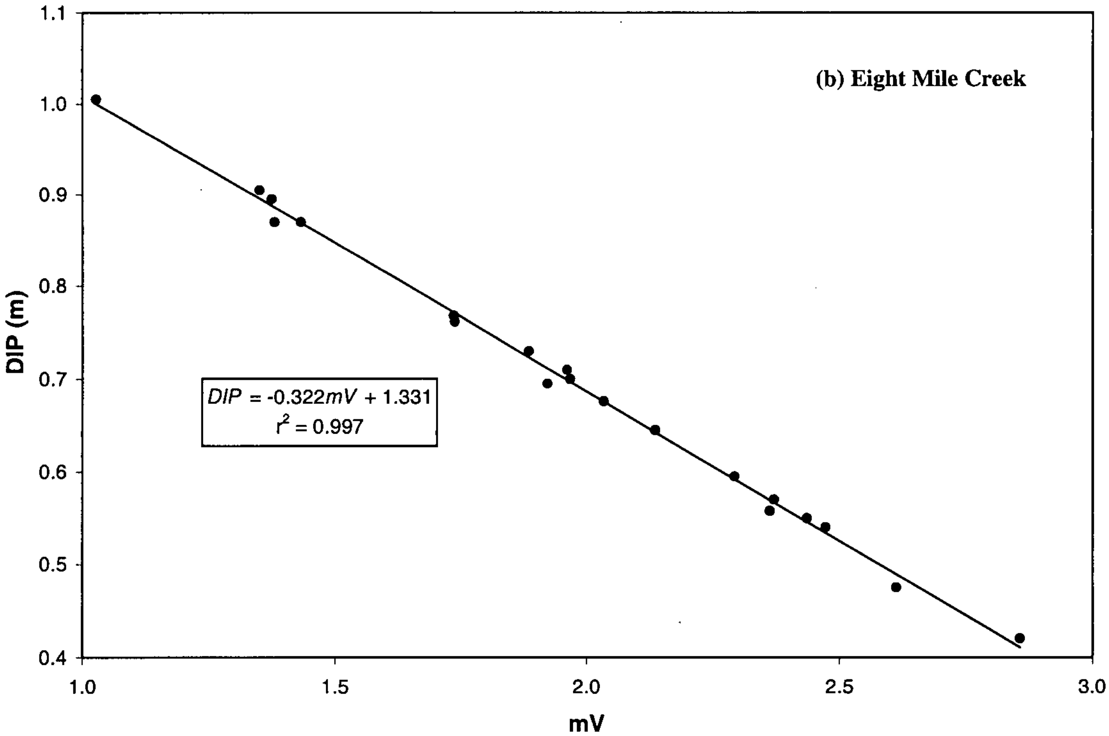


Figure 3.2: Manual stage-mV scatter plots for (a) Place Creek and (b) Eight Mile Creek.

3.2.2 SSC measurement

Error analyses were conducted on a range of SSC measurements. Sources of error were the precision of the electronic balance (±0.1 mg) and volume measurement (±1 mL). For low values of SSC (< 5 mg/L) error was around 10% (0.5 mg/L); for mid-range values (40-60 mg/L), about 1.5% (0.8 mg/L); and for high values (>120 mg/L), approximately 0.7% (0.7 mg/L). Thus measurement errors were small.

An important question is whether the ISCO samples were representative of the stream cross section. Table 3.1 summarises results of a paired sample T-test that was used to test the hypothesis:

$$H_0 : \mu_D = 0$$
$$H_1 : \mu_D \neq 0,$$

where μ_D is the mean of the differences between paired ISCO and right bank DH48 samples.

Table 3.1: Results of ISCO - DH48 Paired Sample T-test

T-test information	**Value**
n	24
Degrees of Freedom (df)	23
T-statistic (T_t)	-1.206
T-critical for Two Tailed Test (T_C)	2.069
$P(\lvert T_T \rvert \leq T_C)$	0.240

The T-statistic is less than the critical T-value (Table 3.1) and so there is no evidence to reject H_0 at a significance level of 5%, thus indicating that the ISCO sampler provided unbiased estimates of SSC in comparison with the DH48 sampler. Figure 3.3a shows a scatter plot of ISCO versus DH48 values of SSC and the proximity of the points to the 1:1 line.

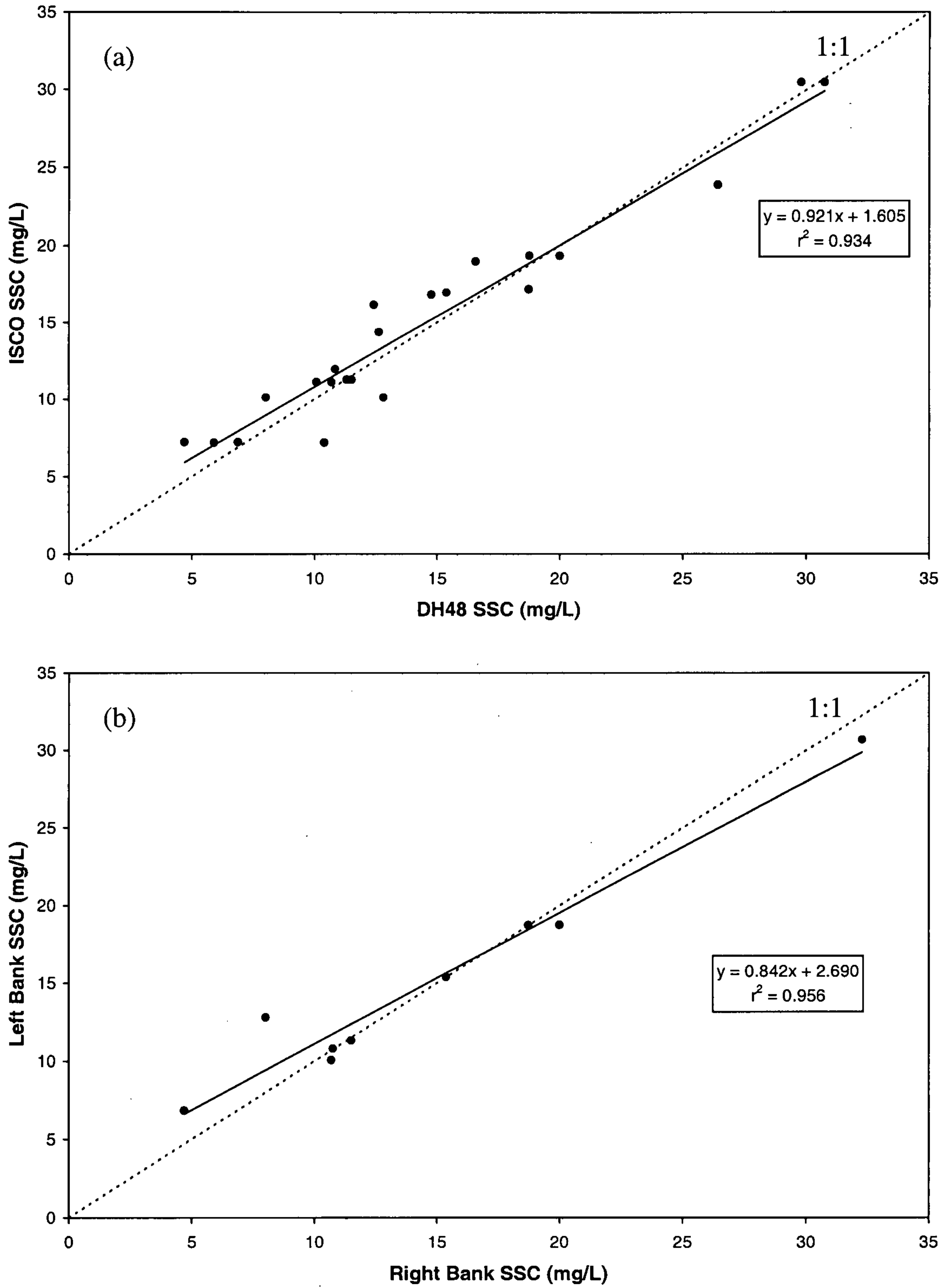


Figure 3.3: (a) ISCO versus DH48 values of SSC for all samples and (b) left versus right bank DH48 values of SSC.

To test the hypothesis that there was a difference in SSC between the ISCO sampler and the eight paired DH48 samples, SSC values were analysed by a two-way Analysis Of Variance (ANOVA) using the General Linear Model function in SYSTAT 9.0. The factors were time of sampling (8 levels) and type of sample (3 levels: ISCO, DH48 right bank, DH48 left bank). Results indicated that time of sampling was significant ($p<0.001$) and type of sample was insignificant ($p=0.502$). There is, therefore, evidence that sampling location does not have a significant influence on SSC. Again, Figure 3.3b shows a plot of left versus right bank SSC, indicating that all points plot close to the 1:1 line.

3.3 Streamflow and SSC variations

3.3.1 Place Creek discharge and SSC time series

A continuous record of discharge was obtained from 12 May to 31 Nov 2000, after which streamflow was minimal and thus not of interest for the purpose of this thesis (Figure 3.4). The SSC series stretched from 18 May to 8 Oct 2000, but was discontinuous. Hourly air temperature (T_A) and daily precipitation (P) records spanned the periods 19 May to 26 Sept and 19 May to 30 Nov, respectively.

Through May and June, background discharge rose and was punctuated by rainfall events on 20 to 21 May (11.4 mm), 26 to 27 May (18.5 mm), 5 June (13.7 mm), 18 to 19 June (7.4 mm) and 1 to 2 July (12.4 mm), and a snowmelt event on 28 to 29 June (Figure 3.4). Following a lull in discharge during early July, discharge rose again and was characterised by an increasing diurnal oscillatory amplitude. From 27 to 28 July, 31.3 mm of rainfall produced the largest recorded discharge of the season (3.83 m^3/s). During early August discharge fluctuated daily, from around 2.0 to 2.8 m^3/s. Cooler air temperatures then

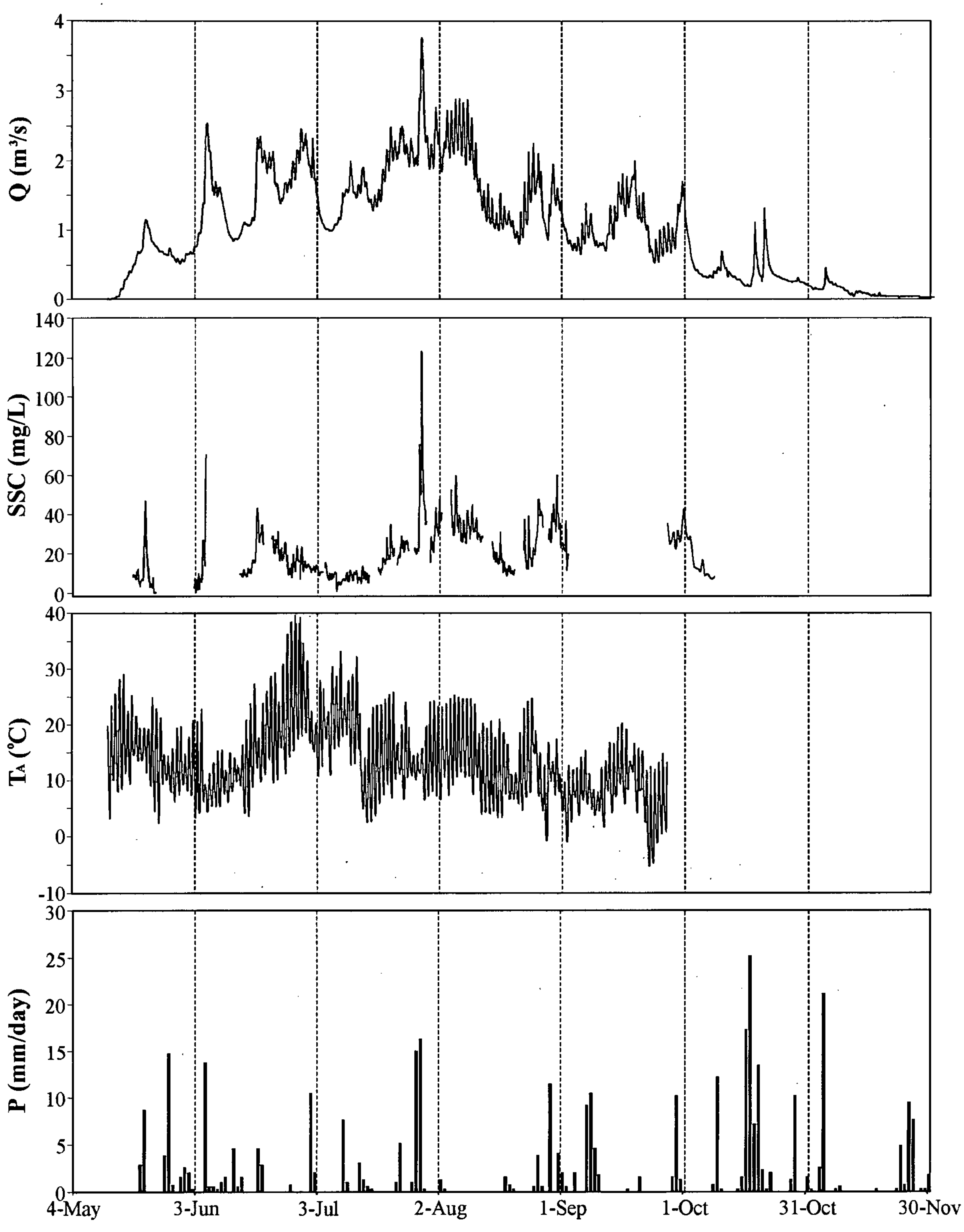


Figure 3.4: Time series of discharge, SSC, air temperature and precipitation for Place Creek (2000 season).

prevailed from 10 to 21 Aug and average daily discharge fell from approximately 2.4 to 1.3 m^3/s. After a period of renewed glacial melt from 22 to 26 Aug, induced by warm air temperatures, background discharge followed a seasonal recession trend and was again punctuated by rainfall and late glacial melt events. From 10 to 30 Nov, discharge remained minimal at <0.1 m^3/s.

