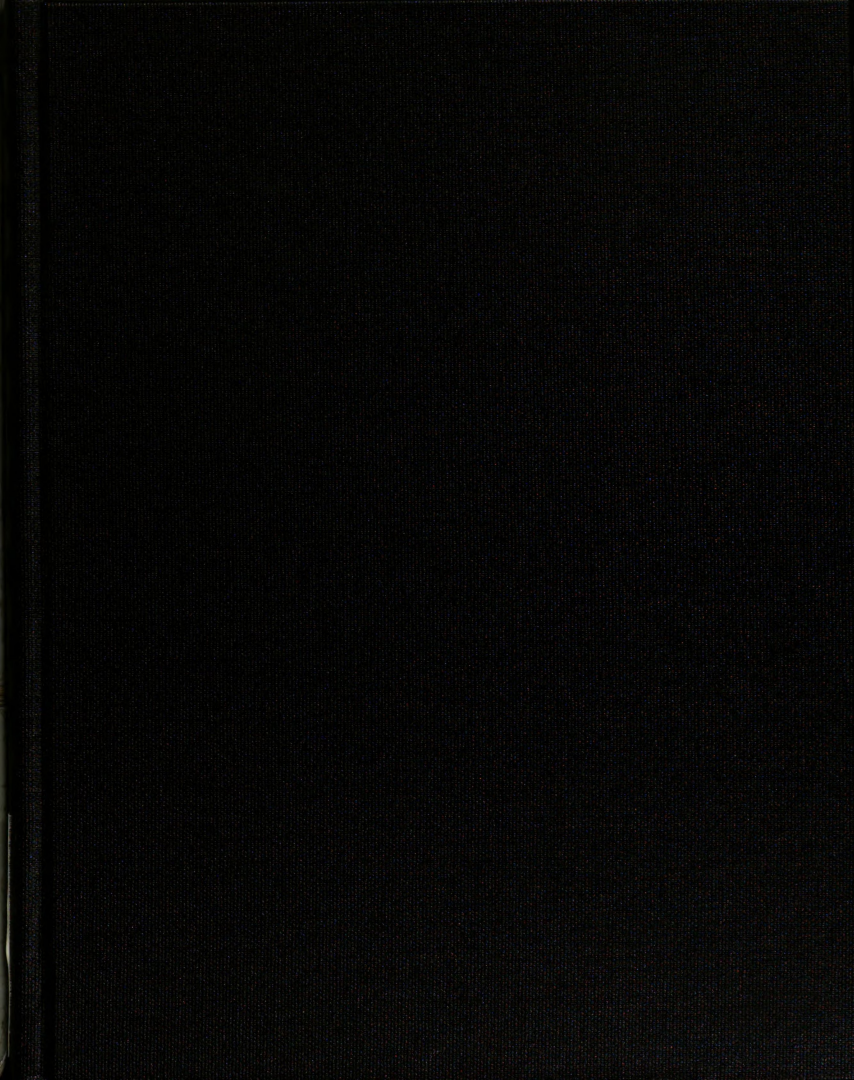




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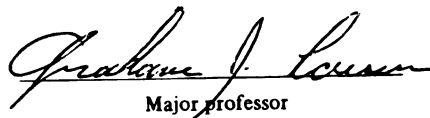
**Sediment Flux as an Indicator of
Glacial Erosion, Matanuska Glacier
Alaska**

presented by

John S.Linker Jr.

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**SEDIMENT FLUX AS AN INDICATOR OF GLACIAL EROSION
MATANUSKA GLACIER, ALASKA**

By

John S. Linker Jr.

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

Department of Geological Sciences

2001

ABSTRACT

SEDIMENT FLUX AS AN INDICATOR OF GLACIAL EROSION MATANUSKA GLACIER, ALASKA

By

John S. Linker Jr.

Gravimetric sampling of daily suspended sediment of melt water, collected at 2 hour intervals during the 1997-2000 ablation seasons for melt streams and selective vents draining the terminus of the Matanuska Glacier, Alaska, was determined in order to assess the temporal variation of sediment flux with discharge and the annual sediment yield. The seasonal pattern of suspended sediment transport in melt water streams shows large sediment pulses early in the ablation season, followed by more subdued variations in sediment flux later in the ablation season. The pulses likely result from the rapid expansion of the developing subglacial drainage system into areas of the glacier subsole where fine products of glacial abrasion are stored. The suspended sediment record also shows that sediment pulses at different vents are generally not in phase and may be due to sudden localized expansion of the subglacial drainage system. Assuming a bed load contribution of approximately 35%, the total sediment flux for the Matanuska Glacier during the 1997-2000 melt seasons ranged from $2.68\text{E}+03$ tonnes km^{-2} for the 2000 melt season to $5.58\text{E}+03$ tonnes km^{-2} for the 1999 melt season. These fluxes represent a range of subsequent erosion rates of 1.01 mm yr^{-1} for the 2000 melt season to 2.08 mm yr^{-1} for the 1999 melt season. These rates are substantially less than rates published for the large glaciers of southeastern Alaska but are comparable to rates published for glaciers in the European Alps and central Asia.

ACKNOWLEDGEMENTS

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INTRODUCTION

Large quantities of sediment are transported by melt water streams emanating from the margins of mountain glaciers and it has been suggested that sediment flux can be used to estimate the rate of glacial erosion (Ostrem, 1975; Gurnell, 1987; Bezing, et al. 1989; Hallet et al, 1996). This is particularly the case with respect to the sediment flux during the ablation season because it generally represents the bulk of the annual sediment flux from glaciers (Collins, 1998).

Certain factors, however, can complicate quantification of the sediment flux. They include the method used to sample suspended sediment, determining the ratio of suspended sediment to bed load, and approximating the influx of sediment derived from subaerial erosion of nonglacierized areas (Fenn, et al., 1985; Collins, 1998). Most importantly, annual variability of sediment production caused by changes in subglacial drainage systems or temporary storage of sediments within and/or beneath the ice necessitates the frequent collection of long term, annual data sets in order to produce a more representative estimation of glacial erosion (Gurnell, 1987; 1996; Bezing, et al. 1989; Hallet et al, 1996; Collins, 1989; 1998).

Results from a number of studies on sediment flux from various glacierised basins have been compiled by Hallet et al (1996), showing that a broad range of estimated erosion rates exist for glaciers around the world (Table 1) based frequently upon suspended sediment data and bed load estimates which often contain great uncertainty. For example, Ostrem (1975) monitored suspended sediment flux from several Norwegian glaciers and subsequently calculated average annual erosion rates ranging from .08 mm yr⁻¹ to .77 mm yr⁻¹ using data collected over a five year period. The bed load flux was not

**Several erosion rates of various glacierised basins
(Hallet, et. al. 1996)**

Glacier	Effective erosion (mm yr⁻¹)	Reference
• Nigardsbreen, Norway	0.15	Hallet, et. al. 1996
• Engabreen, Norway	0.41	Bogen, 1989
• Tsidjore, Swiss Alps	0.56	Bezing, 1987
• Gorner, Swiss Alps	1.4	Bezing, 1987
• Jokulsa, Iceland	3.8	Lawler et. al. 1992
• Hubbard, Alaska	13.71	Carlson, 1989
• Muir, Alaska	28.05	Hunter, 1994
• Margerie, Alaska	60.07	Hunter, 1994

Table 1: Effective erosion rates recorded for several glaciers around the world. Compiled by *Hallet, et. al. 1996*.

accounted for in the erosion rates, however a steel mesh fence was erected at the Nigardsbreen Glacier in attempt to evaluate the bed load. Several weeks of data collection enabled an approximate bed load component of 25% to be generated for the melt water stream (Ostrem, 1975). The flux of suspended sediment was also used by Collins (1998) as an indicator of glacial erosion for the Batura Glacier in the Karakoram Mountains of Pakistan. He calculated an annual erosion rate of approximately 7.7 mm yr⁻¹, generated from suspended sediment data gathered throughout a single ablation season and a conservative bed load estimation of 50% derived from published suspended sediment to bed load ratios estimated from melt water streams draining several other glaciers from around the world (Ostrem, 1975; Gurnell, et al. 1988). In addition, other studies from a diverse group of glacierised basins suggest that sediment fluxes and rates of glacial erosion may vary by several orders of magnitude as a result of variations in the size and type of glacier and the lithologic characteristics of the underlying bedrock

(Ostrem, 1975; Hallet et al., 1996). All of these have shown that rates of glacial erosion can range from approximately 0.1 mm yr^{-1} for relatively small, temperate Norwegian glaciers that override resistant crystalline bedrock to $10\text{-}100 \text{ mm yr}^{-1}$ for the relatively large, temperate glaciers of southeast Alaska which erode less resistant bedrock in a tectonically active region (Hallet et al., 1996).

Research has suggested that the production of glacial sediment can have a profound effect on river dynamics such as aggradation and progradation, in addition to influencing biological aspects such as nutrient content, bacterial growth, and photosynthetic processes (Bogen, 1989). Glacial sediment can also significantly influence the development of hydroelectric power in glacierised basins (Bezing, 1987; Bogen, 1989). In recent years, the role of glacial erosion in global climate change has received much more attention from scientists because of its ability to expose large areas of bedrock to the effects of chemical weathering and its effect on topographical development (Hallet et. al. 1996).

The objective of this research is to calculate the average annual erosion rate for the Matanuska Glacier of south-central Alaska from the flux of suspended sediment measured in melt water streams emanating from the glacier margin over four consecutive melt seasons. The resulting average erosion rate will then be compared to calculated erosion rates for other glaciers around the world.

