HYDROLOGIC PROCESSES INFLUENCING STREAMFLOW VARIATION IN FRYXELL BASIN, ANTARCTICA

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In the McMurdo Dry Valleys, glacial meltwater streams are a critical linkage between the glaciers and the lakes in the valley bottoms. This paper analyzes the physiographic characteristics and six years of discharge data from five streams in order to better characterize the dynamic inputs into Lake Fryxell, a closed basin in Taylor Valley. These feeder streams typically flow only for six to eight weeks during the summer, and streamflow is highly variable on an interannual as well as daily basis. During low flow years, the shorter streams contributed a higher proportion of the total annual inflow into the lake; this pattern may reflect the greater losses to wetting the hyporheic zone. Comparisons of the period of direct sun on the glacier faces with the time of peak flow suggested that solar position and melt from the glacier faces are the dominant controls on the diurnal fluctuations in streamflow. An analysis of streamflow recession showed considerable variability between streams and in some cases, over time. For example, recession coefficients for Canada Stream, a short stream with an incised channel, were fairly invariant with streamflow. In contrast, the recession coefficients for Lost Seal Stream, an unconfined, low gradient stream, increased significantly with increasing discharge. These observations lead to hypotheses for the control of streamflow dynamics in the McMurdo Dry Valleys by climate, solar position, and geomorphic factors.

INTRODUCTION

The McMurdo Dry Valleys region of southern Victoria Land, Antarctica is a large polar desert located along the west coast of the Ross Sea. Climate is extremely cold and dry; air temperatures range from a mean daily low of about –45°C during the winter to a mean daily high of about 7°C during the short summer [*Keys*, 1980]. Annual precipitation is less than 10 cm yr^{-1} [*Bromley*, 1985], and much of this is quickly lost to sublimation. Solar radiation, which is the driving force of the melt cycle, is subject to considerable topographic variability. Average incoming solar radiation on the glaciers ranged from 18 to 52 W m^{-2} during the 1994-1995 season [*Dana et al.*, this volume.]

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The McMurdo Dry Valleys contain a number of lakes fed by meltwater streams from the surrounding glaciers. These lakes have a perennial ice cover and most are closed hydrologic systems, as few streams cross through the coastal ridges to the sea [*Chinn*, 1993]. When precipitation and inflows to the lakes are balanced by evaporation and sublimation losses, lake levels remain constant. During the past century, lake levels have been rising because inflows have exceeded sublimation and evaporation [*Chinn*, 1993].

Streamflow is highly variable on an interannual, seasonal, and daily basis [*House et al.*, 1996; see streamflow data in accompanying CDROM]. Glacial melt and resultant streamflow begins in late November to mid-December and ends in mid-January to early February. Between the glaciers and the lake, the streams flow through unconsolidated alluvium. This alluvium is mostly sand-sized particles interbedded with large cobbles and boulders, predominately composed of gneiss, diorite and schist [*Bockheim*, 1997]. The unconsolidated alluvium and absence of vegetation results in unstable streambanks and large sediment loads at high flows. In some streams the stream bed is stabilized through the formation of stone pavements by a combination of periglacial and fluvial processes, while in other streams bed surfaces remain irregular. A deep, impenetrable permafrost layer lies about 0.5 m below the surface of the alluvium. Substantial interactions between the streams and the permafrost have yet to be documented.

Because the streams are both dynamic aquatic ecosystems and the primary means of delivering water and materials to the lakes, a better knowledge of streamflow processes and dynamics is critical to understanding the entire dry valley ecosystem. Streams with a stone pavement have abundant algal mats within the main stream channel, while those streams with less stable substrates have algal mats on the edge of the adjacent parafluvial zone [*McKnight and Tate*, 1996 a, 1996 b; *Alger et al.*, 1997]. These algal mats are important sources of primary production and nutrient transformations. The combination of hydrologic, geochemical and ecological processes within the streams and hyporheic zone largely determine the inputs of water, nutrients, and organic matter to the lakes [*Simmons et al.*, 1993; *Spaulding et al.*, 1994]. Temporal variations in streamflow can serve as an index of short- and long-term climatic fluctuations and glacial melt rates. Hence the purpose of this paper is to evaluate the temporal and spatial variability of streamflow and then to relate these patterns to predicted glacial melt and the physical characteristics of the individual streams. This information will strengthen our understanding of the physiographic controls on streamflow and the fluctuating inputs of water and materials to the lakes. The analysis presented here will also help guide future, more process-based research on the hydrology of the dry valley streams.