A tentative relation between SSC and discharge can be noted from Figure 3.4, in which peaks in SSC generally corresponded to peaks in discharge. Following the first two SSC events of the season, during mid-May and at the beginning of June, SSC declined from around 40 to 10 mg/L, despite similar discharge event magnitudes. During July, SSC rose and peaked at 123 mg/L during the storm event on 27 to 28 July. For the first 10 days in August, SSC mimicked diurnal flow cycles, but SSC then decreased in mid-August during a dry period of cooler air temperatures. No values of SSC were recorded from 3 to 25 Sep because of time constraints on access to the field site. The last field campaign of the season recorded SSC during the rain event of 28 to 30 Sep, during which similar peak concentrations (43 mg/L) to those at the same discharge during the rain storm on 29 Aug, were measured (44 mg/L).

3.3.2 Eight Mile Creek discharge and SSC time series

The streamflow record for Eight Mile Creek covered the period from 14 May to 31 Nov 2000, again beyond which discharge was minimal and thus not of interest for this investigation (Figure 3.5). Following a period of high discharge during late June and subsequent shift in the stage-discharge rating curve (Figure 2.8b), a break in the discharge series was experienced from 2 July 00:00 to 6 July 15:50, after which the stilling well was

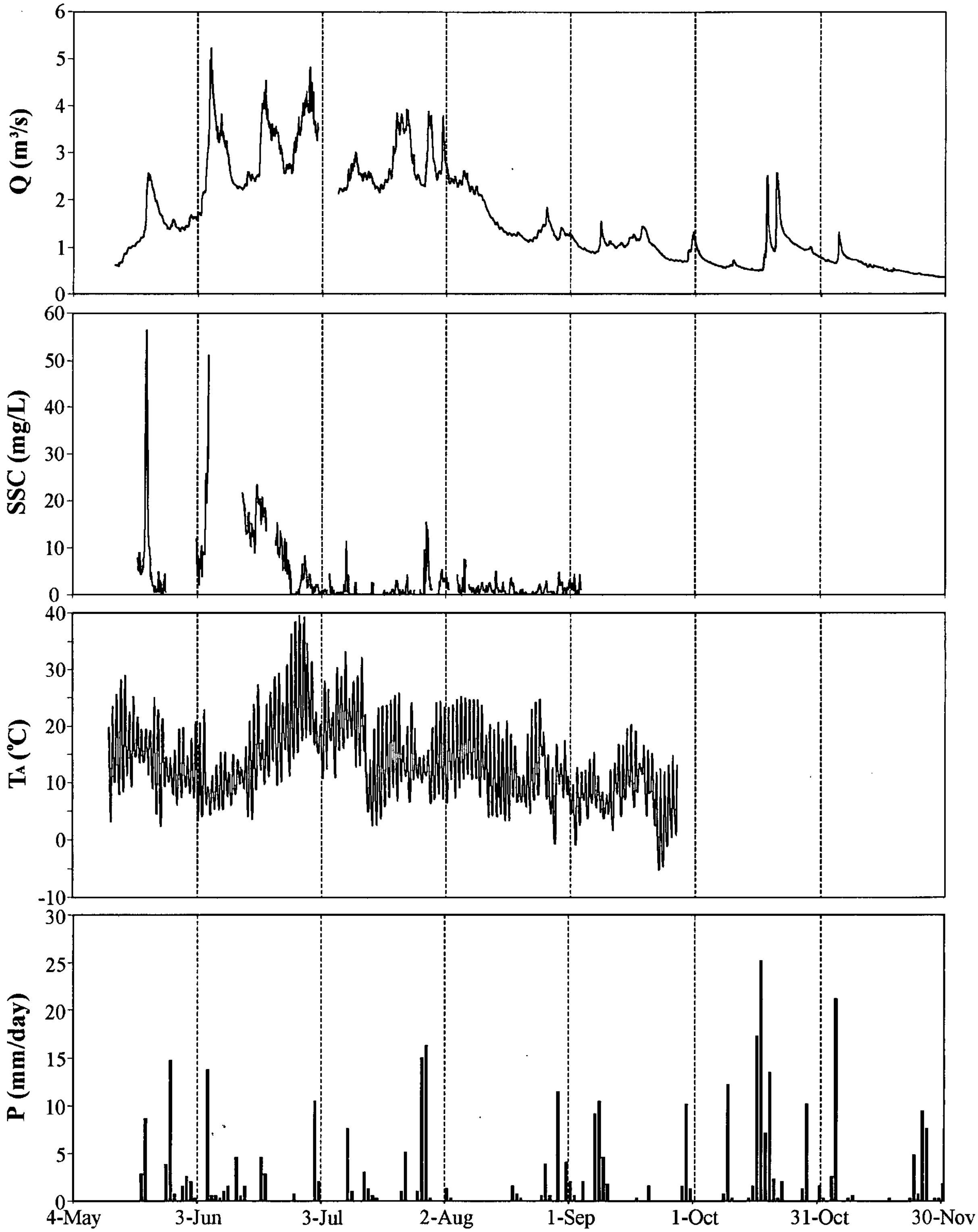


Figure 3.5: Time series of discharge, SSC, air temperature and precipitation for Eight Mile Creek (2000 season).

re-secured. The record of SSC ranged from 19 May to 3 Sep 2000 and as for Place Creek, the series was sporadic.

At the start of the season, discharge rose from 0.6 m^3/s to around 5 m^3/s at the end of June. During this period streamflow responded to the same rainfall and snowmelt events as Place Creek did. Following a drop in discharge to just above 2 m^3/s at the beginning of July, background flow was approximately 2.5 m^3/s, but displayed similar synoptic scale increases as for Place Creek. Despite maximum daily air temperatures of above 30 °C during 24 to 30 June, streamflow dropped rapidly over this period. Background levels of discharge remained at about 2.5 m^3/s through July. The storm event on 27 to 28 July, which produced the maximum seasonal discharge in Place Creek, did not have such a significant impact in Eight Mile Creek. Discharge then declined rapidly, from 6 to 22 Aug, and then more steadily through to the end of the season. Again, during this latter portion of the season, synoptic scale storm events induced responses in discharge similar to those in Place Creek.

Background SSC in Eight Mile Creek was generally <10 mg/L, except during periods of elevated discharge. The maximum recorded SSC over the measurement season was 56 mg/L, which occurred during the first rain event of the season (20 to 23 May). The following three events (same dates as for Place Creek), all of similar peak discharges (around 5 m^3/s), were associated with progressively declining SSC, from >51 mg/L during the second rain event, to 23 and then 8 mg/L for the third and fourth events, respectively. The only other significant periods of suspended sediment transport occurred during the second of two discharge events, closely spaced over time, on 23 and 28 July. For the remainder of the season, minor fluctuations of SSC above 0 mg/L can be attributed to small rain events and possibly measurement error.

3.3.3 Standardised discharge series

During the snowmelt and autumn portion of the season, streamflow was greater in Eight Mile than in Place Creek because the basin area of Eight Mile is almost double that of Place Creek and thus collects more snowmelt and rainfall runoff. Time series of standardised discharge (Q_s), that is discharge per unit drainage area (m^3 s^{-1} km^2), reveal a good correspondence during the major period of snowmelt and spring storm events, from 14 May to June 30 (Figure 3.6). For this period, the linear relation between the two time series is

$$Q_s(EM) = 0.02 + 0.82Q_s(PC) \qquad (r^2 = 0.949, \mathrm{SEE}=0.01), \qquad (3.1)$$

where SEE is the standard error of the estimate. From the beginning of July, melt from Place Glacier began to make a significant contribution to streamflow in Place Creek as inferred from the increase in diurnal discharge cycles. In Eight Mile Creek, however, flows generally decreased from July to October. The differences in standardised discharge for this period probably reflected the effects of glacier melt in Place Creek. From the end of October until the end of the season, Eight Mile yielded more discharge per km^2 than Place Creek, which was probably because there are greater volumes of groundwater in the former basin.

3.4 Seasonal hydrograph division

3.4.1 CUSUM plot of Q ratio

The use of cumulative sums (CUSUMS) provides a powerful technique for identifying regime shifts in time series (Mac Nally and Hart, 1997). For this sub-section, the discharge series for Place Creek will be sub-divided using the time-ordered EM/PC discharge ratio series. The CUSUMS are thus defined as the running tally of the deviations of each value of the EM/PC discharge ratio from the mean of the series, such that

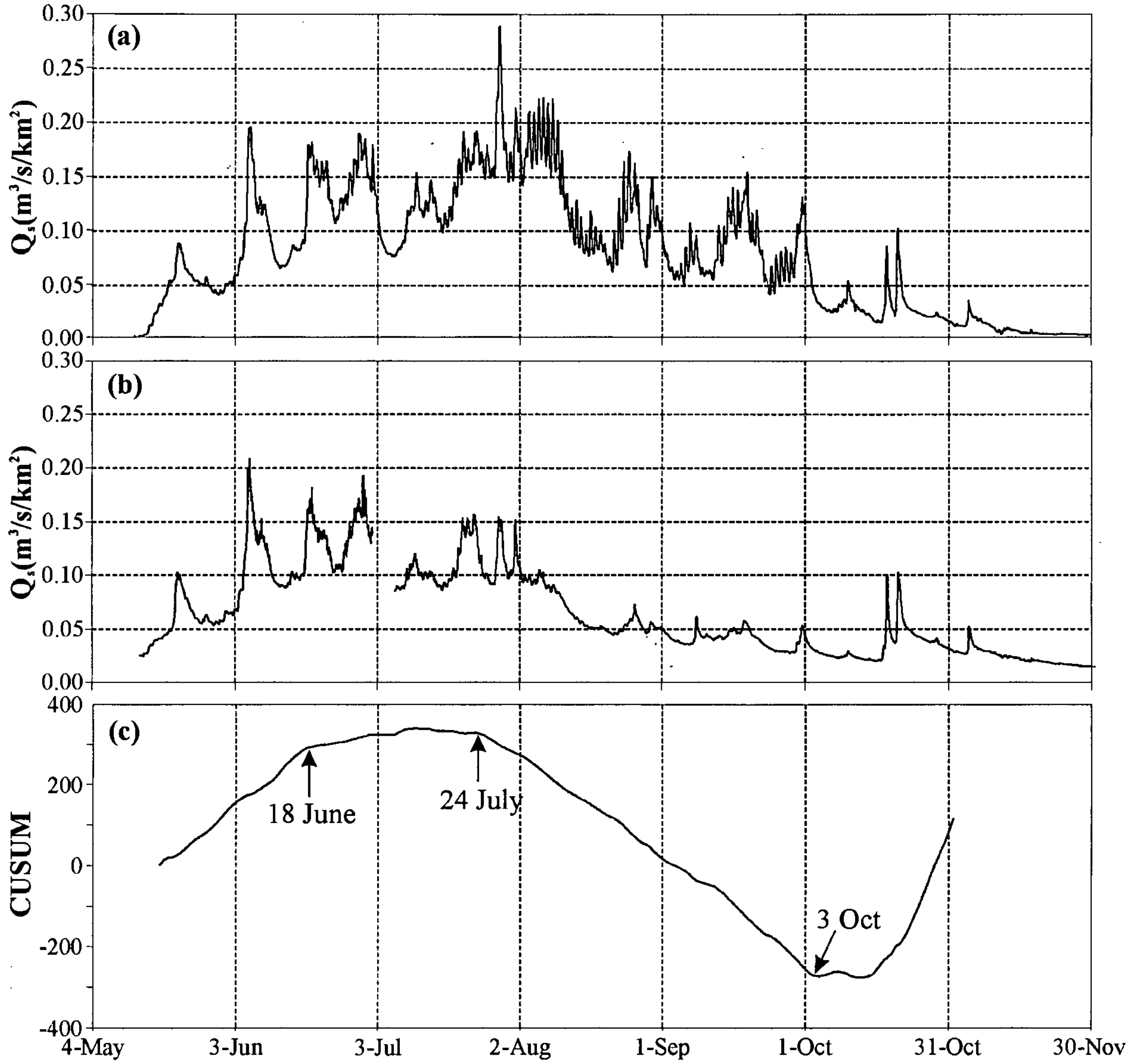


Figure 3.6: Standardised discharge time series for (a) Place Creek and (b) Eight Mile Creek. Arrows on the (c) CUSUMS plot indicate sub-seasonal transition dates.

$$S_r = S_{r-1} + \left(\frac{Q_r - \overline{Q}_r}{\overline{Q}_r} \right), \tag{3.2}$$

where S_r is the rth partial sum, S_{r-1} is the previous partial sum, and Q_r is the rth value of and $\overline{Q}_r$ is the mean of the EM/PC discharge ratio series. The CUSUMS can then be plotted as a time series (Figure 3.6c). Abrupt shifts in the slope of the plot indicate that the ratio between Eight Mile and Place Creek discharges has changed. According to the greatest changes in gradient of Figure 3.6c, the season can be sub-divided into a 'nival' (N) period (start of the season to 17 June), a 'nival-glacial' (NG) transition period (18 June to 23 July), a 'glacial' (G) period (24 July to 2 Oct) and an 'autumn recession' (AR) period (3 Oct to 30 Nov). Discharge and SSC varied amongst the 4 sub-seasons (Table 3.2).

Table 3.2: Descriptive Statistics for Place Creek Sub-seasons.