FIELD DESCRIPTION

The Matanuska Glacier is a large valley glacier that extends north-northwest out of the Chugach Mountains of south central Alaska (Figure 1). It is approximately 45 km in length, ranges in width from 3 km up-glacier to approximately 5 km at the terminus, and occupies about 57% of an elongate drainage basin that covers approximately 665 km² (Strasser et al. 1996). The general bedrock of the basin consists predominantly of sedimentary and low to mid-grade meta-sedimentary rocks (Beikman, 1980). The glacier varies in elevation from 3500 m near its source to approximately 500 m at the terminus (Lawson, et al. 1998). Estimates suggest that the glacier terminus has retreated at a rate of approximately 10-30 m yr⁻¹ over the past decade (Lawson, unpublished).

Proglacial Drainage System

A complex network of subglacial channels emerges from the glacier terminus as individual vents (Figure 2). Several of these occur along the southwestern edge of the terminus and merge to form a shallow proglacial lake and the subsequent headwaters of the South Branch, Matanuska River, which flows approximately 8 km to the west and empties into the Matanuska River. A relatively large vent also emerges from the northern edge of the terminus and is the primary source of water for the North Branch, Matanuska River, which flows approximately 150 m north into the Matanuska River. Another significant vent emerges from the western edge of the terminus and is the source for Bridge Stream, which subsequently flows to the west, entering the South Branch approximately 500 m downstream from the glacier terminus. Several minor vents also

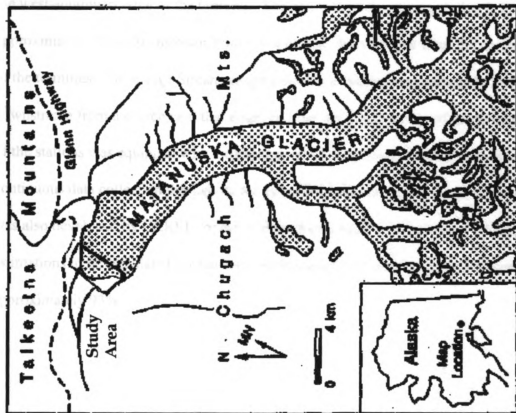


Figure 1: Location of Matanuska Glacier, Alaska (Strasser, et al. 1996)

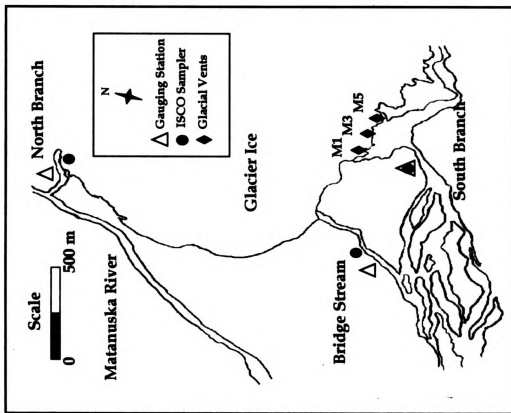


Figure 2: Margin of the Matanuska Glacier

occur along the north-northeast edge of the terminus, but are insignificant and were not sampled for this research.

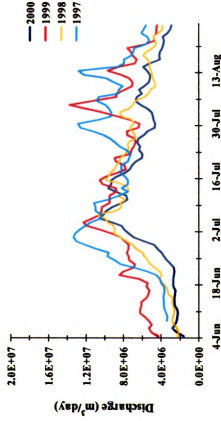
DISCHARGE

Discharge Measurements

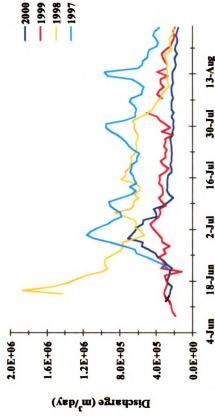
Since May 1995, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) has maintained gauging stations on the South Branch and North Branch, Matanuska River to monitor stream discharge, stream water temperature, conductivity, and dissolved oxygen content every ten minutes (Figure 2). A gauging station was also maintained on Bridge Stream beginning in May 2000.

The South Branch gauging station is located approximately 200 m from the glacier terminus and monitors the combined discharge from all the vents located along the west-southwest edge of the terminus. The North Branch gauging station is located approximately 25 m downstream from a source vent that emerges from the northern edge of the terminus. The Bridge Stream gauging station is located approximately 200 m downstream from a source vent that emerges from the western edge of the terminus. Each of the stations was equipped with a datalogger and nitrogen gas bubbler enabling continuous data collection throughout the year. An annual stage-discharge-rating curve was also developed by CRREL for the three streams, which enabled hourly discharge estimations to be calculated for the entire melt season with a measurement accuracy of approximately 93%.

South Branch, Matanuska River
1997-2000



North Branch, Matanuska River
1997-2000



Bridge Stream
2000

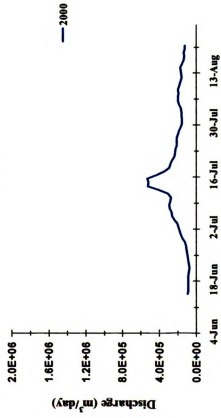


Figure 3: Daily discharge recorded from June-August at the three sample locations. *Note the large peak at the onset of the 1998 melt season at North Branch was caused by ice damming of water and not a true discharge.

Discharge Characteristics

Daily discharge recorded during the 1997-2000 ablation seasons at South Branch and North Branch and during the 2000 melt season at Bridge Stream typically show a substantial rise in discharge occurring between 20 and 26 June, reaching peak discharge between 30 June and 8 July (Figure 3). Peak daily discharges are often 3-4 times the discharge observed at the onset of the melt season. Daily discharge tends to gradually decrease throughout the remainder of the ablation season, with the exception of several large peaks that occurred between 30 July and 14 August 1997 and 2 and 9 August 1999, likely the result of several significant precipitation events.

Melt Season	South Branch	North Branch	Bridge Stream	Total Discharge
• 2000	0.44 km ³	0.02 km ³	0.01km ³	0.47 km ³
• 1999	0.64 km ³	0.03 km ³	————	0.67 km ³
• 1998	0.51 km ³	0.04 km ³	————	0.55 km ³
• 1997	0.65 km ³	0.05 km ³	————	0.70 km ³

Table 2: Total discharge recorded at South Branch and North Branch, Matanuska River and Bridge Stream during June-August 1997-2000. *Note: Bridge Stream was not a significant contributor during much of the 1997-1999 melt season.
% Error: $\pm 7\%$

Total discharge from the Matanuska Glacier recorded between June and August of 1997-2000 ranged from approximately .47 km³ in 2000 to approximately .70 km³ during the 1997 ablation season (Table 2). During the 1997-1999 melt seasons, approximately 94% of the total annual discharge from the glacier flowed through South

Branch, whereas approximately 6% flowed through the North Branch. Discharge through the Bridge Stream was insignificant during most of the 1997-1999 melt seasons and was therefore not measured. During the 2000 melt season, approximately 93% of the total annual discharge from the glacier flowed through South Branch, approximately 5% flowed through North Branch, and approximately 2% flowed through Bridge Stream.

MEASUREMENT OF SEDIMENT FLUX

Suspended Sediment

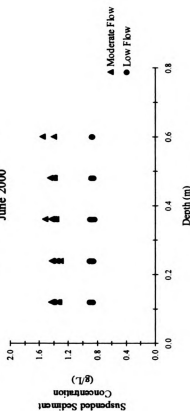
ISCO automatic samplers were utilized to collect suspended sediment samples from the three main streams that drain the Matanuska Glacier (Figure 2). The sampler located on South Branch was deployed approximately 200 m from the western terminus of the glacier, adjacent to the South Branch gauging station, and continuously collected samples from early June through late August, 1997-2000. The sampler located on North Branch was deployed in a large vent that forms the headwaters of the stream, approximately 25 m upstream from the North Branch gauging station, and continuously collected suspended sediment samples from late July through late August, 1999 and early June through late August, 2000. The sampler located on Bridge Stream was deployed approximately 150 m from the edge of the glacier terminus, approximately 50 m upstream from the Bridge Stream gauging station, and continuously collected samples from early June through late August 2000. Bridge Stream was not sampled during 1997-1999 melt seasons because it was not a significant melt water stream.

ISCO samplers were also deployed from mid-June through late August 1999 in several vents (M1, M3, and M5 in Figure 2) located along the west-southwest edge of the glacier terminus. These were sampled in order to compare the suspended sediment recorded at the vents with that recorded at South Branch.

The intake apparatus of each sampler was connected to approximately 15 m of 1.5 cm diameter latex tubing and anchored approximately 10-30 cm above the channel bed within each stream or anchored within the opening of the three vents. Each sampler had the capacity to hold up to twenty-four, 500 ml samples of water, which were later processed by vacuum filtration through individually pre-weighed filter circles. The sediment laden filter circles were then dried in an oven at 110°C and gravimetrically weighed to a precision of ± 1 mg. A sediment concentration in terms of g/L (equivalent to kg/m^3) was then calculated by dividing the mass of the dried suspended sediment sample by the volume of the collected water sample. Concentrations of suspended sediment recorded at South Branch, North Branch, Bridge Stream ranged from 0.3g/L to 32.4g/L.

Several suspended sediment samples collected on South Branch during low and high discharge periods of the 1999 melt season were also dry-sieved in order to approximate the coarsest sediment fraction in suspension. The sieve analyzes show that sediment of 0.5 phi units (coarse sand) and smaller were suspended during low discharge periods, whereas sediment of -0.5 phi units (very coarse sand) and smaller were suspended during periods of high discharge. Therefore, suspended sediment defined in this study is sediment that is less than 0.0 phi units (coarse sand), whereas bed load is defined as sediment that was 0.0 phi units and larger.