The first objective was simply to assess the interannual variability in streamflow among the gauged streams flowing into Lake Fryxell (Figure 1). If the respective contributions are consistent between years or can be related to some of the physical characteristics of the different streams, this would help predict the relative contributions of the ungauged streams flowing into Lake Fryxell.

The dry valley streams exhibit a large diel variation in flow [*von Guerard et al.*, 1994], and this is due to both "source" and "instream" processes. Source processes control the generation of meltwater and are driven largly by climatic factors such as cloud cover, temperature regime, and solar energy inputs to the glacier faces and glacier surfaces. Discharge increases rapidly in response to warmer temperatures and high fluxes of solar radiation. Conversely cold and/or cloudy periods during the summer months will immediately reduce melt, and streamflow can decline by an order of magnitude within a few hours (Figure 2). Much of the melt is believed to come from direct radiation on the nearly vertical glacier faces rather than melt on the more horizontal glacier surfaces [*Fountain et al.*, this volume; *Dana et al.*, this volume]. Thus the second objective of this study was to evaluate the relationship between sun angle on the different glacier faces and the observed daily patterns of flow in five of the dry valley streams.

After the meltwater drains from the glaciers, a different set of instream processes are hypothesized to control stream discharge patterns. Physical characteristics such as the gradient, length, bed morphology, and characteristics of the alluvial material may regulate flow velocity, control the storage of water within the hyporheic zone, attenuate the meltwater hydrograph, and influence sediment transport. It was estimated that 1.3×10^5 m^3 of water was stored in the hyporheic zone along the Onyx River (C. Howard-Williams, personal communication), while a tracer experiment has shown a very rapid exchange between the hyporheic zone and the main channel [*McKnight and Andrews*, 1993; *Runkel et. al.*, in press]. Thus the third objective of this study was to analyze streamflow recession rates as a means of assessing the storage of water in the hyporheic zone and the dynamics of drainage when meltwater generation ceases.

SITE DESCRIPTION

Fryxell Basin

Lake Fryxell Basin is the easternmost basin in the Taylor Valley (Figure 1). The lake is large, shallow and permanently ice-covered. Inflows come from thirteen streams that drain the various glaciers surrounding the basin. The two most prominent glaciers are the Canada and Commonwealth Glaciers, and these are the source of seven of the thirteen streams. The landscape through which the streams flow is a relatively uniform unconsolidated alluvium. The porosity or hydraulic conductivity of this material presumably does not vary between the different streams.