	SSC (mg/L)				Q (m^3/s)			
	N	**NG**	**G**	**AR**	**N**	**NG**	**G**	**AR**
Mean	9.9	16.3	27.7	10.6	0.84	1.71	1.45	0.23
Standard Deviation	11.7	7.6	12.9	2.9	0.50	0.39	0.61	0.19
Minimum	0.0	1.5	8.8	7.4	0.00	0.97	0.52	0.02
Maximum	70.6	42.5	122.6	16.8	2.55	2.54	3.83	1.33
No. Data Points	104	233	388	11	5238	5184	10224	8496

3.4.2 Relations between electrical conductivity and discharge

Unfortunately, laboratory restrictions did not permit HCO_3^- to be determined and so a charge balance calculation for measuring chemical analysis accuracy could not be performed. Given that total anion concentrations (Σ^-) should equal total cation concentrations (Σ^+), however, the strong relation between EC and Σ^+ (Figure 3.7) indicates that EC was a valid measure of Total Dissolved Solids (TDS) for Place Creek.

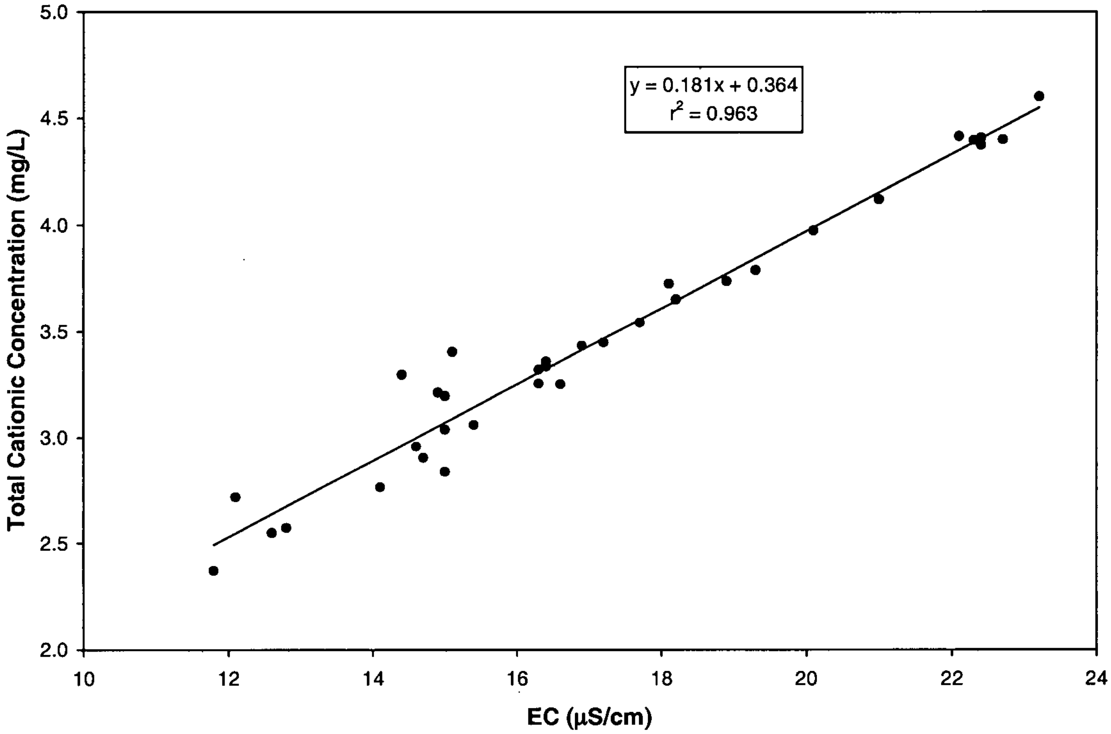


Figure 3.7: Total cationic concentration-EC relation for Place Creek.

To support the validity of the CUSUMS method for defining sub-seasons of the Place Creek discharge series, the relation between EC and discharge for Place Creek, divided into the 4 sub-seasons, can be examined (Figure 3.8). In the literature, hydrograph separation using EC has been successful in separating hydrograph components (Teti, 1979; Laudon, 1995). From Figure 3.8 it appears that there are three distinct groupings of points: a concave-up relation for the nival period, a concave-up relation for the combined glacial and autumn recession periods, and an unstructured group for the nival-glacial transition. These groupings indicate that water sources and/or flow paths varied amongst the hydrologic sub-seasons defined by the CUSUMS technique, supporting their validity.

3.5 SSC-Q relations for Place Creek

3.5.1 Seasonal SSC-Q relation

The time series of SSC and Q (Figure 3.4) indicated that there was a tentative relation between SSC and Q. Accordingly, the simplest way to predict SSC is from a SSC-Q rating curve. A common technique for constructing the rating relation is to use Ordinary Least Squares (OLS) regression, following the function

$$S\hat{S}C_i = \mathrm{b}_0 + \mathrm{b}_1 Q_i , \tag{3.3}$$

where $S\hat{S}C_i$ is the estimated value of SSC, subscript *i* represents a particular value at the time of sampling, and b_0 is the intercept and b_1 the slope of the function. The parameters for the fitted OLS equation for SSC are shown in Table 3.3.

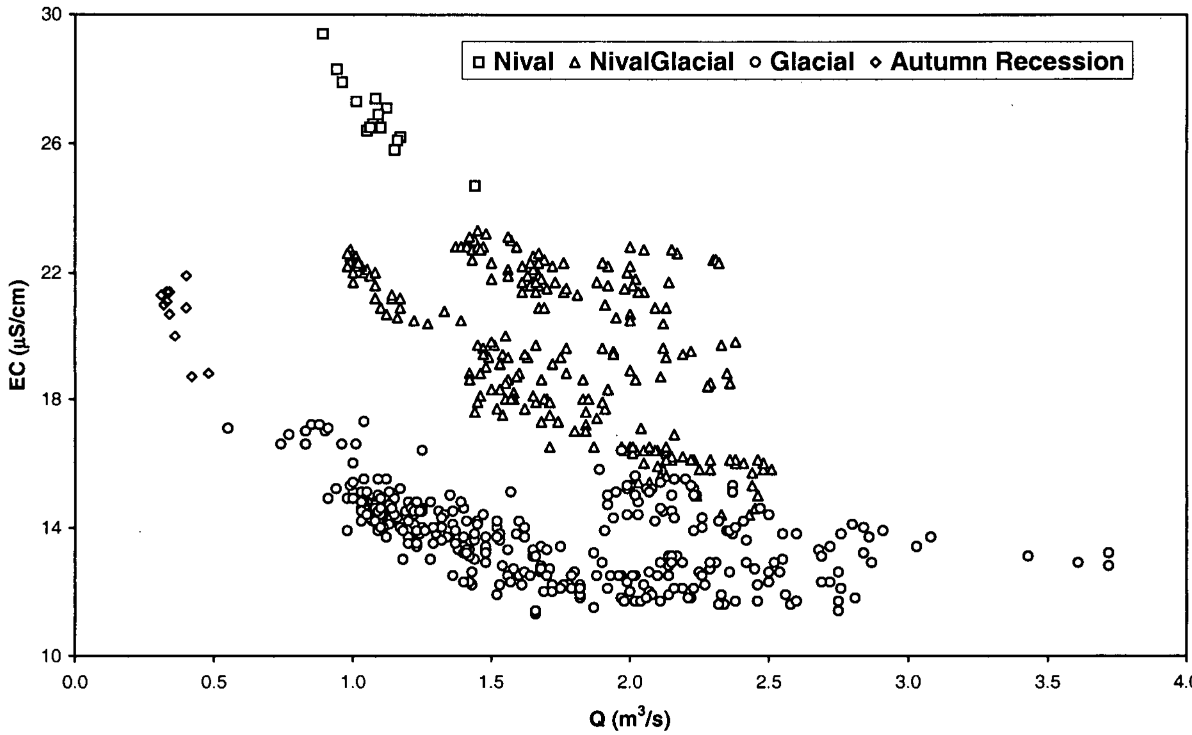


Figure 3.8: EC-Q relations for Place Creek. Data points are grouped by sub-seasonal division dates defined in Figure 3.6c.

Table 3.3: Summary of OLS SSC-Q Seasonal Regression Model (values in brackets are the p-values for b_0 and b_1).

n	r^2	SEE (mg/L)	F-ratio	b_0 (mg/L)	b_1 mg $L^{-1}/(m^3 s^{-1})$
686	0.445	9.8	548.94	-2.36 (0.026)	14.86 (<0.001)

Consistent with the relatively low r^2 value, there is considerable scatter about the regression line (Figure 3.9a). Such low model accuracy is widely noted in the literature (reasons outlined in Section 1.2).

The significance of the seasonal SSC-Q model and its predictive ability cannot, however, be correctly interpreted unless the assumptions of regression are met. These assumptions are: normality of the error terms, equal variances of the errors, independence between error terms, and linearity. Plots of the residuals of the fitted model (Table 3.3) reveal violations of the assumptions (Figure 3.9b, c, d). As values of $S\hat{S}C_i$ increase, absolute values of e_i (that is SSC_i- $S\hat{S}C_i$) increase, indicating heteroskedasticity (Figure 3.9b). Beyond $S\hat{S}C_i$ values of 35 mg/L there are no negative values of e_i, which provides evidence for a lack of fit in the model (Figure 3.9b). Figure 3.9c illustrates autocorrelation (i.e., time dependence) of the residuals. Over the entire season a trend towards higher positive residuals, and thus SSC underestimation, can be seen. On a shorter timescale, this trend is also punctuated by marked short-term SSC underestimation, particularly during the rainfall induced discharge events described in Sub-section 3.3.1.

Violations of the assumptions were tested statistically. To test for normality, the Shapiro-Wilks (W) test (Neter *et al.*, 1996) was used under the hypothesis:

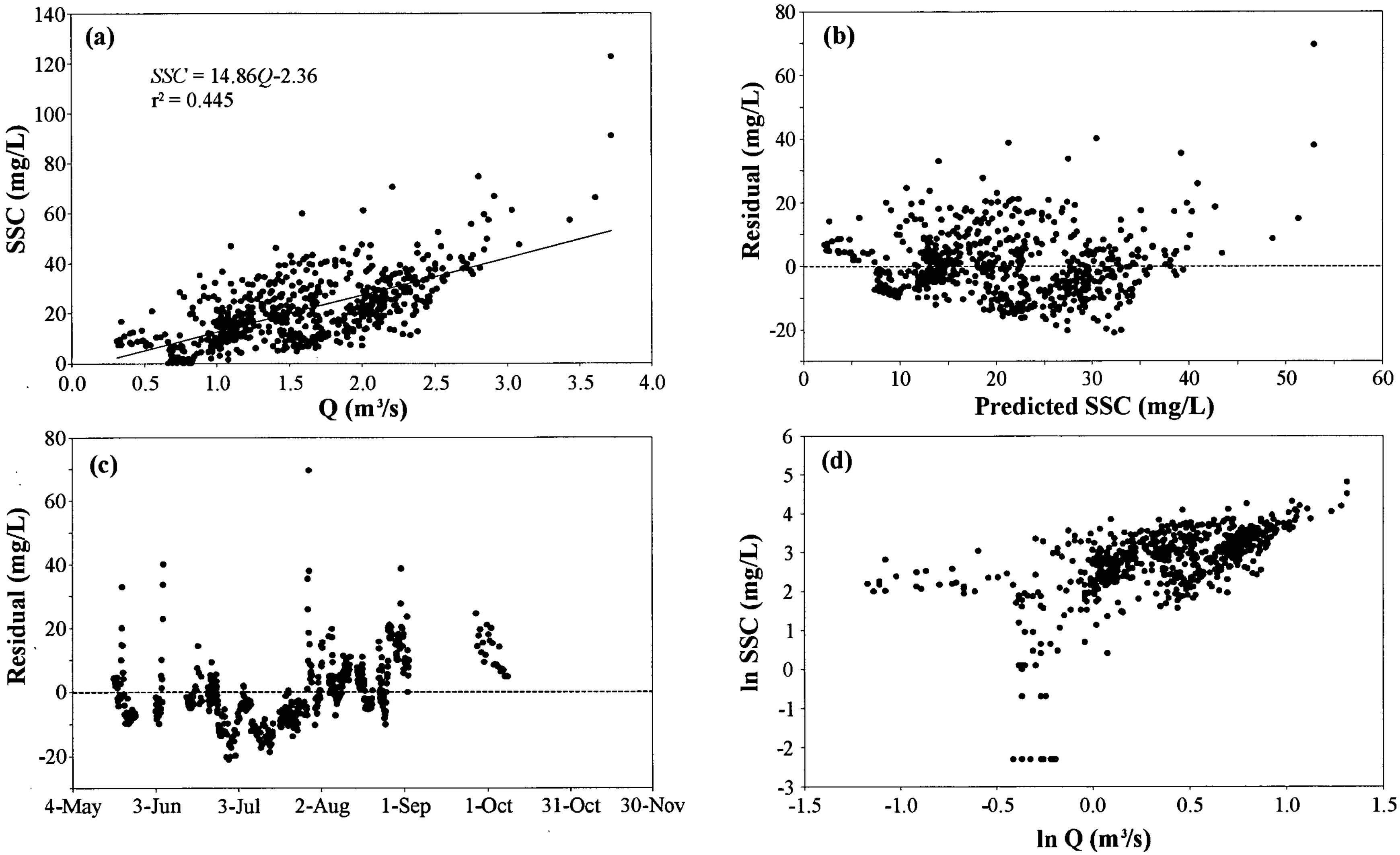


Figure 3.9: (a) simple SSC-Q rating relation; (b) SSC-Q relation residual plot; (c) seasonal and diurnal scale autocorrelation in the SSC-Q relation; and (d) log transformed SSC-Q relation (note the lack of fit for low values of SSC).