Vertical Variability of Suspended Sediment
South Branch, Matanuska River
June 2000



Horizontal Variability of Suspended Sediment
South Branch, Matanuska River
June 2000

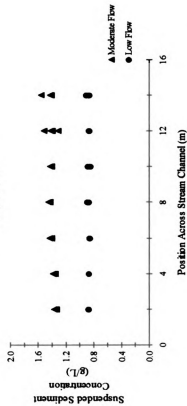
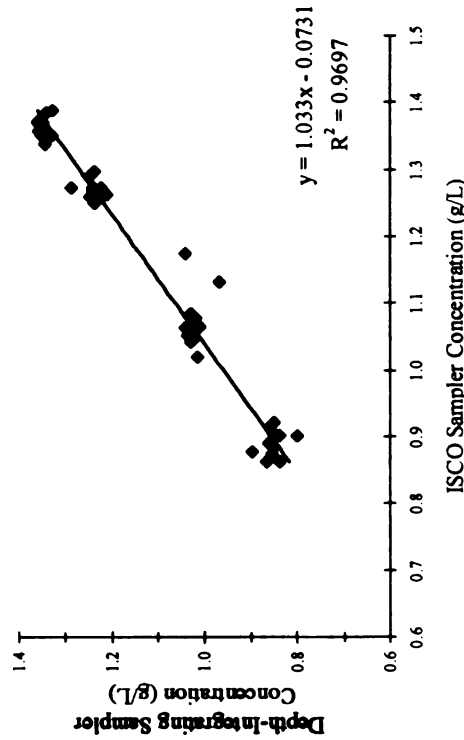


Figure 4: Scatter-plot showing validity of point sampling within the South Branch, Matanuska River. Samples were taken every 2 m across the width of the stream channel and every .12 m vertically within the channel. The table shows actual suspended sediment concentrations recorded at South Branch during low and moderate flow regimes during 7 and 10 June, 2000.

Matanuska Glacier 2000										
Suspended Sediment Distribution at South Branch										
Moderate Flow (I)										
S.S. Con. (g/L)	Depth (m)	Width (m)	S.S. Con. (g/L)	Depth (m)	Width (m)	S.S. Con. (g/L)	Depth (m)	Width (m)	S.S. Con. (g/L)	
1.333	0.12	10	1.404	0.12	10	1.424	0.12	10	1.424	
1.350	0.24	10	1.426	0.24	10	1.426	0.24	10	1.426	
1.367	0.36	10	1.413	0.36	10	1.413	0.36	10	1.413	
1.355	0.48	10	1.413	0.48	10	1.413	0.48	10	1.413	
1.380	0.60	10	1.413	0.60	10	1.413	0.60	10	1.413	
1.388	0.72	10	1.309	0.72	12	1.309	0.72	12	1.309	
1.437	0.84	12	1.516	0.84	12	1.516	0.84	12	1.516	
1.411	0.96	12	1.393	0.96	12	1.393	0.96	12	1.393	
1.400	1.08	12	1.398	1.08	12	1.398	1.08	12	1.398	
1.400	1.20	12	1.400	1.20	12	1.400	1.20	12	1.400	
1.428	1.32	14	1.416	1.32	14	1.416	1.32	14	1.416	
1.428	1.44	14	1.424	1.44	14	1.424	1.44	14	1.424	
1.430	1.56	14	1.419	1.56	14	1.419	1.56	14	1.419	
1.449	1.68	14	1.553	1.68	14	1.553	1.68	14	1.553	
Low Flow (II)										
S.S. Con. (g/L)	Depth (m)	Width (m)	S.S. Con. (g/L)	Depth (m)	Width (m)	S.S. Con. (g/L)	Depth (m)	Width (m)	S.S. Con. (g/L)	
0.866	0.12	10	0.855	0.12	10	0.855	0.12	10	0.855	
0.866	0.24	10	0.880	0.24	10	0.880	0.24	10	0.880	
0.866	0.36	10	0.880	0.36	10	0.880	0.36	10	0.880	
0.868	0.48	10	0.850	0.48	10	0.850	0.48	10	0.850	
0.868	0.60	10	0.863	0.60	10	0.863	0.60	10	0.863	
0.868	0.72	12	0.861	0.72	12	0.861	0.72	12	0.861	
0.868	0.84	12	0.857	0.84	12	0.857	0.84	12	0.857	
0.859	0.96	12	0.857	0.96	12	0.857	0.96	12	0.857	
0.857	1.08	12	0.857	1.08	12	0.857	1.08	12	0.857	
0.857	1.20	12	0.857	1.20	12	0.857	1.20	12	0.857	
0.857	1.32	12	0.857	1.32	12	0.857	1.32	12	0.857	
0.859	1.44	14	0.904	1.44	14	0.904	1.44	14	0.904	
0.868	1.56	14	0.901	1.56	14	0.901	1.56	14	0.901	
0.870	1.68	14	0.857	1.68	14	0.857	1.68	14	0.857	
0.894	1.80	14	0.878	1.80	14	0.878	1.80	14	0.878	
0.882	1.92	14	0.864	1.92	14	0.864	1.92	14	0.864	
Summary Statistics										
MEAN (I)		1.4100	MEAN (II)		0.8664	VAR. (I)		0.0024	VAR. (II)	
ST. DEV. (I)		0.0487	ST. DEV. (II)		0.0154	% ERR. (I)		4.0986	% ERR. (II)	
ST. DEV. (I)		0.0154	ST. DEV. (II)		0.0154	% ERR. (I)		1.6512	% ERR. (II)	

Instrumentation Error
South Branch, Matanuska River
June 2000



ISCO Sampler Suspended Sediment Concentrations (g/L)				
Low Stage I	Low Stage II	High Stage I	High Stage II	
1.387	0.901	1.272	1.046	
1.374	0.920	1.272	1.052	
1.370	0.890	1.272	1.068	
1.385	0.873	1.269	1.065	
1.370	0.903	1.296	1.019	
1.357	0.862	1.269	1.043	
1.357	0.901	1.289	1.062	
1.351	0.918	1.262	1.077	
1.351	0.884	1.265	1.085	
1.351	0.901	1.260	1.064	
1.344	0.862	1.259	1.132	
1.336	0.877	1.248	1.174	

Depth-Integrating Sampler Suspended Sediment Concentrations (g/L)				
Low Stage I	Low Stage II	High Stage I	High Stage II	
1.327	0.800	1.287	1.025	
1.352	0.851	1.240	1.037	
1.348	0.862	1.222	1.022	
1.342	0.854	1.241	1.011	
1.360	0.850	1.237	1.015	
1.358	0.867	1.238	1.030	
1.343	0.845	1.246	1.022	
1.352	0.855	1.211	1.020	
1.330	0.850	1.231	1.029	
1.332	0.839	1.224	1.040	
1.341	0.839	1.247	0.968	
1.343	0.897	1.237	1.041	

Low Stage I	Low Stage II	High Stage I	High Stage II	
St.Dev 0.016	Var. 0.0003	St.Dev 0.022	Var. 0.0005	% Err. 1.984
MEAN 1.352		MEAN 1.254		

Low Stage I	Low Stage II	High Stage I	High Stage II	
St.Dev 0.029	Var. 0.0008	St.Dev 0.042	Var. 0.0017	% Err. 4.055
MEAN 0.871		MEAN 1.048		

Figure 5: Scatter-plot showing the concentration of suspended sediment at South Branch, Matanuska River obtained from ISCO sampler versus depth-integrating sampler. The table shows actual suspended sediment concentrations recorded during low and high stages at South Branch for 7 and 10 June, 2000. Samples were collected every 2 minutes.

In order to test the validity of point sampling, suspended sediment samples were also collected from selective points within the South Branch channel using a depth-integrating sampler. These samples were collected at approximately 2 m intervals across the width of the stream channel and at approximately 10 cm intervals throughout the water column. The suspended sediment concentrations derived from using the depth-integrating sampler exhibit a spatial variability of $\pm 4\%$ for suspended sediment concentrations throughout the stream channel (Figure 4), which can be attributed to mixing caused by turbulent flow.

Samples acquired using the depth-integrating sampler were also compared to samples acquired from using the ISCO sampler at South Branch. A plot of the suspended sediment data (Figure 5) shows that concentrations derived using the depth-integrating sampler vary little compared to suspended sediment concentrations acquired using the ISCO sampler. However, the data does show that the ISCO sampler consistently over-samples suspended sediment by approximately 7%. Subsequently, all suspended sediment concentrations obtained using the ISCO samplers were corrected for this sampling error.

A logarithmic plot of melt water discharge draining the Matanuska Glacier versus suspended sediment recorded at South Branch and North Branch, and at Bridge Stream is presented in Figure 6. It shows that a considerable amount of scatter exists between suspended sediment and discharge. This is likely the result of remobilization of sediment within the stream channel and/or exhaustion and exposure of stored sediment at the glacier bed caused by fluctuations in the subglacial drainage network. (Fenn et al, 1985; Gurnell, 1987). However, the plot does show a general increase in suspended sediment

with discharge which has also been observed in other studies of suspended sediment in glacial streams (Ostrem, 1975; Fenn, et al, 1985; Gurnell, 1987; Bogen, 1996; Collins, 1998).

The relationship between suspended sediment and discharge in most other studies has been approximated by an exponential curve (Ostrem, 1975; Gurnell, 1987; Bogen, 1996). Similar curves can also be fitted to the suspended sediment and discharge data from the 1997-2000 melt seasons at Matanuska Glacier. Because of the annual variability of suspended sediment, individual curves must be generated between suspended sediment and discharge for each melt season (Ostrem, 1975; Gurnell, 1987).

The total daily suspended sediment flux for each of the three melt water streams is shown in Figure 7. In addition, Figures 8 and 9 show the suspended sediment flux and discharge recorded at South Branch during June-August of 1997-2000, at North Branch during June-August 1999-2000, and at Bridge Stream during June-August 2000. The daily suspended sediment flux was calculated as a product of the measured suspended sediment concentration and the average discharge summed over a 24 hour period. However, for years in which no suspended sediment data were collected, at North Branch during the 1997-mid 1999 melt seasons, and on days in which equipment failure caused no suspended sediment sample to be collected, such as at the South Branch from 28 through 30 June 2000, estimations of suspended sediments were derived from the regression curves generated for each particular melt season.