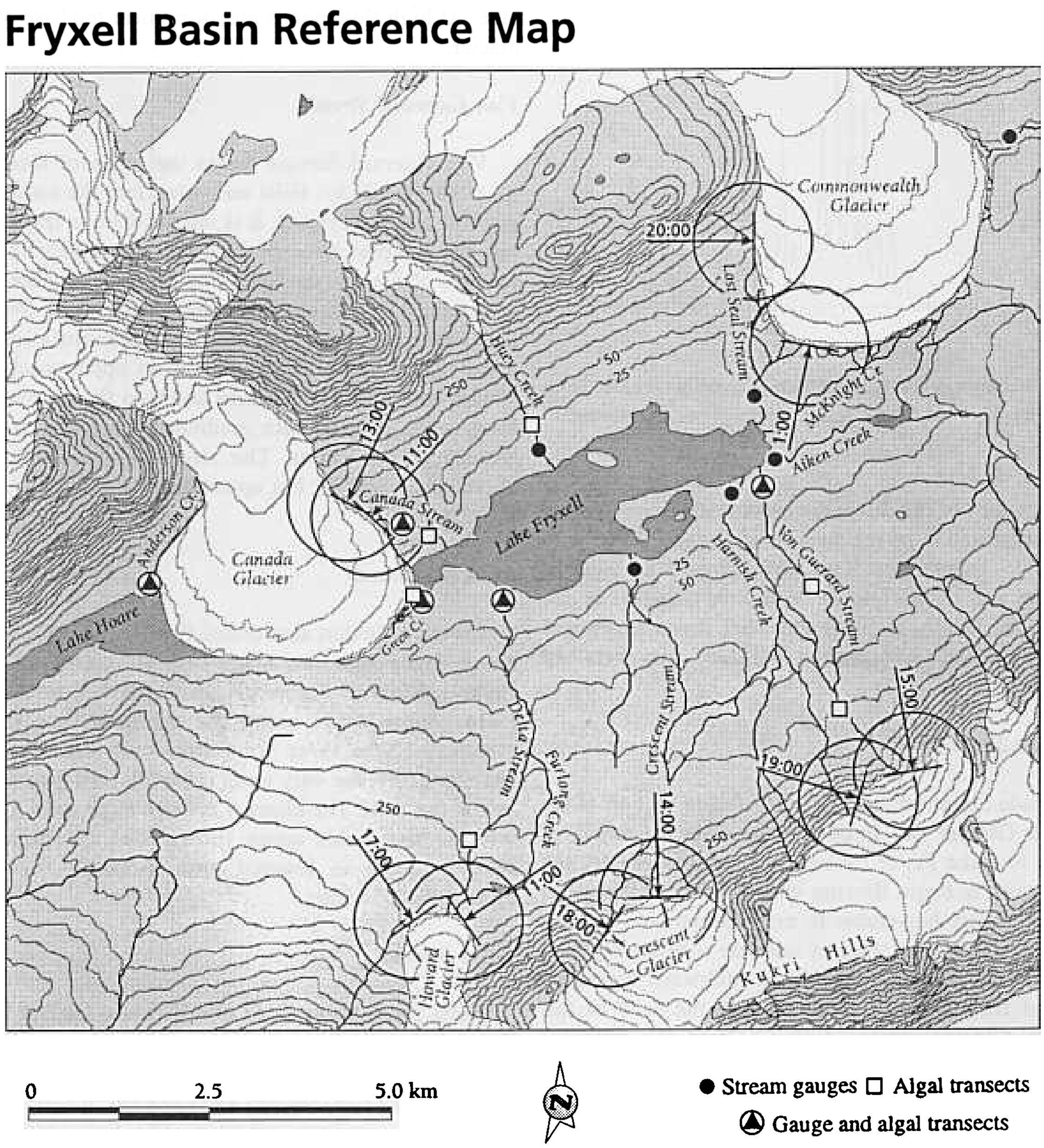

Fig 1. Map of the lower Taylor Valley, showing Lake Fryxell and inflowing streams. The aspects of the glacial meltwater source areas on the alpine glaciers draining into five of the streams are indicated, as is the time of day when the sun is directly facing these aspects. Elevations are in meters.

Streamflow, water temperature and specific conductance have been measured since the 1990-1991 field seasons except for the austral summer of 1992-1993. Of the thirteen streams draining into Lake Fryxell, streamflow data have been collected at 15-minute intervals at eight streams and periodically at five streams [*von Guerard et al.*, 1994]. Periodic measurements are of limited value due to the high short-term variability of streamflow.

Five streams were selected for analysis in this paper: Canada, Lost Seal, von Guerard, Crescent, and Delta Streams (Figure 1). These streams were selected because

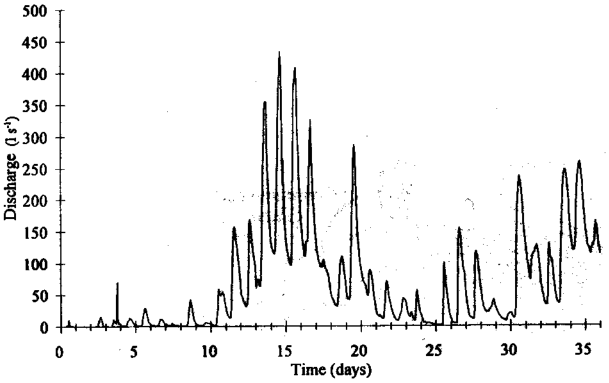

Fig 2. Hydrograph for Canada Stream from November 26 to December 31, 1991. Time zero is midnight on 26 November 1991.

of the quality of the discharge records and because they are representative of the streams in Fryxell Basin with regard to length, gradient, and aspect, as well as duration and magnitude of flow [*von Guerard et al.*, 1994]. The length, gradient and other characteristics of these streams are summarized in Table 1 and described below.