H_0: error terms normal

H_1: error terms not normal

The probability value for the computed W-statistic was less than 0.001, indicating that at a significance level of 0.05, H_0 can be rejected. Thus, it can be concluded the error terms are not distributed normally.

Homoskedasticity was tested for by generating a 'pseudo-White's' test statistic (χ^2) using SAS 6.12. The hypothesis tested was:

H_0: equal variances

H_1: unequal variances

The probability value for the χ^2-statistic was less than 0.001. At a 5% significance level χ^2 is thus significant and the null hypothesis can be rejected. It can be concluded that there is evidence for heteroskedasticity.

For independence, a Durbin-Watson (DW) test was performed under the hypothesis:

H_0: $\rho = 0$

H_1: $\rho \neq 0$,

where ρ is the lag-1 autocorrelation amongst the error terms. The DW test statistic was 0.269. At a 5% significance level, the critical bounds for the test statistic were 1.65 for the lower and 1.69 for the upper bound (for >100 samples and 1 parameter (Q)). The test statistic is below the lower bound and so H_0 can be rejected, thus suggesting the presence of residual autocorrelation.

Lastly, for lack of fit, the residual plot was assessed visually and concluded to be non-linear at the upper end. The linearity assumption must, therefore, also be rejected. In an attempt to reduce heteroskedasticity and normalise the variable distributions a $\log_e$ transformation of the discharge and SSC data was performed. The $\log_e$ transformation linearised the SSC-Q relation for high values of discharge, but a large number of low values of SSC then exhibited a non-linear relation with streamflow (Figure 3.9d). Additionally, the variances clearly became heteroskedastic. Thus, transforming the variables did not appear to provide a solution to the problems of non-linearity and heteroskedasticity.

3.5.2 Sub-season SSC-Q relations

This section tests the hypothesis that the nature of the SSC-Q relation for Place Creek differs among the hydrologic periods defined in Sub-section 3.4.1. Given that the autumn recession period only has 11 data points, which are all spaced between 3 to 8 Oct, this sub-season will be ignored. Further analyses and reference to the "Entire season" thus refer to the other three periods.

Given that the data set has been sub-divided into three groups it is not possible to compare r^2 values, either between sub-seasons or against the whole season, because the data in each group are different. By introducing a dummy variable into a SSC-Q OLS model for the first three sub-seasons, however, a single value of r^2 can be generated and compared to the value for the Entire season.

Beginning with an OLS model for the Entire season (Table 3.4), a dummy variable for each sub-season was introduced, leading to the expression

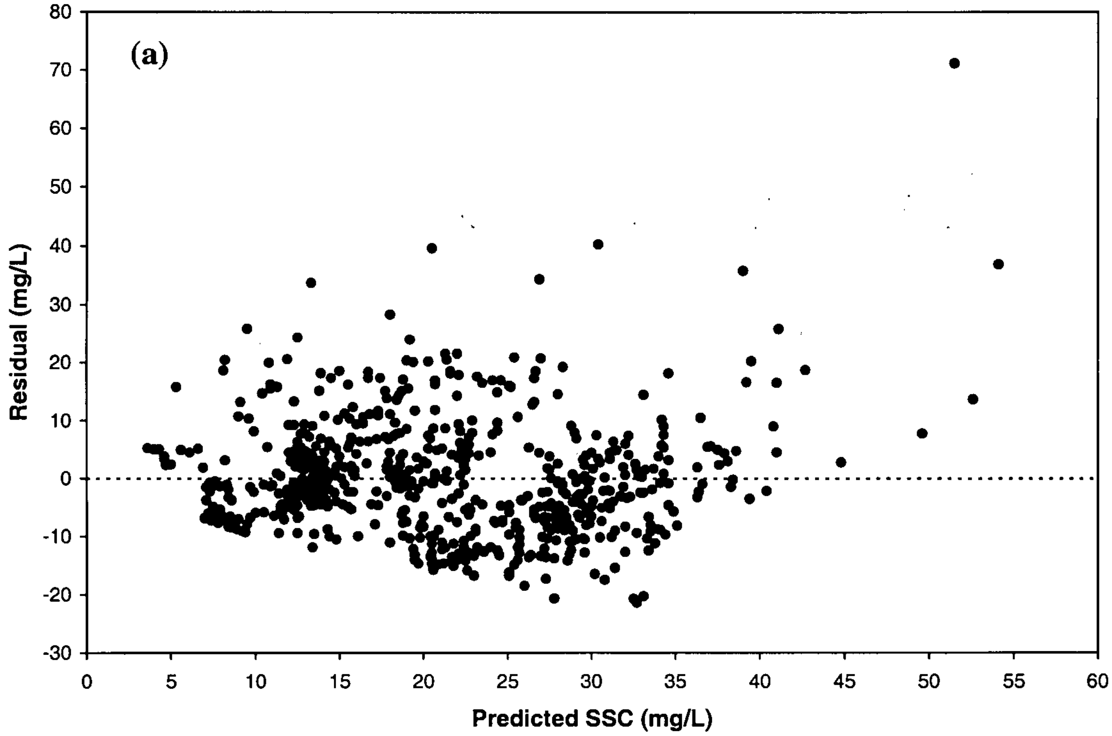
$$S\hat{S}C_i = b_0 + b_1Q_i + b_2S_{i1} + b_3S_{i2} + b_4Q_iS_{i1} + b_5Q_iS_{i2}, \qquad (3.4)$$

where S_{i1} = 1 if nival period, otherwise 0; and S_{i2} = 1 if nival-glacial period, otherwise 0. Equation 3.4 includes interaction terms for both the slope and intercept of the original Entire season rating function (Table 3.4). The R^2 value for the dummy-season model is 0.648, an increase of 0.202 from the Entire season model, and the SEE has also decreased from 9.8 to 7.8 mg/L (Table 3.4). Thus the dummy-season model has improved the accuracy of SSC predictions. Statistical analysis revealed significantly different slopes and intercepts amongst subseasons (details provided in Appendix A).

Table 3.4: Summary of SSC-Q OLS Regression Models (values in brackets are the p-values for b_0 and b_1).

Sub-season	n	r^2	SEE (mg/L)	F-ratio	b_0 (mg/L)	b_1 mg $L^{-1}/(m^3\ s^{-1})$
Entire season	675	0.446	9.8	540.83	-3.20 (0.004)	15.31 (<0.001)
Dummy model	675	0.684	7.8	246.70	-	-
Nival	104	0.583	7.6	142.70	-18.10 (<0.001)	31.32 (<0.001)
Nival-glacial	233	0.393	5.9	149.57	-4.38 (0.012)	11.86 (<0.001)
Glacial	338	0.516	9.0	358.43	-1.33 (0.367)	15.67 (<0.001)

Comparing the residual plot for the sub-seasonal model against the Entire season model (Figure 3.10), it appears that the residuals are more homoskedastic and linear in the former, which indicates that seasonal division has also improved the validity of the regression assumptions. From Figure 3.11, however, it is clear that although the different slopes and intercepts of the sub-season models account for general seasonal differences in hydrologic control on proglacial suspended sediment dynamics, over 30% scatter remains to be explained. In order to account for remaining scatter, a number of other explanatory variables were introduced into each sub-season rating function.



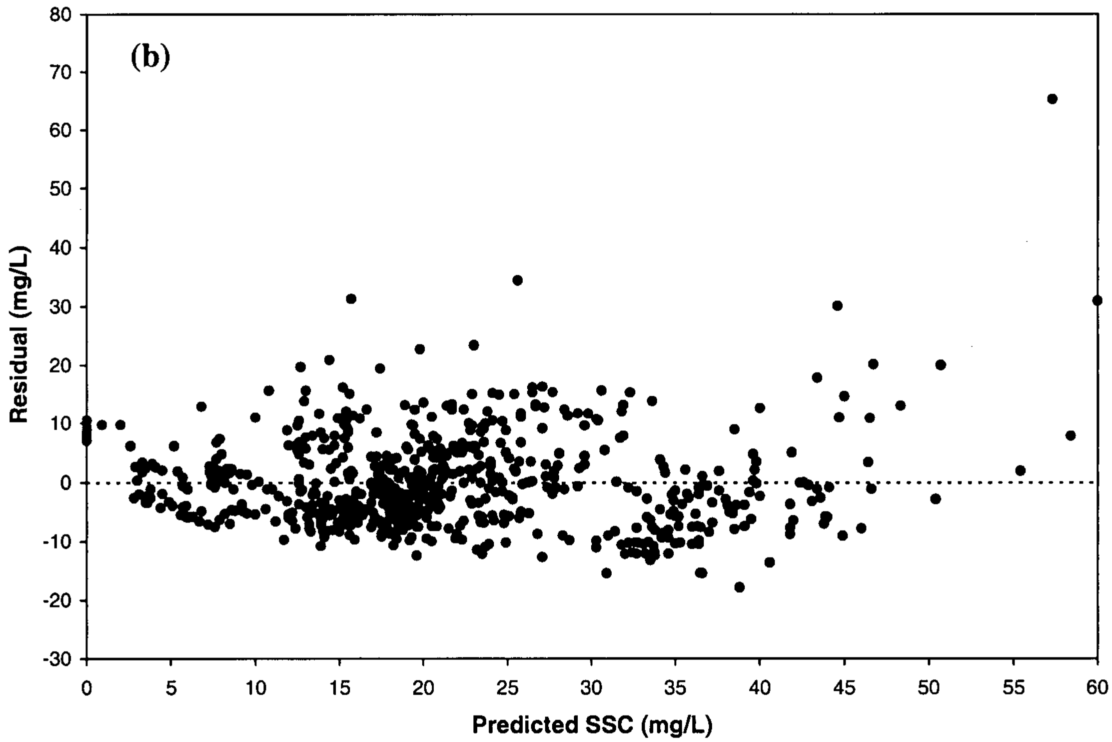


Figure 3.10: (a) Seasonal versus (b) sub-seasonal SSC-Q relation residual plots.

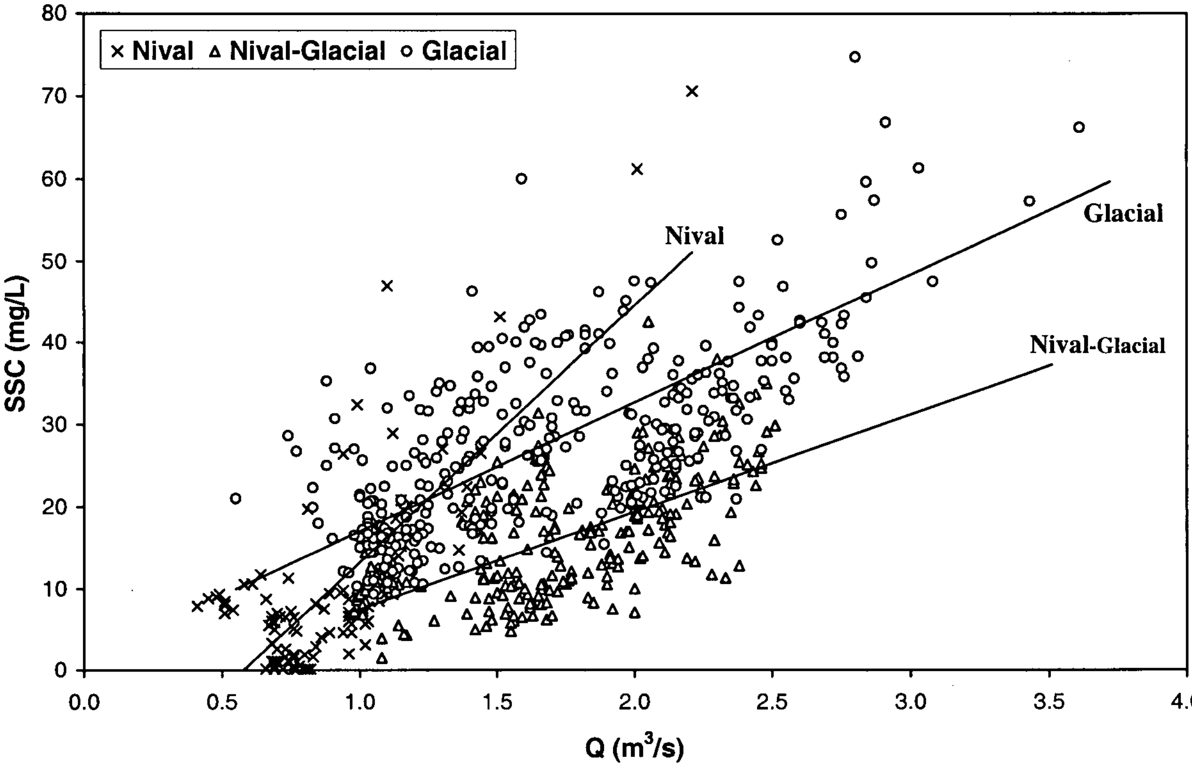


Figure 3.11: Sub-seasonal SSC-Q rating relations (note that SSC scale has been reduced so that the grouping of points can be more readily distinguished).

3.5.3 Multiple regression models

A suite of variables from which to select for Multiple Linear Regression (MLR) was derived from published literature and consideration of local factors that may have influenced proglacial suspended sediment transport in Place Creek. Reasons for selecting these variables are outlined below. Each variable has been drawn from relevant literature unless otherwise indicated.

1. $\mathbf{Q^2}$ was selected to account for the non-linearity present in Figure 3.11. Having fitted a non-linear function to the data set, in the form SSC = aQ^b, using the non-linear regression tool in SYSTAT 9.0, an associated r^2 value of 0.454 did not show great improvement over the value of 0.446 for the Entire season model (Table 3.4).