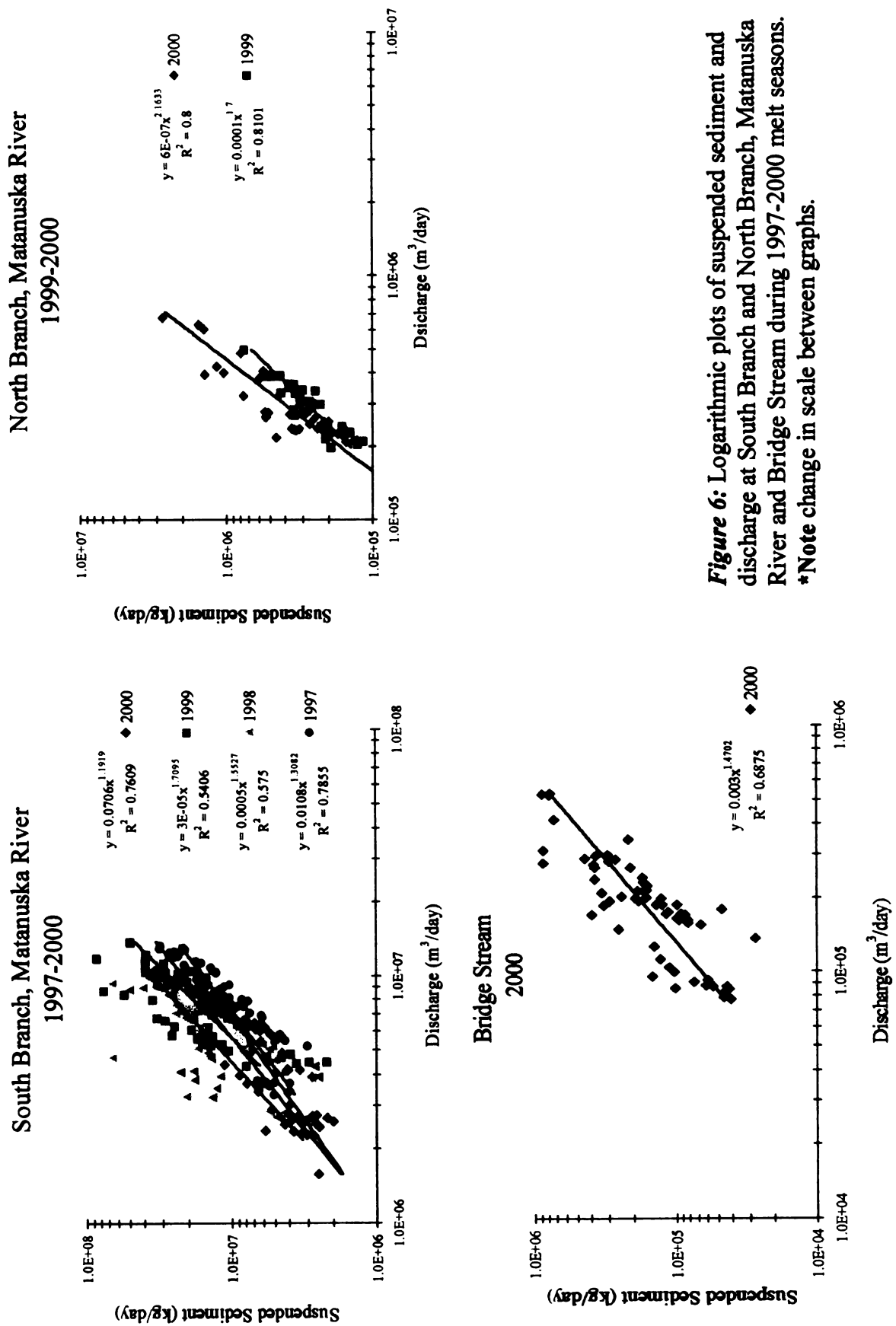


Figure 6: Logarithmic plots of suspended sediment and discharge at South Branch and North Branch, Matanuska River and Bridge Stream during 1997-2000 melt seasons.
***Note** change in scale between graphs.

Bed load

Assuming sediment is released to subglacial melt waters by the melting of debris-rich basal ice and by erosion of subglacial sediment, a ratio of suspended sediment to bed load can be estimated by analyzing the grain size distribution within debris that occurs in basal ice and subglacial sediment exposed along the glacier margin. Sedimentological analysis of debris-rich basal ice at the Matanuska (Lawson, 1979) shows the distribution of grain sizes to range from -4 to 10.0 phi size (pebble to clay) with approximately 75% of the grains being less than 0 phi size (coarse sand). Analyses of several sediment samples collected at approximately 15-20 meter intervals from subglacial sediment exposed along the glacier margin show the distribution of grain sizes to range from -2 to 10.0 phi size (pebble to clay), with 60% of the grains being less than 0 phi size (coarse sand). These grain size distributions indicate that fluvial sediment derived from the melting of basal ice would result in approximate suspended sediment to bed load ratio of 75:25, whereas fluvial sediment derived from erosion of subglacial sediment would result in approximate suspended sediment to bed load ratio of 60:40. In this study, the suspended sediment to bed load ratio is assumed to be approximately 65:35. As fluctuations in melt water discharge occur and the development of the subglacial drainage system evolves during the melt season, the suspended sediment to bed load ratio likely experiences some degree of variability, however the exact amount of variability is currently uncertain. Therefore, the suspended sediment to bed load ratio of 65:35 is believed to be a conservative estimate leading to an upper limit to the range of sediment yield and higher degree of erosion for the Matanuska Glacier.

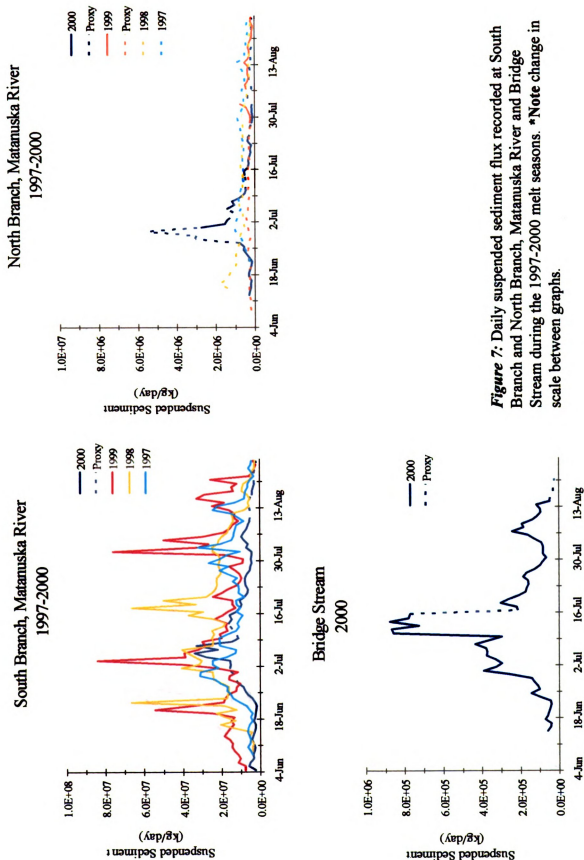


Figure 7: Daily suspended sediment flux recorded at South Branch and North Branch, Matanuska River and Bridge Stream during the 1997-2000 melt seasons. *Note change in scale between graphs.

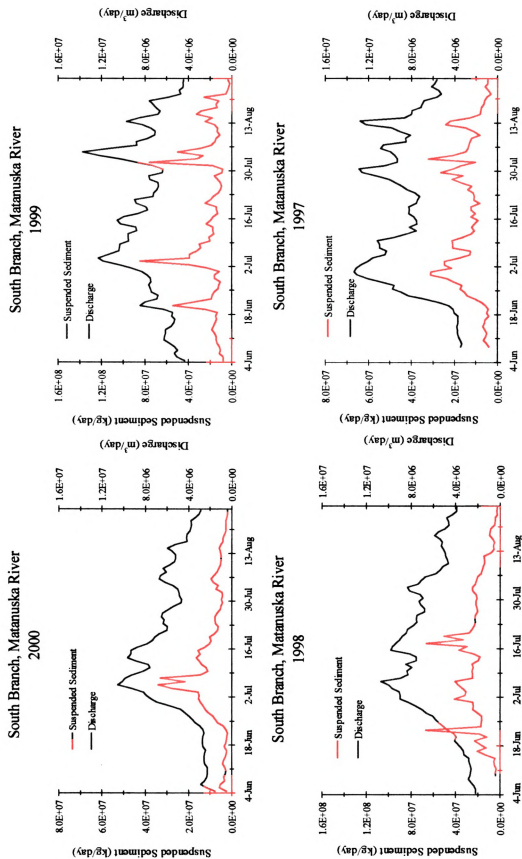


Figure 8: Plots showing suspended sediment and discharge recorded at South Branch, Matanuska River during June-August of the 1997-2000 melt seasons. *Note changes in scale between graphs.