Canada Stream

Canada Stream drains the north-facing section of the Canada Glacier and is one of the largest sources of inflow to Lake Fryxell. Canada Stream is usually the first stream to begin flowing into the lake, as it reaches the lake in late November to early December. It is the shortest of the five streams and has a relatively low gradient of 0.03 m m^{-1} (Table 1). Meltwater enters the channel from a large section along the face of the Canada Glacier. Water draining from the northern section of the face enters a well-defined channel, while water from the more southern part of the source area drains into a pond. Outflow from this pond then enters the channel and continues to the gauge located about 1 km upstream of Lake Fryxell. Between the gauge and the lake, the stream flows through an incised channel with boulders in the streambed. In the last 0.5 km reach the flow spreads out through a large alluvial fan.

Lost Seal Stream

Lost Seal Stream drains a large source area along the western and southern faces of the Commonwealth Glacier. It is slightly longer and considerably flatter than Canada Stream (Table 1). The channel itself is wide and shallow and is gauged about 0.3 km from the lake. At high flow ponds may form near the base of the glacier.

Von Guerard Stream

Von Guerard Stream drains the northern face of a glacier in the Kukri Hills and flows into the southeastern end of Lake Fryxell. It is intermediate in length and has the steepest average gradient. The steeper upper reaches of the stream have a bed of large cobbles and boulders, and this section may remain snow-covered into the summer due to the accumulation of wind-blown snow. Below this steep upper reach, the stream enters a wide, flat area and then flows through a long reach of moderate gradient before the channel widens at the outlet. The stream gauge is located approximately 0.25 km upstream of the inlet to Lake Fryxell.

Crescent Stream

Crescent Stream also drains from the glaciers of the Kukri Hills into the south-central region of Lake Fryxell. Most of the meltwater is derived from three main source areas along the northern face of the glaciers. These three tributaries converge into one channel below the very steep upper reaches located just below the face. The channel is considered to be stable, with no observable scour, fill, or sand transport. The stream gauge is located approximately 0.25 km upstream of the inlet.

Delta Stream

Delta Stream originates from Howard Glacier in the Kukri Hills and flows into the southernmost section of Lake Fryxell. It is the longest of the five streams, and in contrast to von Guerard and Crescent Streams, it has a relatively uniform gradient. The bed consists of coarse particles arranged in a flat pavement and is also considered relatively stable.

METHODS

Inflows to Lake Fryxell

Existing data were used to calculate the correlations in daily flows between streams and the interannual variability in discharge for each stream. To evaluate the relative contribution of each stream to the annual water budget for Lake Fryxell, flows were estimated for the intermittently gauged streams and direct glacier

TABLE 1. Physiographic Characteristics an Estimated Accuracy of the Gauging Record for the Streams Used in This study. The Pond at the Base of the Source Glacier for Lost Seal Stream exists at High Flows Only.

Stream	Length (km)	Gradient ($m\ m^{-1}$)	Length/ gradient	Pond at base of glacier face	Elevation at base of source glacier (m)	Type of gauge	Estimated error in discharge (%)
Canada	1.5	0.03	50	yes	100	rectangular weir	<10
Lost Seal	2.2	0.02	110	yes	125	6 in. Parshall flume	10–15
Von Guerard	4.9	0.08	61	no	375	channel control	10
Upper reach	0.5	0.55					
Lower reach	4.4	0.05					
Crescent	5.6	0.07	80	no	350–450	channel control	10–15
Upper reach	0.7	0.28					
Lower reach	4.9	0.05					
Delta	11.2	0.03	370	no	300	channel control	10–15

inflows. The basis for these estimates is discussed in detail by *House et al.* [1996]. Flows in the intermittently gauged streams (McKnight Creek, Harnish Creek, Bowles Creek, Mariah Creek, and Andrews Creek) were derived largely from numerous direct measurements during the 1993-1994 field season. Visual observations indicated that the sum of the direct glacier inflows were approximately equal to the average of the annual flows for Canada Stream and Green Creek. To evaluate the interannual and daily variability, correlation matrices were constructed using total annual and mean daily flows for the 1990-1991 through 1995-1996 seasons