2. $\mathbf{Q_{t-1}}$. By lagging Q at different intervals (current time (t) - 0.5 hr, t-1 hr, t-1.5 hr ... t-250 hr) and then separately adding each variable into regression function 3.3, the optimum lag for Q was selected as t-1 hr, based on R^2 values. The reason for lagging discharge was to account for the residual autocorrelation noted in Figure 3.9c (Gurnell *at al.*, 1994). As stated in Section 2.4, the SSC sampling interval was irregular. Such irregularity complicates attempts to correct for residual autocorrelation (e.g. using ARIMA modelling). By lagging the diurnal phasing of discharge to the best-match fit with the diurnal phase of SSC, it is possible, however, to account for some degree of the residual autocorrelation in the Entire season OLS function (Table 3.4).

3. $\mathbf{\Sigma Q}$. Cumulative discharge over the monitoring period ($m^3 \times 10^{-6}$) was incorporated into the suite of predictor variables because it accounts for seasonal changes in suspended sediment supply. The assumption of ΣQ is, therefore, that processes governing seasonal

changes in suspended sediment supply are represented by the increasing flux of snowmelt, glacial melt and storm runoff that passed through the drainage basin. Specifically, ΣQ acts as a surrogate for suspended sediment supply exhaustion (Hodson and Ferguson, 1999).

4. $\mathbf{\Delta Q_3}$ represents the rate of change of discharge over 3 consecutive hours and was obtained by subtracting from current values discharge, values recorded 3 hr previously. It was thus positive during the rising hydrograph limb and negative during the falling limb. Recent literature suggests that SSC is more dependent on ΔQ, rather than the current discharge, Q (Willis *et al.*, 1996). The optimum time-interval selection for ΔQ was obtained using the same method outlined for Q_{t-1}, with $\Delta Q_{0.5}$, ΔQ_1, $\Delta Q_{1.5}$ … ΔQ_{250}.

5. $\mathbf{SSC_{(ref)}}$. Many SSC MLR models published in contemporary literature adopt various lagged values of SSC as autoregressive predictors (e.g. Hodson and Ferguson, 1999). Such variables, however, limit the predictive capacity of the model because an intense sampling programme must be conducted to obtain lagged values of SSC. An alternative approach would be to include a measured, reference value of SSC for each day. If successful, this approach could provide an effective trade-off between minimising costs of monitoring while maintaining accuracy of predicted SSC values. Inspection of diurnal-scale SSC time series for Place Creek indicated that peak values generally occurred at approximately 18:00. By using the daily value of SSC, measured at 15:00, to predict values between 9:00 that day and 8:00 the following morning (approximate timing of beginning and end of diurnal phase of SSC), a low maintenance sampling programme could be used to 'tune' the overall model to the physical state of the sediment

supply system for each day. This is a variable that has not, to the knowledge of the author, been used in previous studies similar to this one.

6. $\mathbf{P_{24}}$ was calculated by summing precipitation (mm) over the 24 hour period previous to the time of each SSC sample. Evidence from the literature suggests that precipitation is an important determinant of SSC during high discharge storm events (Hodgkins, 1999).

7. $\mathbf{T_A}$ was used as a surrogate for glacial melt and thus accounted for diurnal fluctuations in discharge during the dominant summer ablation period (Aizen *et al.*, 1996).

Values of variables 1 to 7 were entered into a SYSTAT 9.0 spreadsheet for each of the 675 values of SSC. To construct MLR models, the data set was again divided into its respective sub-seasons and variables were selected by backwards stepwise interactive selection. The selection was interactive because $SSC_{(ref)}$ and ΔQ_3 were 'forced' into each model. After analysing similar MLR models from the literature, it was expected that $SSC_{(ref)}$ and ΔQ_3 should, physically, provide the most explanation for the scatter in Figure 3.11. Selection criteria were an Alpha-to-Enter level of 0.049 and an Alpha-to-Remove level of 0.050. The resulting sub-season MLR models are given in Table 3.5. The number of data points used to derive each model is less than those used for corresponding sub-season models (Table 3.4) because on occasions SSC was not measured at 15:00 and thus a value of $SSC_{(ref)}$ could not be used with other values of SSC that same day.

Table 3.5: Results of MLR analysis showing n, adjusted R^2, SEE, F-ratio, intercept values (b_0) and regression coefficients for separate predictors (p-value shown in parentheses, otherwise not significant ('ns')). The strongest predictor (highest T-statistic) is underlined.

Sub-season	**n**	**R^2_{adj}**	**SEE**	**F-ratio**	**b_0**	**$SSC_{(ref)}$**	**ΔQ_3**	**Q**	**Q^2**	**Q_{t-1}**	**ΣQ**	**P_{24}**	**T_A**
Nival	93	0.91	3.6	195.449	-1.74 (0.021)	0.13 (0.055)	37.25 (0.000)	ns	<u>6.88</u> (0.000)	ns	1.43 (0.024)	1.47 (0.000)	ns
Nival-glacial	220	0.80	3.4	122.037	18.98 (0.000)	<u>0.67</u> (0.000)	14.50 (0.000)	-14.28 (0.002)	6.07 (0.000)	ns	-0.74 (0.000)	-0.35 (0.002)	-0.14 (0.000)
Glacial	304	0.80	6.0	201.654	-28.66 (0.000)	0.28 (0.000)	17.36 (0.000)	<u>15.32</u> (0.000)	ns	ns	2.12 (0.000)	0.56 (0.000)	-0.29 (0.001)

In Sub-section 3.5.1 it was shown that the original OLS model (Table 3.3) failed to meet all of the regression assumptions. Under the same hypotheses and using the same tests as those described in Sub-section 3.5.1, Table 3.6 summarises the sub-seasonal MLR model assumption test statistics.

Table 3.6: Summary of MLR Assumption Test Statistics (PRESS is the Prediction Sum of Squares).

Sub-season	**Pr<W**	**Pr>χ^2**	**DW**	**PRESS**
Nival	0.1126	0.2536	1.176	1839
Nival-glacial	0.1325	0.0257	1.139	2779
Glacial	<0.001	0.0304	0.863	11860

For the nival period, the normality and equal variances tests were passed. For the nival-glacial sub-season, the data were normally distributed, but slightly heteroskedastic. For the glacial period, the data were again slightly heteroskedastic, but not normally distributed. The upper and lower bounds of the Durbin Watson test statistic were, for each sub-season, 1.78 and 1.57, respectively. There is, therefore, evidence of minor autocorrelation in each model.

The validity of the models can be assessed from the values of the PRESS statistic, which are calculated by summing the squares of the differences between each observed value of SSC and its predicted value based on a regression function developed from the remaining $n - 1$ values of SSC. The values of PRESS are thus a useful measure of how well the use of the fitted values for a subset of each sub-seasonal MLR model can predict the observed values of SSC (Neter *et al.*, 1996). For the Entire season model (Table 3.4), the PRESS statistic (not shown) was 65242. Although PRESS values cannot be directly compared between models, since they are all based on different samples, the values for the MLR nival and nival-glacial sub-seasons (Table 3.6) are much lower than for the Entire season model, indicating that both MLR models have small prediction errors. For the glacial period the prediction errors are larger than for the other two periods, but still represent a great improvement in the predictive capacity over the OLS Entire season model.

3.5.4 SSC-Q hysteresis relations

Several types, strengths and scales of SSC-Q hysteresis can be noted according to seasonal, synoptic and diurnal changes in dominant hydrologic sources. To allow process inferences to be made from the hysteresis loops in Place Creek, examples from different sub-seasons and synoptic-scale events will be compared. It must be noted that quantitative measures of hysteresis have not been developed and so qualitative analysis must suffice. To ensure minimum subjectivity, the direction of the loop will describe its type and relative enclosed area its strength. Figure 3.12 gives examples of hysteresis loops with their associated discharge and SSC time series plots.

For storm runoff events, hysteresis was strong and clockwise early in the season (Figure 3.12a), but later in the season was weaker and anticlockwise (Figure 3.12b). For snowmelt events, both strong and weak clockwise hysteresis occurred within sequential days during late June (Figure 3.12c). On the first day, discharge and SSC peaked at approximately the same time (27 June at 00:00). Although they again peaked at similar times the following evening (27 June at 21:00), discharge did not begin to fall for another 6 hr, therefore inducing stronger clockwise hysteresis. Further complexities can be noted in Figure 3.12d, in which the latter part of the loop is vertical and anticlockwise, indicating a negative SSC-Q relation. Another interesting loop on 20 to 21 July (Figure 3.12e) depicts a 'figure 8' formation

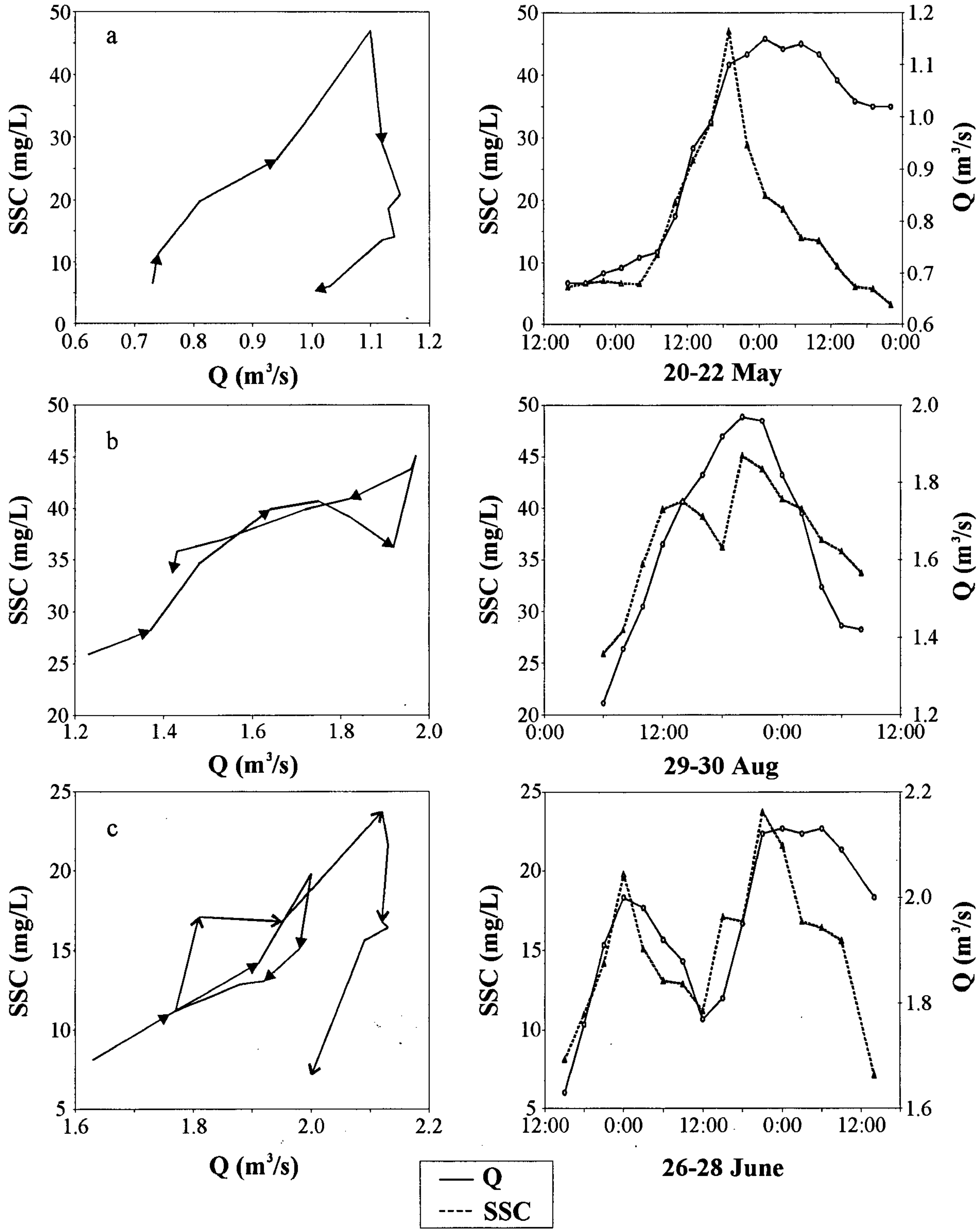


Figure 3.12: Examples of SSC-Q hysteresis for: ((a) and (b)) storm runoff events; (c) a snowmelt event; and ((d) and (e)) more complex SSC-Q relations. Arrows on SSC-Q plots indicate direction of hysteresis (filled and open arrows divide discharge cycles/events). Time plots (right) correspond to hysteresis loops.