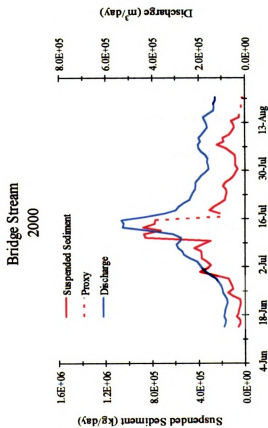
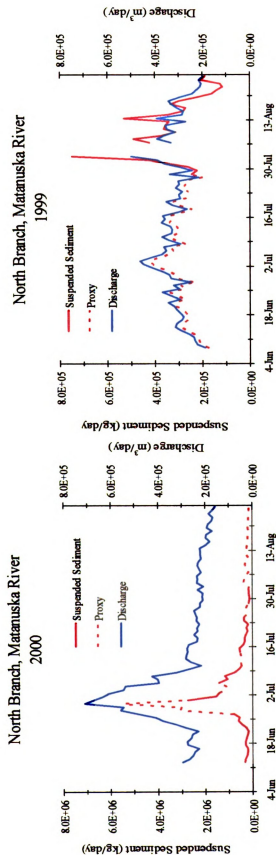


Figure 9: Plots showing suspended sediment and discharge recorded at North Branch, Matanuska River, June-August, 1999-2000 melt seasons and Bridge Stream, June-August, 2000 melt season. Suspended sediment at North Branch during the 1997-1998 melt seasons were completely generated from proxy data and are therefore not shown. No data exists for Bridge Stream during the 1997-1999 melt seasons. *Note changes in scales between graphs.

SUSPENDED SEDIMENT FLUX CHARACTERISTICS

South Branch, Matanuska River

Suspended sediment concentrations recorded at the South Branch, Matanuska River show substantial variability in daily and annual suspended sediment flux for the 1997-2000 melt seasons. For example, Figure 7 shows that the 1998 and 1999 melt seasons display a highly variable pattern of suspended sediment pulses throughout much of the ablation season, whereas the 1997 and 2000 melt seasons show a much more subdued pattern of suspended sediment variability.

Suspended sediment concentrations for the 1997 melt season range between 0.5 g/L and 8.2 g/L, producing an average concentration of 1.6 g/L (Table 3). The 1997 melt season was characterized by several peaks in suspended sediment that were approximately twice the suspended sediment values at the beginning of the melt season (Figure 7 & 8). A relatively gradual increase in suspended sediment began on 20 June and reached peak concentration between 28 and 30 June, coinciding with the initial rise and peak of melt water discharge. Several suspended sediment peaks were also recorded between 29 July and 6 August and 11 and 15 August and were likely the result of precipitation events observed from rainfall records.

Suspended sediment concentrations recorded on South Branch during the 1998 melt season show an apparent range of concentrations between 0.5 g/L and 32.4 g/L, producing an average of approximately 2.9 g/L which is significantly more than the average concentration recorded at South Branch during the 1997 melt season (Table 3). The 1998 melt season exhibited a relatively highly variable pattern of daily suspended

	2000 Range	Average	1999 Range	Average	1998 Range	Average	1997 Range	Average
• South Branch	0.5 - 7.8 g/L	1.5 g/L	0.6 - 20.8 g/L	2.5 g/L	0.5 - 32.4 g/L	2.9 g/L	0.5 - 8.2 g/L	1.6 g/L
• North Branch	0.2 - 16.4 g/L	1.5 g/L	—	—	—	—	—	—
• Bridge Stream	0.3 - 10.1 g/L	1.19 g/L	—	—	—	—	—	—
• Vent - M1	—	—	0.4 - 5.6 g/L	1.8 g/L	—	—	—	—
• Vent - M3	—	—	0.5 - 29.3 g/L	3.5 g/L	—	—	—	—
• Vent - M5	—	—	0.8 - 3.0 g/L	1.5 g/L	—	—	—	—
% Error: $\pm 4\%$								

Table 3: Suspended sediment concentrations recorded at South Branch and North Branch, Matanuska River, Bridge Stream, and glacial vents (M1, M3, M5) for June-August during the 1997-2000 melt seasons. *Note concentrations that were not recorded or were based primarily upon proxy data generated from discharge data are not present in the table.

sediment concentrations shown as several large suspended sediment peaks, approximately 3-4 times greater than the initial concentrations recorded at the onset of the melt season (Figure 7 & 8). The first of these peaks occurred as a sharp peak between 16 and 21 June and paralleled a rise in discharge. A second peak occurred between 1 and 9 July and coincided with a peak in discharge, while a third large peak occurred between 16 and 22 July and paralleled a rise in discharge resulting from a precipitation event. The remainder of the melt season displayed a gradual decrease in suspended sediment concentrations until 12 August in which a significant drop in suspended sediment occurred.

Suspended sediment recorded at South Branch for the 1999 melt season produced concentrations that ranged between 0.6 g/L and 20.8 g/L and average approximately 2.5 g/L (Table 3). These values are similar to the concentrations recorded at South Branch during the 1998 melt season, but are significantly higher than those recorded during the

1997 melt season. The 1999 melt season exhibited a relatively highly variable pattern of daily suspended sediment concentrations similar to the pattern observed for the 1998 melt season (Figure 7 & 8). Several substantial suspended sediment peaks, approximately 2-4 times greater than concentrations recorded at the onset of the melt season, were observed throughout the melt season. Two substantial peaks occurred between 18 and 22 June and 1 and 5 July and paralleled a rise in discharge. A third and fourth peak occurred between 1 and 8 August and 12 and 20 August, a likely result of several precipitation events later in the melt season recorded in rainfall data.

Suspended sediment concentrations at South Branch for the 2000 melt season ranged between 0.5 g/L and 7.8 g/L and averaged approximately 1.48 g/L (Table 3). These concentrations are similar to the concentrations recorded at South Branch during the 1997 melt season, but are less than the concentrations recorded during the 1998 and 1999 melt seasons. The pattern of daily suspended sediment observed during the 2000 melt season is much more subdued than the patterns observed during the 1998 and 1999 melt seasons, but similar to the pattern observed during the 1997 melt season (Figure 7). The 2000 melt season was characterized by a relatively gradual rise in concentration that began on 20 June and gradually increased to a peak concentration between 4 and 10 July which paralleled a peak in melt water discharge. The remainder of the melt season displayed a gradual decrease in suspended sediment concentrations.

North Branch, Matanuska River

Suspended sediment concentrations for the North Branch, Matanuska River during the 2000 melt season ranged between 0.2 g/L and 16.4 g/L and averaged approximately 1.5 g/L (Table 3). The relatively subdued pattern of daily suspended

sediment concentrations observed at North Branch during the 2000 melt season are similar to the patterns of daily suspended sediment concentrations recorded during the 2000 melt season at South Branch (Figure 7 & 9). A rise in suspended sediment concentration occurred on 21 June and reached a peak concentration on 30 June, four-times greater than concentrations recorded at the onset of the melt season. Suspended sediment values throughout the remainder of the melt season were similar to the concentrations of suspended sediment at the beginning of the melt season.

Bridge Stream

Suspended sediment concentrations at the Bridge Stream during the 2000 melt season ranged between 0.3 g/L and 10.1 g/L and average approximately 1.19 g/L (Table 3). A relatively higher amount of variability in daily suspended sediment concentrations was recorded at Bridge Stream than was recorded at North Branch, but less variable than daily suspended sediment concentrations recorded at South Branch (Figure 7 & 9). A relatively gradual rise in concentration occurred on 22 June and reached a peak between 10 and 15 July six-times greater than the concentrations recorded at the onset of the melt season. A small sediment pulse also occurred between 3 and 14 August, the result of a precipitation event.

Glacier Vents

The suspended sediment concentration recorded at the M1, M3, and M5 vents during the 1999 ablation season show some similarities, but also several differences with the suspended sediment concentrations recorded at South Branch (Figure 10). The average concentration of suspended sediment recorded at each of the three vents ranged

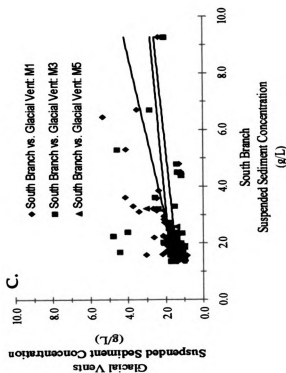
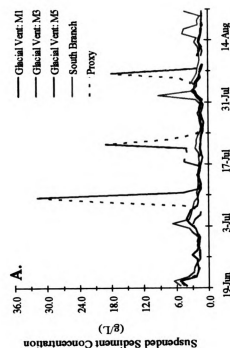
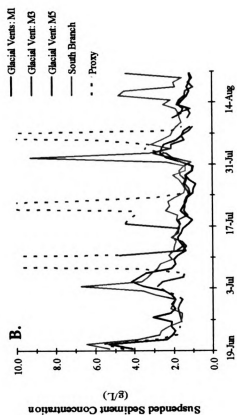


Figure 10: A & B) Line graphs showing daily suspended sediment concentrations recorded during June-August of the 1999 melt season for South Branch, Matanuska River and glacial vents (M1, M3, M5).
***Note** change in scale between graph A and graph B.
 C) Scatter plot showing the lack of correlation between suspended sediment concentrations at South Branch and at the glacial vents (M1, M3, M5). ***Note** sampling of glacial vent M5 began later in the melt season compared to the other vents.