To further characterize the variability in the daily flow pattern among the five streams, the estimated proportion of melt from the glacier surfaces and glacier faces were inferred from daily hydrographs for eight different days in the 1990-1991 and 1991-1992 field seasons. To separate these two sources of melt it was assumed that glacial surface melt provided the baseflow component of the hydrograph, while the peak of the daily hydrograph occurred in response to melt from the face of the source glacier. The separation of baseflow from peakflow was made using the straight line method [*McCuen*, 1989], and the ratio of peak height to baseflow was determined for each of the eight days for the five streams.

Solar Position and Lag Times

To determine the time lag between peak solar intensity and time of peak daily discharge, it was first necessary to determine the period of peak insolation on the faces of the glaciers that feed the five streams. Aspects of the source areas were identified from the 1:50,000 map of the Lake Fryxell quadrangle (Figure 1). The maximum period of time that the glacier faces were exposed to direct radiation was determined for each stream from the mapped aspects and the known path of the sun during the melt season. Peak solar intensity is reached when the solar azimuth is normal to the face. In the Lake Fryxell Basin, the sun revolves counterclockwise about the basin while maintaining a continuous low angle to the horizon and is approximately due north at 1400 h.

The average time of daily peak streamflow was calculated for each stream for each year of record. Periods at the start of the season, when the streambed was becoming saturated, and at the end of the season, when melt had slowed, generally exhibited more variability with regard to the timing of the daily peak flow and were excluded from this analysis. Days during the main flow period with little of no melt were also excluded from this analysis. The mean time of peak flow and corresponding standard deviation were compared with the range of time that each source area receives direct solar radiation. Thus two lags were determined, with the first lag being the time between the first direct solar radiation on the glacier face and the average time of peak flow. The second lag was the time between when the source area last receives direct solar radiation and the average time of peak flow. The calculated mean lags were then related to the length and gradient of each of the five streams.

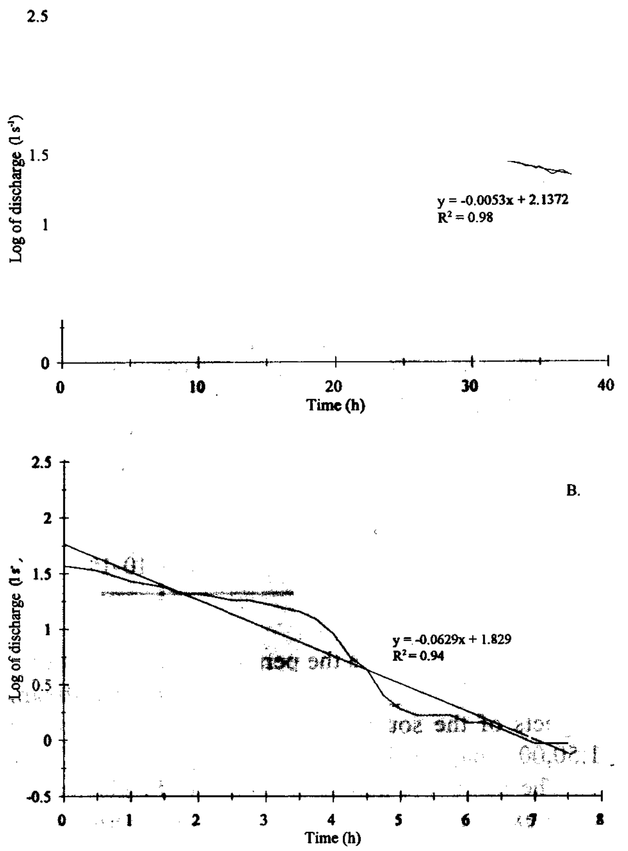

Fig 3. Log of discharge versus time for A. Canada Stream from December 18 to December 20, 1990, and B. Delta Stream from January 14 to January 15, 1991. Time zero is the beginning of the recession period.