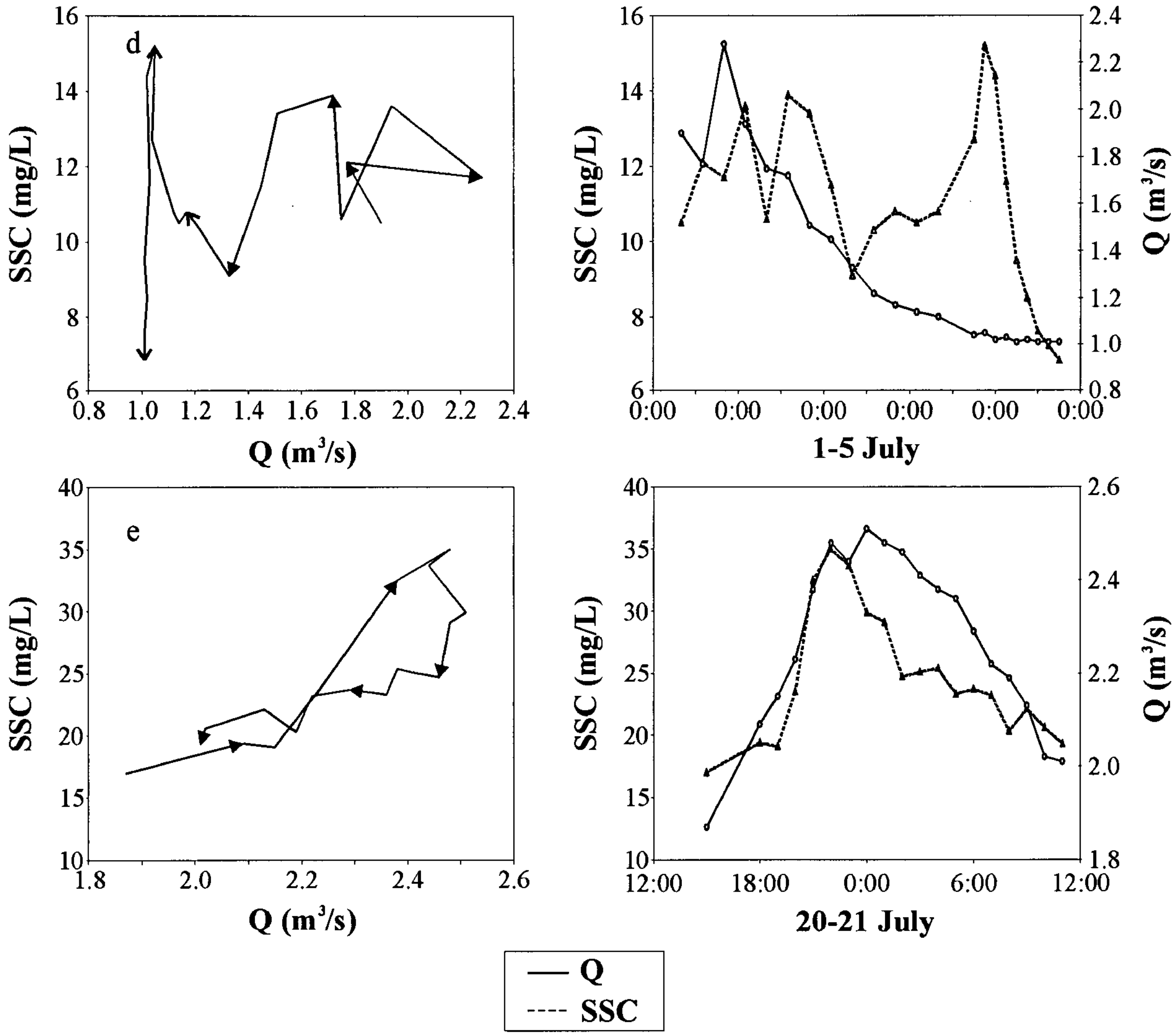


Figure 3.12 (continued)

(Williams, 1992), combining initially clockwise and then anticlockwise sub-loops. The former occurred during high discharge and the latter at lower discharge.

During the glacial season, the dominant diurnal SSC-Q hysteresis was strong and clockwise (Figure 3.13), indicating that SSC peaked before discharge. On a synoptic scale, hysteresis was also clockwise during mid to late August, as indicated by the clockwise progression of the loops themselves.

To aid the comparison of hysteresis loops in Figure 3.12, Figure 3.14 illustrates the pattern of SSC and its proportion that was organic material, for four discharge events. All four plots indicate that organic SSC was approximately constant throughout the events, but from event a through d, a progressive decrease in organic SSC occurred. Given that total SSC rose and fell in each event, while the percentage organics remained approximately constant, the latter had a negative relation with SSC (Figure 3.14). This percentage was much lower (10-20%) during the fourth event than for the previous three events (20-100%). Since this last event was dominated by snowmelt, while the others were principally rainfall induced, Figure 3.14d confirms that sediment sources differed for different sources of runoff to the main channel.

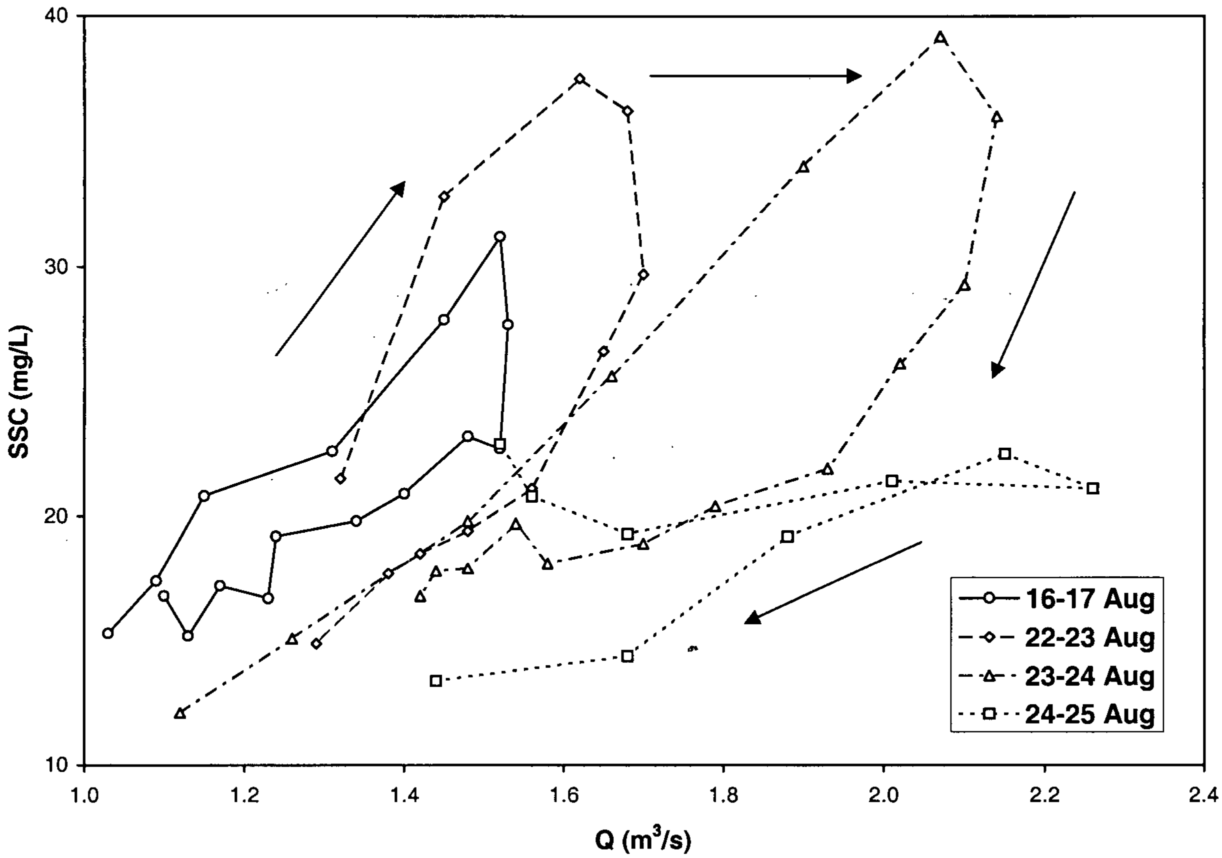


Figure 3.13: Diurnal and synoptic scale SSC-Q hysteresis during the main ablation period (arrows indicate direction of synoptic scale hysteresis). All individual loops have a clockwise direction.

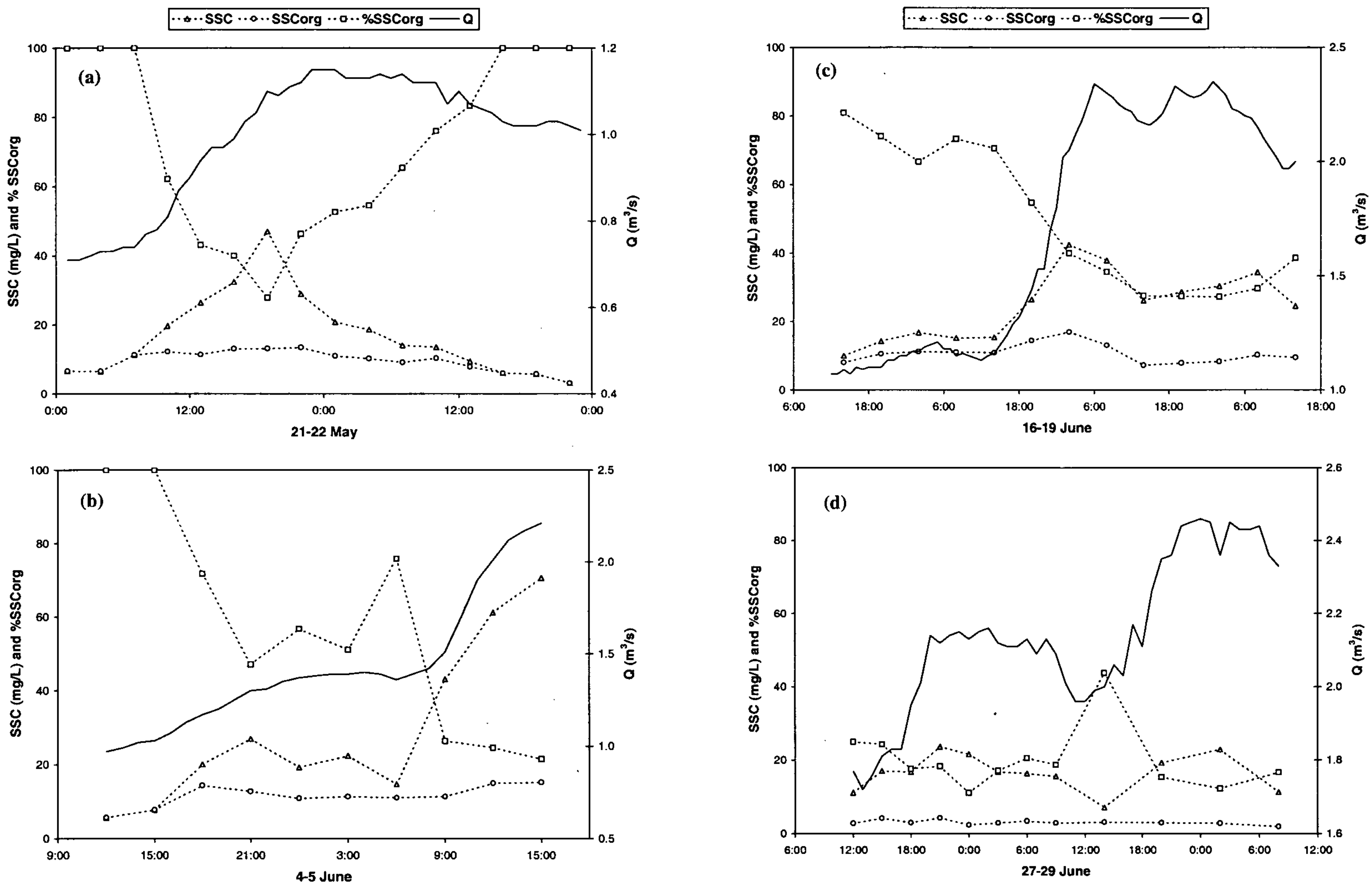


Figure 3.14:Time series of organic SSC as a percentage of total SSC for four different discharge events in Place Creek.

3.6 Upstream-downstream comparisons of SSC

This section focuses on changes in SSC between Place Lake outlet and the valley site during two glacial melt cycles, one at the beginning and one at the end of August (Figure 3.15). As a result of time constraints, an adequate stage-discharge rating curve could not be established at the lake outlet. Data from 4 to 6 Aug clearly show that SSC at the lake outlet was approximately constant over the sampling period, at around 55 mg/L. In the valley, however, SSC followed a diurnal increase-decrease pattern, with a peak value of 60 mg/L at 20:00 and minimum value of about 30 mg/L at 10:00 on 5 Aug. Respectively, these times are also similar to those of the maximum and minimum values of valley discharge.

At the end of August the SSC data series were complicated by a rain event, which appears to have caused an increase in SSC at the lake outlet, from 59 to 75 mg/L, during the period of rain (01:00 to 19:00 on 29 Aug). During this period, sediment runoff was observed from morainal slopes at the lakeside. In the valley, minimum SSC values were similar to values recorded in early August, but maximum values were approximately 40 mg/L and thus less than upstream values.