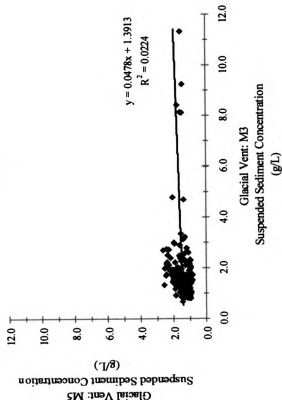
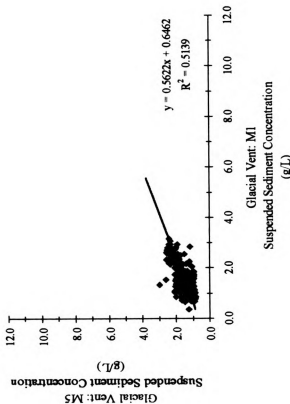
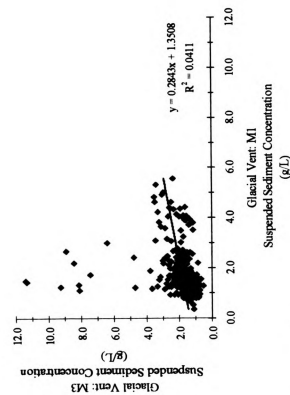


Figure 11: Scatter plots showing correlation of suspended sediment concentrations recorded between glacial vents (M1, M3, M5). ***Note** that M1 vs. M3 graph is during June-August, 1999, while graphs M1 vs. M5 and M3 vs. M5 are during July-August, 1999.

between 1.53 g/L and 3.48 g/L, similar to the 2.5 g/L average suspended sediment concentration observed on South Branch (Table 3). Significant increases in suspended sediment concentrations recorded between 20 and 24 June, 2 and 7 July, and 1 and 8 August in each of the vents were also observed at South Branch. However, for much of the 1999 melt season, the suspended sediment concentrations recorded in the vents were out of phase with each other and with concentrations recorded at South Branch (Figure 10 & 11). For example, an increase in concentration at the M3 vent during 18 and 23 June is represented by low sediment concentrations in the M1 and M5 vents and at South Branch. Also, two large peaks in sediment concentration on South Branch between 16 and 19 August and 22 and 25 August are not observed in any of the vents.

TOTAL SEDIMENT YIELD

The summations of estimated daily suspended sediment and bed load for the 1997-2000 melt seasons are shown in table 4 and indicate a substantial range of total sediment yield over the four-year period (Figure 12). The lowest recorded sediment yield was $2.68\text{E}+03$ tonnes km^{-2} observed during the 2000 melt season, while the 1999 melt season produced the highest sediment yield of $5.58\text{E}+03$ tonnes km^{-2} . The average sediment yield over the 1997-2000 period was $4.32\text{E}+03$ tonnes km^{-2} ($\pm 6\%$).

During the 1997-1999 melt seasons, South Branch contributed approximately 96% of the total sediment whereas North Branch contributed approximately 4% of the total sediment. During the 2000 melt season, South Branch contributed approximately

Melt Season	South Branch, Mat. River	North Branch, Mat. River	Bridge Stream	Total Susp. Sed.
2000	1.83E+03	1.24E+02	3.53E+01	1.99E+03 tonnes km ⁻²
1999	4.08E+03	5.79E+01	————	4.14E+03 tonnes km ⁻²
1998	3.87E+03	1.13E+02	————	3.98E+03 tonnes km ⁻²
1997	2.58E+03	1.03E+02	————	2.69E+03 tonnes km ⁻²
				Ave. Annual Susp. Sed 3.20E+03 tonnes km ⁻²
		Total Sed.Yield of Mat. Glacier 1997-2000 Melt-Season	Erosion Rate of Mat. Glacier 1997-2000 Melt-Season	
Melt-Season				
2000		2.68E+03 tonnes km ⁻²	1.01 mm yr ⁻¹	
1999		5.58E+03 tonnes km ⁻²	2.08 mm yr ⁻¹	
1998		5.37E+03 tonnes km ⁻²	1.99 mm yr ⁻¹	
1997		3.63E+03 tonnes km ⁻²	1.39 mm yr ⁻¹	
		Ave. Annual Sed. Yield 4.32E+03 tonnes km ⁻²	Ave. Annual E.R. 1.62 mm yr ⁻¹	% Error: ± 6%

Table 4: Total suspended sediment recorded at South Branch and North Branch, Matanuska River and Bridge Stream during June-August of 1997-2000 melt seasons. Table also shows total sediment yield and subsequent erosion rate for the Matanuska Glacier for the 1997-2000 melt seasons. ***Note:** Total sediment yield is based upon recorded suspended sediment concentrations and an estimated bed load component of 35%.

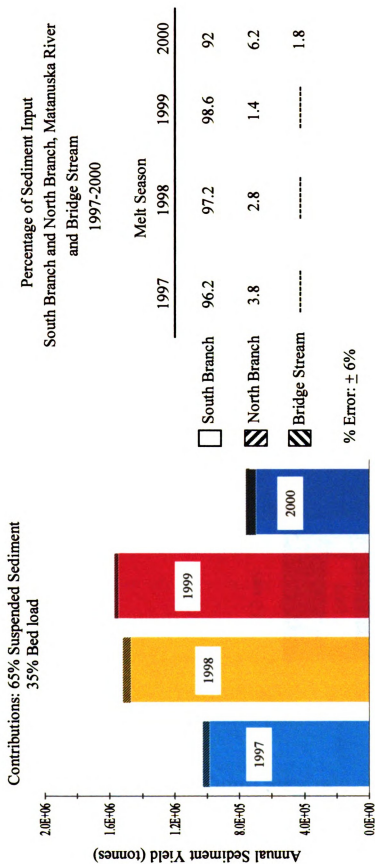
95% of the total sediment while North Branch contributed approximately 3.6% and Bridge Stream approximately 1.4% of the total sediment (Figure 12).

The total sediment yield recorded from the three melt water streams assumes that other possible areas of sediment deposition, such as morainal development, are minimal. This assumption is substantiated due to the lack of significant moraines occurring along the glacier margin, suggesting that the large quantity of sediment transported in the melt water streams represents a significant majority of the sediment produced by the glacier.

EROSION RATE

An average annual erosion rate for the Matanuska Glacier was calculated by dividing the total sediment yield by the total area of the basin covered by glacier ice, approximately 380 km², and subsequently dividing by an estimated bedrock density of 2.65 g/cm³ (Table 4). The resulting average annual erosion rates range from 1.01 mm yr⁻¹ during the 2000 ablation season to 2.08 mm yr⁻¹ for the 1999 ablation season, producing an average annual erosion rate of approximately 1.62 mm yr⁻¹ over the entire 4 year period (Figure 13).

It is assumed in this study that the input of sediment by subaerial erosion of the nonglacierised areas of the basin is minimal and does not significantly contribute to the total sediment yield and subsequent erosion rate of the Matanuska Glacier. Further studies are needed to estimate quantitatively the amount of sediment that is produced by subaerial erosion; however, the Matanuska Glacier is situated within a large, U-shaped valley that extends up to approximately 1500 meters above the surface of the glacier. Hypothetically, if the rate of subaerial erosion in the nonglacierised areas was similar to the rate of erosion at the glacier bed, the relief above the glacier's surface would likely be significantly less than what is observed.



*Figure 12: Total sediment yield of Matanuska Glacier during June-August of 1997-2000 melt seasons. *Note input of sediment from South Branch and North Branch, Matanuska River and Bridge Stream are shown within total sediment output for each melt season. Actual contribution percentages for 1997-2000 melt season are shown in the table on the right.*

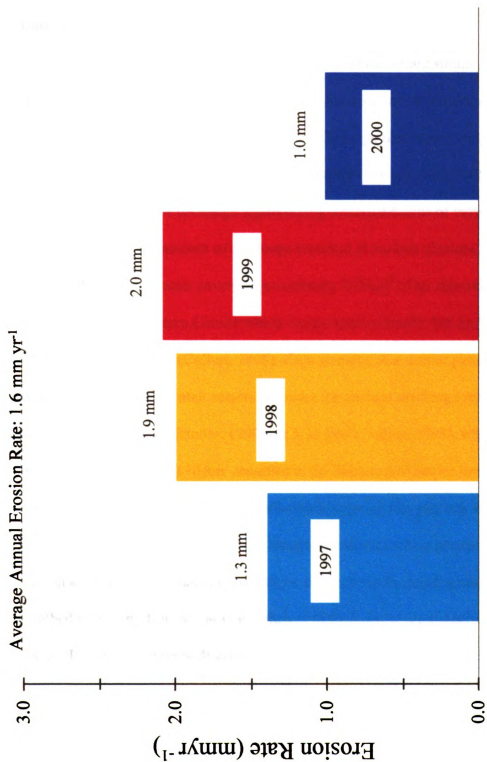


Figure 13: Average annual erosion rate of the Matanuska Glacier derived from sediment collected during June-August of 1997-2000 melt seasons. Values calculated by dividing the total amount of sediment produced by the area of the glacier within the basin.

DISCUSSION

Melt water Discharge

The daily discharge fluxes recorded at Matanuska Glacier are similar to the pattern of daily discharge observed at many glaciers from around the world. A substantial rise in discharge early in the melt season, a peak in discharge that occurs early-mid July, and a subsequent gradual decrease in discharge throughout the remainder of the melt season is the general trend of discharge apparent in glacierised basins of varying sizes, despite a wide range in the amount of discharge recorded at various glaciers. For example, the Matanuska Glacier covers approximately 380 km^2 of an approximately 665 km^2 basin, similar to the Batura Glacier which covers approximately 365 km^2 of an approximately 649 km^2 basin (Collins, 1998). Each glacier has a similar pattern of daily discharge flux throughout the melt season, however the amount discharge recorded at the Batura Glacier during April-October, 1990 was 1.25 km^3 (Collins, 1998), which is substantially more than $0.47\text{-}0.70 \text{ km}^3$ recorded at the Matanuska Glacier during May-August of 1997-2000. The causes of such differences between two glaciers with such similar characteristics may be the result of climatic variations such as precipitation events that affect discharge directly, such as rain fall, or indirectly, such as adjustment of the glaciers albedo resulting from variations in the amount of glacier ice exposed to the atmosphere. The pattern of daily discharge flux at the Gornergletscher, Switzerland (Collins, 1990) is also similar to that of the Matanuska, however, the Gornergletscher occupies approximately 68.6 km^2 of an 82 km^2 basin which is a much smaller area than the Matanuska. The smaller glacier area is represented in the total discharge recorded at

Gornergletscher during 1983-1988, ranging in value from 0.099-0.135 km³, which is considerably less than that at the Matanuska. The lower discharge readings at the Gornergletscher may also be the result of an increased albedo caused from snowfall early in September (Collins, 1990), which is not observed at the Matanuska Glacier until later in the year.