Recession Analysis

An analysis of recession curves was conducted in order to assess the storage of water within the hyporheic zone and the drainage characteristics of each stream. We selected periods from the existing discharge records when there was no detectable increase in discharge due to the daily melt cycle. Hydrographs were plotted at 15-minute time intervals to confirm the identified recession period (Figure 2). For those hydrograph periods that showed no diurnal melt patterns, the log of the discharge was plotted against time [*Eagleson*, 1970]. The slope of this line was defined as the recession coefficient (Figures 3a and 3b).

X-Y scatterplots were constructed to assess the relationships between recession coefficients and magnitude of flow. Since the recession coefficients were expected to vary with the extent of hyporheic zone saturation, we only used recession coefficients obtained after the seasonal maximum flow. Given the high interannual variability in streamflow, we also tested the relationship between these coefficients and seasonal maximum flow.

RESULTS

Interannual and Daily Variability in Discharge

Average annual streamflows in the Lake Fryxell basin show tremendous interannual variability (Table 2). For each stream except Lost Seal Stream, the total discharge in 1990-1991 was 15–30 times the discharge in 1994-1995. These large annual differences imply a high interannual variability of both source and instream processes, and a need to consider the volume of annual streamflow when evaluating other measurements.

The results in Table 2 also show considerable interannual variations in relative flow. Green Creek, for example, contributed less than seven percent of the estimated total inflow to Lake Fryxell in 1993-1994 but 18% in 1994-1995. Streams with similar locations within Lake Fryxell Basin do not necessarily follow similar patterns from year to year. Total discharge in 1991-1992 for Von Guerard, Crescent, and Delta Streams, all on the south side of Lake Fryxell, was respectively 88%, 38%, and 64% of their respective discharges in 1990-1991. These differences between streams and between years may stem from the variation in the pattern of snowfall on the glaciers. Increased albedo on snow-covered ice reduces melt, particularly in these conditions where solar radiation is so important. Annual discharge of streams in the Lake Bonney basin exhibits less interannual variability. This is attributed to the lack of snow on the lower parts of the glaciers and lower overall precipitation as compared to Fryxell Basin (Fountain, unpublished data). Differences between streams may also stem from the different aspects of the source glaciers, the interannual variations in solar position during warm periods when most of the flow is generated, and physical characteristics of the individual streams.

In general, the total annual discharge was significantly correlated among the five different streams (Table 3). The strongest relationships were between Delta and Canada Stream ($R^2 = 0.99$) and Von Guerard and Lost Seal Stream ($R^2 = 0.99$). These two pairs of streams are at the eastern and western ends of Lake Fryxell, respectively, and they have at least one

TABLE 2. Annual Streamflow in the Lake Fryxell Basin and Estimated Percent Contribution to Lake Fryxell.

Stream site	Length	1990-1991		1991-1992		1993-1994		1994-1995	
	km	$x10^3$ m^3	%	$x10^3$ m^3	%	$x10^3$ m^3	%	$x10^3$ m^3	%
Canada Stream	1.5	510	15	300	13	130	14	32	20
Huey Creek	2.1	200	6	72	3	51	5.5	0	0
Lost Seal Stream	2.2	530	15	470	20	190	21	19	12
§Aiken Creek	1.3	250	7	280	12	57	6.2	8.7	5
Von Guerard Stream	4.9	160	5	140	6	68	7.4	7.2	5
Crescent Stream	5.6	210	6	80	3	39	4.2	4.8	3
Delta Stream	11.2	220	6	140	6	63	6.8	3.1	2
Green Creek	1.2	330	10	220	9	61	6.6	28	18
McKnight Creek	2.0	*	*	*	*	41	4.5		
Harnish Creek	5.1					53	5.8		
Bowles Creek	0.9					22	2.4		
Mariah Creek	0.9					26	2.8		
Andrews Creek	1.5					20	2.2		
Intermittent streams	*	610	18	430	17	NA	NA	26	16
Direct glacier inflow		420	12	260	11	99	11	31	19
Total		3440	100	2390	100	920	100	160	100

*Indicates data not available. NA = not applicable. §The stream length for Aiken Creek is only for the reach between Many Glaciers Pond and Lake Fryxell.