For the case of approximately constant discharge at the lake outlet (i.e., early August upstream-downstream field campaign), an approximate suspended sediment budget was constructed, assuming that the total outflow over a diurnal cycle is the same at Place Lake outlet and Place Creek at the valley site. The sediment fluxes can thus be expressed as

$$SSF_{PLO} = \overline{SSC}_{PLO} \cdot \int Q(PC)\mathrm{dt} \tag{3.5}$$

$$SSF_{V} = \int Q(PC) \cdot SSC\mathrm{dt}\,, \tag{3.6}$$

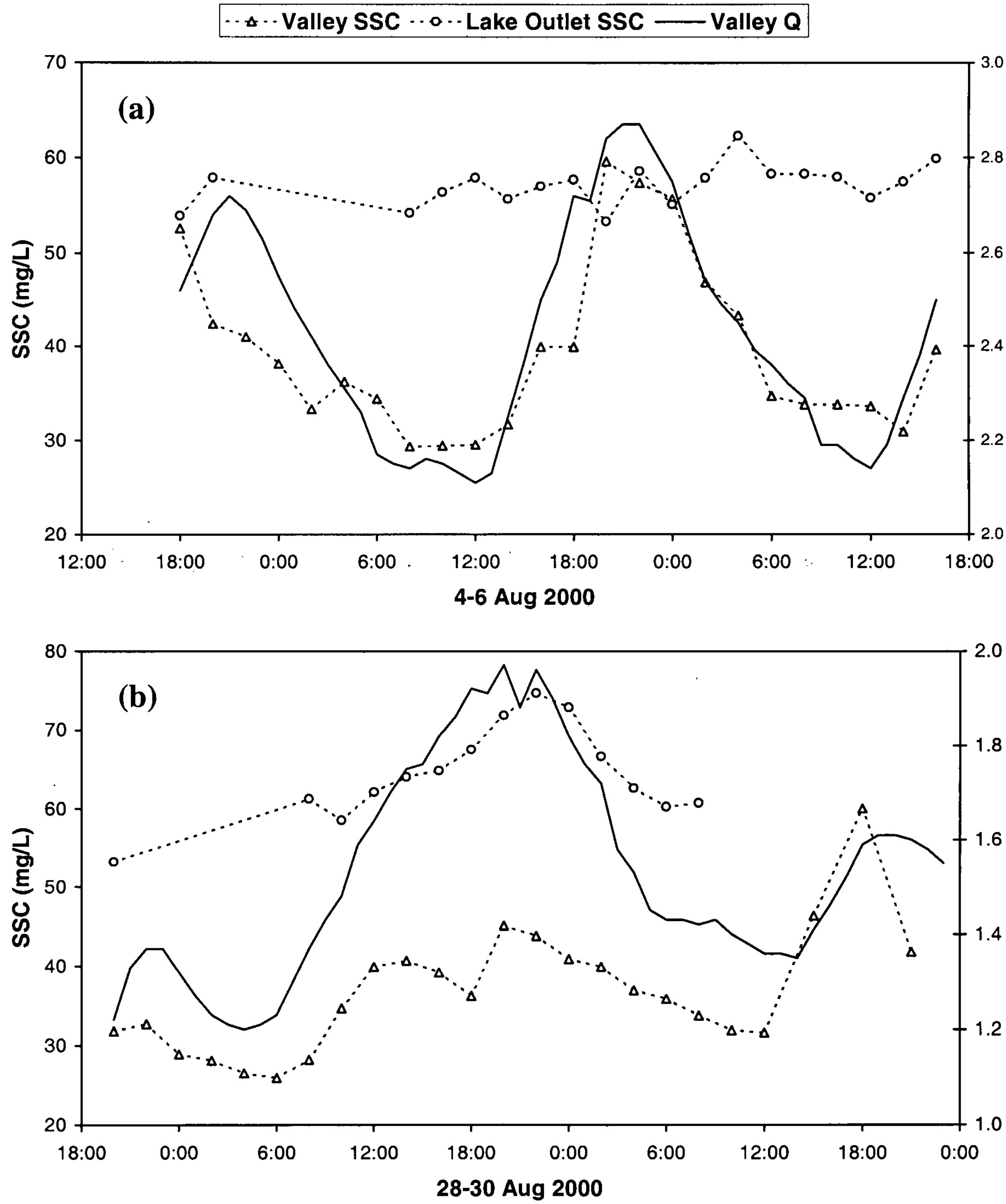


Figure 3.15: Upstream-downstream comparison of lake outlet SSC, and valley discharge and SSC for (a) early August and (b) late August 2000.

where SSF_{PLO} and SSF_V are the suspended sediment fluxes over a daily discharge cycle at Place Lake outlet and the valley bottom, respectively, $\overline{SSC}_{PLO}$ is the average hourly SSC at the lake outlet over a daily discharge cycle, and $Q(PC)$ is average hourly discharge at the valley bottom. Equations 3.5 and 3.6 can be approximated as

$$SSF_{PLO} = \overline{SSC}_{PLO} \cdot \sum (Q \cdot \Delta t) \tag{3.7}$$

$$SSF_V = \sum (Q \cdot SSC \cdot \Delta t), \tag{3.8}$$

where Δt is the change in time (seconds).

For the lake outlet, the total daily sediment flux for 5 Aug 12:00 to 6 Aug 11:59 was 12300 kg (12.3 t) and for the valley bottom was 9300 kg (9.3 t). Approximately, the suspended sediment budget at the basin outlet was –3000 ±200 kg (–3 ±0.2 t). Errors for suspended sediment fluxes were calculated considering errors in SSC (±2%) and discharge (±5%) measurement.

3.7 Chapter summary

Sub-division of the seasonal discharge hydrograph for Place Creek was achieved by comparison of its standardised discharge with that for Eight Mile Creek. The CUSUMS technique revealed four clear sub-seasons (nival, nival-glacial transition, glacial and autumn recession). For each sub-season, four distinct groups of points on an EC-discharge plot supported the method of hydrograph separation. Relations between SSC and discharge were highly scattered, but showed improvement when data were divided into nival, nival-glacial and glacial sub-seasons. Multiple regression models further improved the accuracy of SSC prediction and the ability of the models to meet the regression assumptions. Hysteresis loop characteristics for diurnal scale SSC-Q relations provided additional evidence of the influence of different sources of runoff on suspended sediment transport within glacier-fed rivers. Finally, comparison of upstream-downstream SSC suggested that SSC at the lake outlet was approximately constant, but that at the valley bottom SSC fluctuated with diurnal discharge in the glacial period. Further evidence of the significance of in-channel sediment storage on the downstream delivery of sediment in Place Creek was provided by a negative daily sediment budget at the basin outlet.

Chapter 4
Discussion

Discussion in this chapter will be focused on Place Creek and Eight Mile Creek will only be used as a reference basin.

4.1 Hydrologic control on SSC

4.1.1 Seasonal scale

From the groups of points in the EC-Q relation (Figure 3.8) it can be hypothesized that there are three main hydrologic sources of streamflow within Place Creek: (1) water from Place Lake with an EC of about 10 to 12 μS/cm (measured at the lake outlet during early and late August 2000 by the author); (2) water from a baseflow reservoir with values of EC around 40 μS/cm (as measured on 16 Jan 2000); and (3) high-EC water that is generated during the nival period (25 to 30 μS/cm). Unfortunately, this hypothesis cannot be addressed with the current data. The distinct groupings of points in Figure 3.8, however, suggest that the relative contributions of these sources vary amongst sub-seasons. The significance of the dummy variables and their interaction with Q in function 3.4 indicates that seasonal changes in the hydrologic sources of discharge (i.e., snow-melt, glacial-melt and a nival-glacial combination) alter the simple SSC-Q rating relation. Different areas of a catchment deliver different quantities and quality of sediment to a stream channel. In the initial part of the nival period, the slope of the nival SSC-Q regression function was steeper than for the nival-glacial and glacial functions (Figure 3.11), indicating that sediment entrainment efficiency was greatest early in the season, as previously found by Chikita (1993). The decrease in the regression slope during the nival-glacial transition period may reflect the retreat of the snowpack to the upper portion of the basin above the tree-line (Figure 2.3), where soils were likely thinner and provided less sediment for entrainment. Additionally, during this transition period, the glacier was only making a small contribution to streamflow, as indicated by the similarity of standardised discharges between Place and Eight Mile Creeks (Figure 3.6), and thus suspended sediment supply from Place Lake was also minor. The regression slope for the glacial period was similar to the slope for the nival-glacial sub-season, but the intercept was greater for the former period. It could be argued, therefore, that the sediment discharge mechanisms during these two periods were analogous, but that during the latter, the increase in glacier-melt discharge from Place Lake supplied more suspended sediment than for the same discharge during the former sub-season.

As a result of differences in the SSC-Q relation through sub-seasonal changes in water sources, the need to sub-divide seasonal hydrographs in glacierised basins is of fundamental importance to any investigation of suspended sediment transport within such catchments. Previous studies were highlighted in Section 1.2 as using subjective methods for hydrograph division. In this study, the comparison of Place Creek with a similar basin that had no current glacial effect provided a better means of dividing the seasonal hydrograph for Place Creek.

4.1.2 Synoptic scale

During the first two discharge events of the season (20 to 23 May and 4 to 7 June respectively), SSC peaked at 47 and >71 mg/L in Place Creek. The third event, on 18 to 19 June, produced discharge values similar to those for the second event, but SSC peaked at only 43 mg/L. Although streamflow during both the second and third events was similar, rainfall during the former was almost double that during the latter. It is possible, therefore, that the latter was a rain-on-snow event because air temperature was higher on 18 to 19 June than on 5 June. Intuitively, it would seem that snowmelt runoff should carry less sediment to the channel than does storm runoff because the snowpack acts as a protective layer, thus reducing runoff access to sediment sources, whilst raindrops provide an impact mechanism to loosen soil particles. Further evidence of this claim is provided by the fourth, snowmelt, event (28 to 30 June), during which little rain fell. Again, peak discharge during this event was similar to that reached during the second and third events. Assuming from the minimal rainfall that the bulk of discharge was induced by snowmelt runoff, the associated peak recorded SSC of 23 mg/L suggests that snowmelt runoff only carried a relatively minor sediment load to the stream channel. Figure 3.14 also showed that snowmelt events transported a smaller percentage of organic sediment as the nival season progressed. This finding supports the speculation made in Sub-section 4.1.1 that snowmelt runoff entrains less sediment towards the end of the nival period because of the rising elevation of snowmelt to areas where soils and vegetation cover are thinner.

Another explanation for the progressive decrease in event-discharge SSC from the second to fourth events would be synoptic scale sediment supply exhaustion, in which, for example, most of the small grains, loosened by freeze-thaw cycles during the winter, or deposited during the previous autumn, were washed into the stream by the first and second events. Additionally, on daily timescales within the fourth synoptic period, increasing diurnal snowmelt discharge cycles were associated with progressively smaller corresponding diurnal SSC cycles. Such a negative relation between SSC and discharge could be evidence of intra-event sediment exhaustion.

4.1.3 Diurnal scale – glacial period

In order to discuss the hydrologic control on SSC on a diurnal timescale, focus will be made on the glacial period when predominantly fine-grained material, the product of glacial erosion, was transported down Place Creek. Figure 3.15a (4 to 6 Aug) suggests that there was a constant supply of fine sediment evacuated from Place Lake during diurnal glacial melt cycles. Since SSC in the valley mimicked the pattern of discharge, it is unlikely that inputs of water between the two sites induced the diurnal fluctuation of SSC in early August. Assuming no significant measurement errors, a more plausible explanation is that short-term storage and re-mobilisation of fine sediment between Place Lake and the valley bottom occurred during the 24 hr cycle. On the falling hydrograph limb, large within-channel boulders may have provided a surface onto which clay and silts were deposited. During the rising hydrograph limb, some of this fine sediment could have been re-mobilised as the water level rose up around the boulders. Estimates made in Section 3.6 revealed that between 5 Aug 12:00 and 6 Aug 11:59, approximately 12,000 kg of sediment left Place Lake, but only 9000 kg passed by the valley-bottom site. Thus the value of –3000 ±200 kg for the approximate daily suspended sediment budget at the mouth of the basin may provide evidence for a net loss of sediment to channel storage during diurnal glacier melt cycles. It must be noted, however, that the sediment budget is an estimate and to validate the difference in upstream-downstream fluxes would require lake outlet discharge to be measured.

At the end of August (Figure 3.15b), suspended sediment supply from the Place Lake was complicated by rainfall runoff, as evidenced by the undulating SSC series at the lake outlet, which was probably induced by periodic inputs of sediment from the slopes surrounding the lake. The only time at which valley SSC approached values measured at the lake outlet was at the glacial melt discharge peak on 30 Aug. It can be deduced, therefore, that either transient stores of fine glacial sediment were not re-mobilised during the storm event, or that the rainfall component of discharge, generated downstream of the lake outlet, had a relatively low SSC and thus served to 'dilute' the glacial component of total SSC. The former is possible because streamflow was approximately 1 m^3/s less in the late August measurement period than in early August. Thus maximum discharge on 29 Aug would not have risen to heights on within-channel boulders that minimum streamflow reached on 5 Aug. The latter is plausible because at the synoptic scale it was shown in Section 4.1.2 that storm event sediment supplies were progressively exhausted from event to event, unless discharge rose beyond values previously reached in the season (i.e., during the largest event of the season, on 27 to 28 July).

4.1.4 Integrated temporal scales

The separate SSC-Q rating relations for Place Creek (Figure 3.11) indicated that seasonal suspended sediment transport is principally controlled by two sources of streamflow, glacial and nival, combined with a nival-glacial mixture and rainfall runoff. The points within the three sub-seasons plot in different areas of the SSC-Q plot. Initially, the slope of the relation was steep during the nival period as early season discharge events (both rainfall and snowmelt derived) flushed out sediment that had accumulated over the preceding winter. In the nival-glacial period, the slope decreased because only sand-sized material was being transported and large discharge events did not entrain as much sediment as earlier in the season. Finally, during the glacial period, the average suspended sediment particle size likely decreased from sand- to silt- and clay-sized material. Accordingly, the intercept of the SSC-Q rating function increased as more sediment could be transported at relatively lower discharges, than over the nival-glacial transition period. Thus from a seasonal to sub-seasonal scale, the groups of points in Figure 3.11 moved in an anticlockwise direction, producing anticlockwise hysteresis.

At the diurnal scale, Sub-section 3.5.4 highlighted different types and strengths of diurnal scale hysteresis. Changes in diurnal hysteresis imply that different sediment and water delivery processes occur through the season. For storm runoff events, the strength and clockwise direction of hysteresis during the early season suggest that the bulk of suspended sediment was flushed through the basin during the rising limb of storm hydrographs (Figure 3.12a). Later in the season, however, the loops were both tighter and anticlockwise during rain events (Figure 3.12b), indicating that the sediment did not reach the channel until the falling hydrograph limb. The seasonal change in the character of storm-hysteresis probably reflects the decrease in supply of near-bank sediment, which would have been washed into the channel during early season storm events. Thus sediment that is supplied to the channel during late season storms may take a longer time to be transported to the channel by rainfall runoff.