Suspended Sediment Concentrations- Melt water Streams

The average annual suspended sediment concentrations recorded on South Branch over the four-year period generally varied with discharge. For example, the 1998 and 1999 melt seasons were characterized by relatively high average suspended sediment concentrations and relatively high melt water discharges. The 2000 melt season was characterized by relatively low average suspended sediment concentrations and relatively low melt water discharge. An exception to this, however, was the 1997 melt season characterized by relatively low average suspended sediment concentrations and relatively high melt water discharge. A possible explanation for this anomaly may stem from a large discharge peak that occurred between late June and early July. The broad peak in discharge was substantially higher than any other increase in discharge throughout the remainder of the melt season. The occurrence of such a significant discharge peak following the onset of the melt season entrained substantial amounts of sediment from the base of the glacier, which may have exhausted the supply of sediment to melt waters and subsequently lowered the sediment concentrations throughout the remainder of the melt season.

Each of the four melt seasons typically exhibit lower daily suspended sediment concentrations later in the melt season compared to daily suspended sediment concentrations recorded earlier in the melt season (Figure 14A&B). For example, daily suspended sediment concentrations recorded in early June 1997-2000 during low discharge stages on South Branch, were considerably higher than daily suspended sediment concentrations recorded in mid-late August 1997-2000 during similar discharge stages on South Branch. This results from the removal of basal sediment during late June and early July which exhaust the sediment supply of melt water occurring during mid-late August, subsequently lowering suspended sediment concentrations (Ostrem, 1975; Collins, 1989; 1998).

The fluctuation of daily suspended sediment concentrations recorded within each melt season, in addition to the annual variability of sediment can be attributed to the development of the subglacial drainage network. Accumulation of sediment occurs at the sole of the glacier during the waning stages of the melt season and continues until melt water discharge increases at the onset of the next melt season. As the development of subglacial channels evolve across the base of the glacier, areas of stored sediment become exposed and rapidly entrained in melt waters producing peaks in daily sediment concentrations (Collins, 1998). If sediment is not continually delivered to the melt water system, entrainment of sediment will eventually exhaust the supply of stored sediment at the glacier sole and subsequently produce lower concentrations, even with rising discharge (Ostrem, 1975; Collins, 1998). However, sediments that are not exposed to subglacial melt waters during a particular melt season become stored in isolated areas at the glacier bed and are susceptible to evacuation during the proceeding melt season.

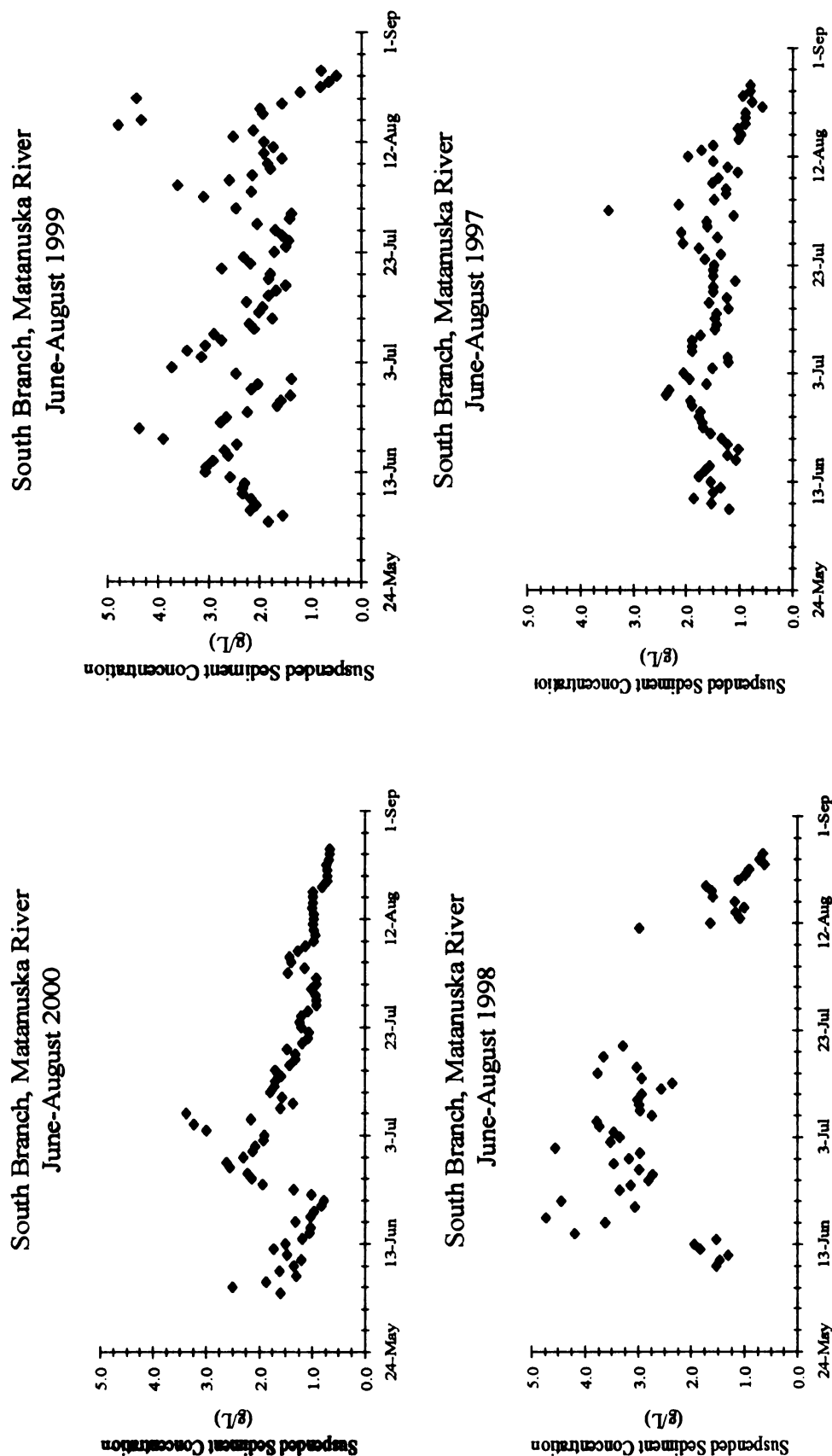
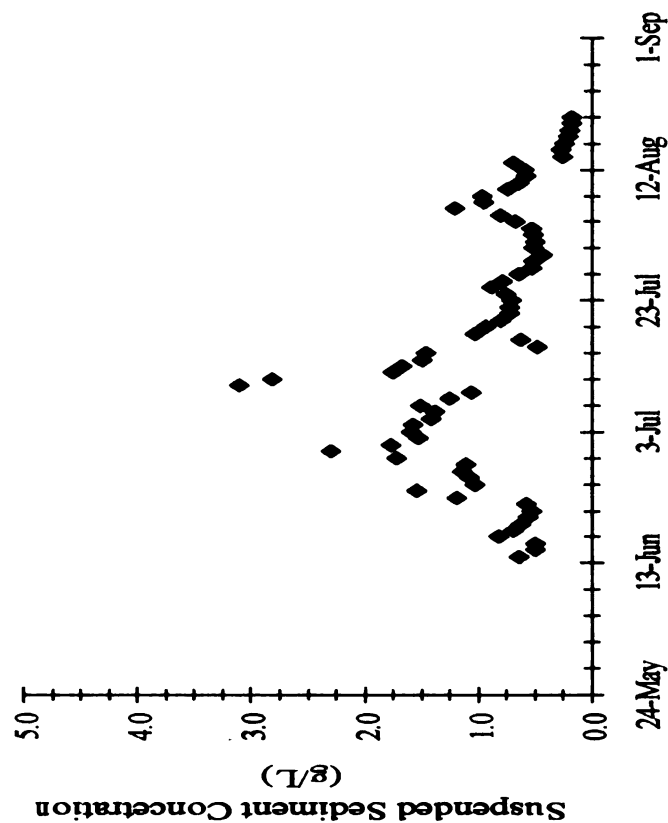


Figure 14 A: Scatter plot showing the daily recorded suspended sediment concentrations at South Branch during June-August of 1997-2000 melt seasons. ***Note:** Suspended sediment concentrations at the beginning of the melt season are generally higher than the suspended sediment concentrations later in the melt season.

Bridge Stream June-August 2000



North Branch, Matanuska River June-August 2000

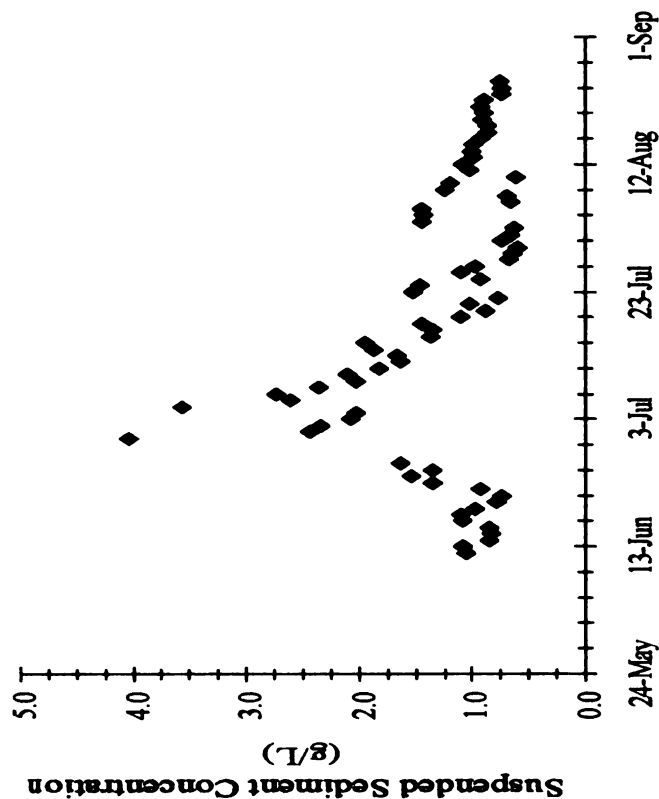


Figure 14 B: Scatter plot showing the daily recorded suspended sediment concentrations at North Branch and Bridge Stream during June-August of 2000 melt season. ***Note:** Suspended sediment concentrations at North Branch and Bridge are generally higher early in the melt season and relatively lower late in the melt season, similar to the observations at South Branch.