During the nival period, complex hysteresis was noted in Figure 3.12d, in which the latter part of the loop was vertical and anticlockwise. This irregular loop illustrates the importance of preceding events, which in this case was a rain event. On the falling limb of the storm hydrograph, maximum daily air temperature rose from 20°C on 2 July to 28°C on 3 July. It is plausible, therefore, that although discharge was declining, the storm runoff proportion of streamflow was also declining and being replaced by nival-glacial meltwater which may have initially been carrying higher values of SSC. Another interesting loop on 21-22 July (Figure 3.12e) depicts a 'figure 8' formation. The 'figure 8' loop in Figure 3.12e combined initially clockwise and then anticlockwise sub-loops. The former occurred during higher and the latter at lower discharge, implying that following peak flow, sediment availability was great enough that SSC decreased more slowly than discharge. This figure 8 loop also occurred at the end of the nival-glacial season and so again it may be that diurnal changes in hydrologic sources, from nival to glacial, are reflected in the pattern of SSC-Q hysteresis.

During the glacial season, clockwise hysteresis at both diurnal and synoptic scales (Figure 3.13) provided evidence of sediment flushing prior to daily and synoptic peaks in discharge. It is probable that such flushing is of sediment stored within the channel. This sediment may have been derived from its deposition during falling diurnal hydrograph limbs on a daily timescale and, on a synoptic scale, from its deposition during the receding weekly hydrograph limb following high flows during early August.

The integration of diurnal, synoptic and seasonal timescales is of fundamental importance in the attempt to understand the proglacial suspended sediment transport system in Place Creek. It has been argued in this thesis that different water sources exert different hydrologic controls on downstream values of SSC in Place Creek. However, to predict accurately how SSC will respond to different hydrologic conditions, effects of processes at different timescales must be integrated. The aim of the next section is, therefore, to show how the MLR models presented in Sub-section 3.4.3 incorporate the ideas of integrated timescales presented in this Sub-section and to analyse the process inferences that can be made from the significant variables in each sub-season MLR model.

4.2 Modelling SSC

Figure 4.1 summarises the stages followed in this study in order to obtain predictions of SSC, firstly using the CUSUMS technique to sub-divide the seasonal discharge series and then using the MLR models in Table 3.5. Temporal scales are shown above each stage and the final predicted value of SSC represents the integration of the timescales within which each stage operates. Within the sub-seasonal stage, the nival-glacial and then glacial periods are indirectly influenced by the legacies of previous sub-seasons within the entire hydrological season. The diurnal and synoptic scales are combined because each of the predictor variables operates within both scales.

Considerable improvement in the accuracy of the sub-season MLR models, over the sub-season OLS models (Table 3.4), is shown by the high adjusted R^2 (R^2_{adj}) values (Table 3.5). The R^2_{adj} for the nival period may be slightly higher because *n* was smaller and only spanned the period 18 May to 17 June. The prevailing hydrologic conditions and sources of suspended sediment within this time were likely to be more similar than for the entire nival period. For the nival-glacial period, however, the hydrology of the basin was transitional and for the glacial season the period encompassed over two months. During these latter sub-seasons, therefore, it could be expected that model accuracy would be lower than for the nival season because as time increases the stochastic element in the data set may also increase. Such stochastic model elements can, in part, be attributed to short-term SSC autocorrelation and be accounted for by adding a lagged SSC predictor variable to each of the models in Table 3.5 (Hodson and Ferguson, 1999). Having added SSC, lagged by sample interval, as an additional predictor, R^2_{adj} values improved by up to 0.1. The MLR models

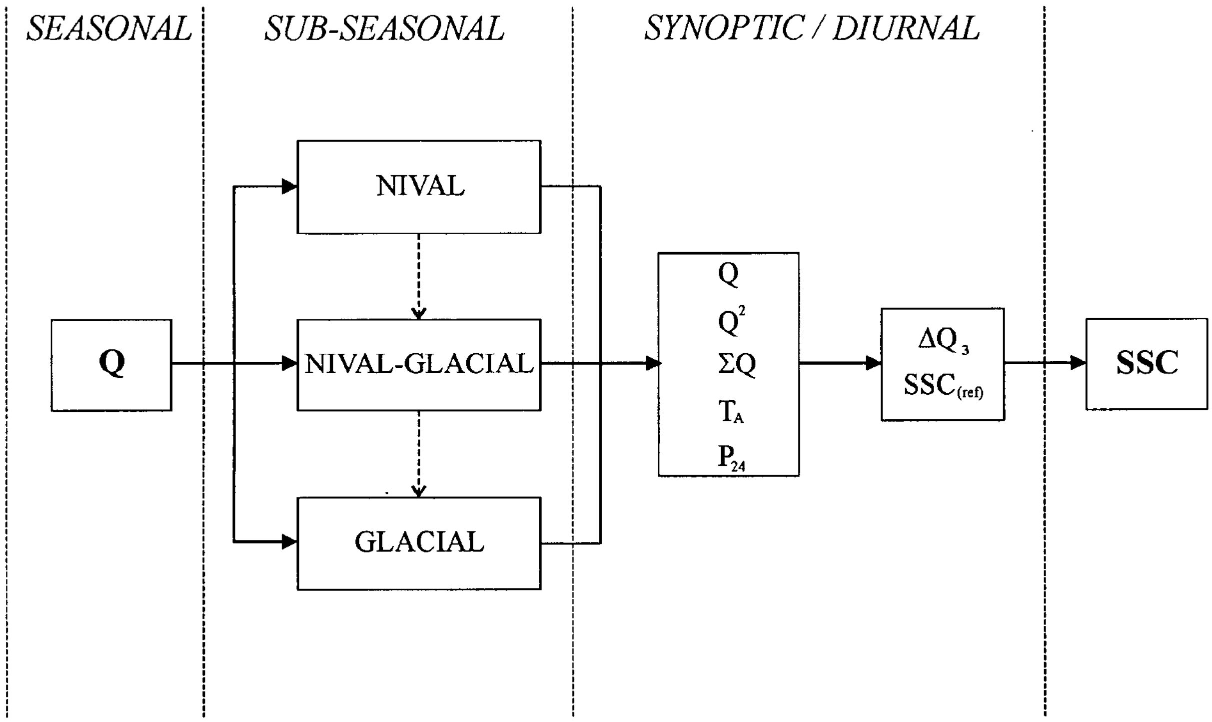


Figure 4.1: Flow chart model for prediction of SSC from sub-seasonal MLR models.

would, however, become redundant for cost-effective SSC prediction because a close-interval sampling scheme would be required to calculate values of such lagged SSC variables.

In all of the sub-season MLR models, Q_{t-1} was not significant because its contribution to the model is provided through the combination of the other significant predictor variables. Its insignificance in, for example, the nival season may reflect low mean SSC (9.9 mg/L) for the nival period (Table 3.2) and that when SSC was highest (during rain events), most of the variability in SSC was explained by P_{24}.

For the nival period, the predictors are (in order of decreasing significance) Q^2, P_{24}, ΔQ_3, ΣQ and $SSC_{(ref)}$. All these variables have positive coefficients, indicating that as they increase they cause a collective increase in SSC. From what was reported earlier in this section, it appears that for the nival period, ΣQ does not, therefore, represent a decreasing supply of sediment. Rather, its positive coefficient possibly reflects the relatively high values of SSC recorded during the rainfall events over the nival period rather than an increasing area of suspended sediment supply. Even though it is insignificant, $SSC_{(ref)}$ is included in the model because it was 'forced' in through the selection process. Its contribution to the overall model may be relatively small because mean SSC for the nival season was low compared to the nival-glacial and glacial seasons (Table 3.2).

The MLR model for the nival-glacial period incorporates $SSC_{(ref)}$, ΔQ_3, Q^2, ΣQ,T_A, P_{24} and Q in order of decreasing significance. For this model, the increasing importance of $SSC_{(ref)}$ is reflected in the increased variability of SSC through the nival-glacial season and thus the need for a reference value. As glacial melt became a more established component of stream discharge during July, ΔQ_3 also became more important because the major portion of daily suspended sediment transfer occurred on the rising hydrograph limb in Place Creek. The coefficient of P_{24} was negative because rainy conditions correlated with subdued snow and glacial melt production. Discharge and T_A became significant, but also had negative coefficients, possibly because the individual effects of the variables are confounded by the other predictors. The negative coefficient of ΣQ implies that seasonal sediment supply exhaustion played a significant role in the temporal control on SSC through the nival-glacial period.

During the glacial sub-season, the MLR model contains Q, $SSC_{(ref)}$, ΣQ, ΔQ_3, P_{24} and T_A in order of decreasing significance. Air temperature is the only variable with a negative coefficient and this is likely to be a function of the passage of storm systems with associated pulses of high SSC. A positive coefficient is produced for ΣQ, indicating that during the ablation season, the supply of suspended sediment (dominantly glacially derived) was not exhausted as commonly noted in the literature. As for the nival-glacial model, $SSC_{(ref)}$ and ΔQ_3 were significant. The former shows that the hydrologic control on proglacial suspended sediment dynamics changed on short timescales. The latter again provides evidence that most sediment is transported during the rising limb of the diurnal glacial melt hydrograph.

Overall, the MLR models in Table 3.5 can be relied upon to give accurate predictions of SSC because the PRESS statistics were low (Table 3.6). Additionally, the regression assumptions are generally met for these models. The need for $\log_e$ transformations and associated problems of bias is thus avoided. Although the glacial MLR model did not meet the regression assumptions, most MLR SSC prediction models proposed in the literature acknowledge that such assumptions are difficult to meet, given white noise in the data set (e.g. Hodgkins, 1999). Frequently, measurements are discarded in the literature without adequate reason, besides being outliers. In this study, no data were discarded because no obvious measurement error was noted for any of the samples. From discussions of transient sediment storage in Section 4.1, it may be that during the glacial period, the relation between SSC and its suite of glacial period predictors is complicated by short term pulses of sediment derived from within channel stores such as the surface of large boulders.

Chapter 5
Conclusions

5.1 Summary of key findings

5.1.1 SSC-Q relations in a glacier-fed stream

Place Creek is dominated by a nival- and glacial-melt discharge regime, which is punctuated by storm runoff events. A simple SSC-Q rating relation was shown in Sub-section 3.5.1 to be an inaccurate SSC prediction tool. In order to investigate the hypothesis that different sources of water exert different controls on the SSC-Q relation, the seasonal Place Creek discharge series was divided into sub-seasons. Corresponding sub-seasonal OLS rating curves showed great improvement. Coupled with EC data that supported the hypothesis that streamflow within the sub-seasons was derived from different sources (snowmelt, glacier-melt and groundwater), it can be concluded that a fundamental source of explanation for the scatter in the seasonal SSC-Q relation is provided by the transition from nival to nival-glacial and finally to glacial sources of runoff, combined with periodic inputs of storm runoff through the season.

5.1.2 Multiple regression models

The use of MLR models to predict SSC from a suite of variables has arguably been extended in the literature to the point at which they are no longer time or cost efficient to evaluate over subsequent seasons. The simple sub-seasonal MLR models presented in Sub-section 3.5.3 can be evaluated from easily measured predictors and thus provide a cost efficient tool with which to predict accurately SSC in Place Creek over future seasons. The MLR models themselves represent an integration of timescales, from seasonal to diurnal. Their improved accuracy from the sub-seasonal OLS models indicates that they provide additional explanation for the scatter in the SSC-Q relation that cannot be accounted for at the sub-seasonal scale. The detailed data set that was used to derive the MLR model parameters in this thesis represents an extensive and accurate record of SSC, something that has rarely been achieved in the literature.

5.1.3 Within-channel transient sediment storage

Place Creek appears to be an example of a sediment-transfer system that is dominated by a transient diurnal storage mechanism within the ablation season, possibly provided by the surface of large within-channel boulders. Such storage has not been widely acknowledged in the literature, largely because of a lack of intensive studies of upstream-downstream changes in SSC in streams with minimal tributary or groundwater inflow. Place Lake was shown to be a regulating sink for fine glacially-derived sediment, while diurnal fluctuations of downstream SSC and a negative suspended sediment budget at the basin mouth suggested that the sediment was deposited and re-mobilised within the channel. These data are compatible with the boulder storage hypothesis.

5.2 Future research

Clearly this thesis presents a number of claims that require further evidence to validate. Future research projects could (a) generate daily sediment budgets for the entire glaciofluvial lacustrine system; (b) investigate the trapping efficiency of Place Lake and how it varies with discharge; (c) undertake a more extensive upstream-downstream monitoring campaign of SSC and discharge; (d) analyse the caliber of the suspended sediment transported down Place Creek in order to identify spatial and temporal changes in sediment-source areas; (e) collect geochemical data from water samples for diurnal, synoptic and seasonal hydrograph separation with the aim of providing more detailed divisions of water sources that affect the

SSC-Q relation, particularly to investigate the hypothesis that the changes in the EC-Q relation reflect seasonal changes in the location of water sources.

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Appendix A

```
Dummy coding used for categorical variables in model.
Categorical values encountered during processing are:
SEASON (3 levels)
          0,         1,         2
Step # 0 R =  0.805 R-Square =  0.648
Effect              Coefficient   Std Error  Std Coef     Tol.  df        F      'P'
In
___
  1 Constant
  2 Q                    15.673       0.722      0.683 0.53046   1 471.126    0.000
  3 SEASON                    .           .          . 0.08622   2  23.614    0.000
  4 SEASON*Q                  .           .          . 0.09959   2  21.165    0.000
Out                 Part. Corr.
___
    none
-------------------------------------------------------------------------------

Estimates of effects
                                      SSC
   CONSTANT                           1.332
   Q                                 15.673
   SEASON       0                   -19.436
   SEASON       1                    -5.716
   SEASON       0
   Q                                 15.642
   SEASON       1
   Q                                 -3.811

                              Analysis of Variance
Source                Sum-of-Squares   df  Mean-Square     F-ratio       P

Regression               75547.344      5    15109.469     246.677       0.000
Residual                 40977.537    669       61.252
--------------------------------------------------------------------------------
```