Therefore, the sediment flux in melt waters is heavily influenced by the spatial extent and evolution of the subglacial drainage network within a particular melt season, thus producing variability of total annual sediment observed between melt seasons (Collins, 1998).

Suspended Sediment Concentrations-Glacial Vents

The “out of phase” relationship recorded between peaks of suspended sediment concentrations in vents and on South Branch, Matanuska River (Figure 11 & 12) is potentially due to the presence of a shallow proglacial lake that separates the vents from South Branch. The proglacial lake may serve as a temporary reservoir for sediment that is too large to be transported in suspension, but that may become remobilized during times of higher discharge.

The “out of phase” relationship between suspended sediment concentrations in different vents shown in Figure 12 may be attributed to the seasonal development of the subglacial drainage system. As the drainage system evolves throughout the melt season, the alternating active and inactive subglacial channels flush out stored sediment at the glacier sole and expose additional quantities of stored sediment to subglacial melt water (Collins 1989; 1998). This would cause individual vents to fluctuate from relatively high suspended sediment concentrations to relatively low suspended sediment concentrations depending upon migration of subglacial channels.

Suspended Sediment Flux

The suspended sediment fluxes observed during the 1997-2000 melt seasons for the Matanuska are similar to the suspended sediment patterns observed for multiple glacierised basins. In most cases, the general trend of recorded suspended sediment fluxes parallels the flux of melt water discharge. However, the suspended sediment flux at South Branch during the 1998 and 1999 melt seasons record large abrupt suspended sediment pulses that occur with the start of the rising limb of discharge in mid June. The sediment pulses are likely the result of an initial flush of sediment stored at the glacier sole. Frequency of suspended sediment pulses during the early to mid-stages of the melt season are the result of the developing drainage systems beneath the glaciers flushing large quantities of stored sediment from the glacier sole relatively early in the melt season and introducing new sources of sediment to subglacial melt waters (Collins, 1989; 1998). Several considerable pulses of suspended sediment at the Matanuska during August 1998 and 1999 coincided with several precipitation events, showing that relatively significant precipitation events are capable of producing large fluxes of suspended sediment.

Bed Load

The bed load component of sediment transported in melt water streams is frequently derived from conservative estimates generated from studies of various proglacial streams around the world. The bed load estimate of 35% used in this study is derived from sedimentological analyzes of debris-rich basal ice and subglacial sediment and is similar to the bed load component estimated from sediment traps deployed at the Tsidjiore Nouve Glacier by Bezingue et al (1989). The relatively small component of bed load at the Matanuska Glacier is representative of the erodable meta-sedimentary bedrock

beneath the glacier (Beikman, 1980). For example, abrasion of phyllites, slates, and shales at the glacier bed produce large amounts of silts and clays and little amounts of sand size particles due to the lack of quartz. However, Ostrem's (1975) estimated suspended sediment to bed load ratio of 75:25 at the Nigardsbreen Glacier suggest that glaciers overriding a more resistant crystalline bedrock, such as the Norwegian glaciers, may also have a relatively small component of bed load.

Erosion Rate

The erosion rate at the Matanuska Glacier is similar to $0.97\text{--}1.13\text{ mm yr}^{-1}$ of erosion calculated for the Tsidjiore Nouve Glacier of Switzerland by Bezingé, et al. (1989). However, it is significantly less than high rates of erosion indicated for large tidewater glaciers of the fjords in south east Alaska (Hallet, et al. 1996) and also considerably less than the 7.66 mm yr^{-1} of erosion calculated by Collins (1998) for the Batura Glacier, Pakistan. The erosion rate at the Matanuska is however substantially more than an erosion rate of 0.15 mm yr^{-1} proposed by Hallet, et al. (1996) for the Nigardsbreen Glacier, Norway. The Tsidjiore Nouve Glacier is a relatively small temperate glacier that overrides metamorphic bedrock similar to the Matanuska. In addition, Bezingé, et al. (1989) calculated approximately 25-46% of sediment in melt water streams at the Tsidjiore Nouve was transported as bed load. In comparison, the Batura Glacier is similar in size to the Matanuska Glacier and erodes similar bedrock, however discharge recorded by Collins was approximately twice than discharge recorded at the Matanuska. Collins also estimated a 50% bed load contribution for the Batura, whereas a bed load estimate of 35% is utilized for the Matanuska. The Nigardsbreen Glacier, which is relatively small compared to the Matanuska and erodes a more resistant

bedrock, produced a relatively lesser amount of sediment and lower erosion rate than the Matanuska Glacier (Bogen, 1996; Hallet, et al., 1996).

The 1.6 mm yr^{-1} erosion rate at the Matanuska Glacier incorporates several assumptions that will need further investigation. The foremost assumption is that the sediment used to calculate the erosion rate is derived from processes occurring at the bed of the glacier and does not incorporate any material from the nonglacierised areas of the basin. Further research is needed to verify the impact that subaerial erosion has on the resulting sediment yield and subsequent erosion rate of the glacier.

Another important assumption that is incorporated within glacial erosion rate studies is that the sediment flux recorded during a series of melt seasons is representative processes that occur during the particular time interval. However, sediment stored at the glaciers bed has the potential to remain in storage for several decades or possibly longer depending upon the evolution of the subglacial drainage system. Once these reservoirs are exposed to melt water activity, an enhanced sediment flux would likely result and potentially lead to an inaccurate overestimation for the current rate of erosion at the glaciers bed.

Another assumption in this study is that the suspended sediment to bed load ratio remains constant throughout the melt season. However, as discharge rises and falls, and areas of stored sediment are exposed to melt water, the ratio of suspended sediment to bed load may fluctuate also, affecting the overall bed load component. Despite these assumptions, the proposed erosion rate of 1.6 mm yr^{-1} for the glacier seems to be a reasonable estimate. It is based upon several years of data which is important in balancing the annual fluxes in sediment production. The bed load component of this

study is also based upon sedimentological data from the proposed source of the glacial sediment and not based upon hypothetical estimates or derivations of bed load estimates from other glacierised basins.

The sediment mass fluxes and subsequent erosion rates of the Matanuska Glacier lead to discussion of glacial effects on relief development in south central Alaska. The development of mountain topography depends on the interactions between tectonic uplift and processes of erosion. In order for glaciers to maintain or accentuate relief in mountainous regions, the rate of lowering at the glacier bed must equal or exceed the regional rate of tectonic uplift over long periods of time (Collins, 1998). Recent estimates of tectonic uplift for the Chugach Mountains near the Matanuska Glacier indicate a range of tectonic uplift rates from $7 \pm 2 \text{ mm yr}^{-1}$ to $11 \pm 5 \text{ mm yr}^{-1}$ during 1995-2000 (Freymueller, unpublished). This would indicate that the current erosion rate of 1.6 mm yr^{-1} for the Matanuska is significantly less than the topographical uplift produced by tectonic activity, however a much longer term data set is needed before an accurate comparison between tectonic uplift and glacial erosion can be substantiated.

CONCLUSION

Total annual suspended sediment flux in melt water stream draining temperate glaciers provide reasonable estimates of glacial erosion, yet the considerable seasonal variation in suspended sediment fluxes from the Matanuska Glacier emphasize the need for frequent, consecutive sampling of melt water streams throughout the melt season in order to accurately quantify sediment yields and erosion rates for glacierised basins.

Annual sediment fluxes are shown to depend upon the magnitude of melt water discharge and the extent of its ability to entrain sediment stored at the glacial sole. These interactions will also depend upon the timing and magnitude of the events in one year with respect to those occurring in preceding melt seasons (Collins, 1998).

Suspended sediment fluxes observed at vents along the glacier terminus suggest that the evolution of the subglacial drainage system is a dynamic process that continually exposes large quantities of sediment to glacial melt water while exhausting sediment reservoirs in other areas. The development of the subglacial drainage network generates suspended sediment fluxes between individual vents and proglacial streams that are frequently out of phase with one another, except during periods of relatively high discharge.

The total sediment flux from the Matanuska Glacier, including a conservative bed load estimate of 35%, is $4.32\text{E}+03 \pm 6\%$ tonnes $\text{km}^{-2}\text{yr}^{-1}$, equivalent to an average annual erosion rate of 1.6 mm yr^{-1} . This is substantially lower than erosion rates proposed for the large tidewater glaciers of south east Alaska, yet significantly higher than those proposed for small, Norwegian glaciers (Hallet, et al. 1996). The sediment flux record assumes minor input of sediment from the nonglacierised areas of the basin, which must be quantified in order to substantiate the assumption.

Recent records of tectonic uplift indicate that the proposed erosion rate for the Matanuska is less than the rate of tectonic uplift for the Chugach Mountains. However, extrapolation of the glacial erosion rate back to the peak glacial period may suggest that the rate of erosion was capable of maintaining or accentuating topographic relief of the basin. The potential influence that glaciers can have on tectonic processes over a long-

term period should promote the measurement of sediment fluxes in melt waters draining other glacierised basins.

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