TABLE 3. Coefficients of Determination (R^2) for Total Annual Flow and for Mean Daily Flow for 1990-1991 through 1995-1996. In Each Case the Number in Parentheses below the Coefficient is the p-Value.

	Total Annual Flow					Mean Daily Flow				
Stream	Canada	Crescent	Delta	Lost Seal	Von Guerard	Canada	Crescent	Delta	Lost Seal	Von Guerard
Canada		0.95	0.99	0.89	0.89		0.58	0.69	0.56	0.68
		(0.022)	(0.004)	(0.054)	(0.057)		(0.0001)	(0.0001)	(0.0001)	(0.0001)
Crescent			0.92	0.74	0.74			0.69	0.68	0.69
			(0.041)	(0.14)	(0.14)			(0.0001)	(0.0001)	(0.0001)
Delta				0.94	0.94			—	0.71	0.75
				(0.032)	(0.031)				(0.0001)	(0.0001)
Lost Seal					0.99					0.74
					(0.002)					(0.0001)
Von Guerard										

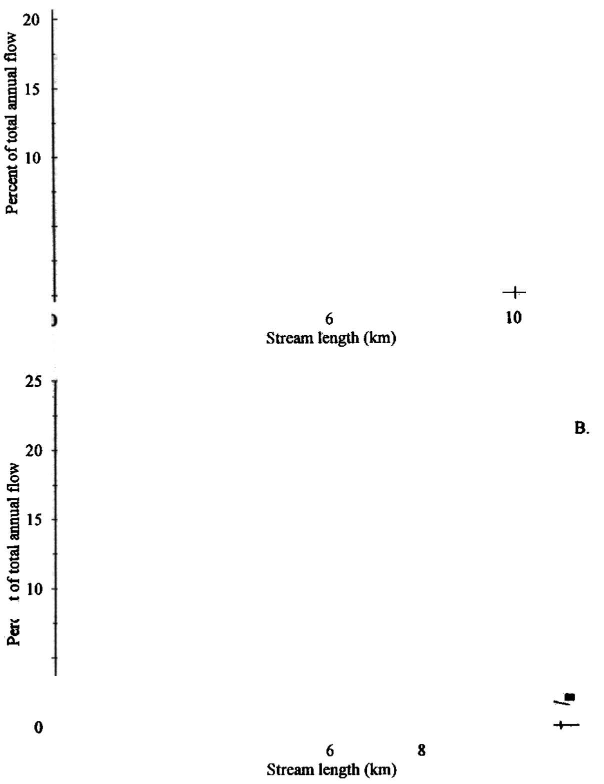

Fig 4. Relationship between percent of total inflow to Lake Fryxell and stream length for A. summer of 1990-1991 and B. summer of 1994-1995.

source area with a similar aspect. However annual discharge in Crescent Stream was not well correlated with the annual discharge in either Lost Seal or Von Guerard Streams, even though the latter also drain northwards from the Kukri Hills. Nevertheless the generally high correlations suggest that regional climate is the dominant control on streamflow. In a warm versus a cold year, all streams will have higher annual flows despite the fact that their relative contributions may vary. Correlations were not as strong when comparing mean daily flows for the five streams, although all comparisons were significant ($p<0.0001$) (Table 3). The poorer correlations for shorter time periods suggests that each stream is subject to considerable short-term variability in source and possibly instream processes.

The more intensive measurements during the 1993-1994 summer indicated that the ungauged streams contributed about 20% of the total inflow to Lake Fryxell. Intermittent measurements made in the other three years were consistent with this estimate. The 20-fold variation in total inflows to Lake Fryxell mean that the contributions of the streams to the basin-scale water budget change quite substantially, and one would also expect considerable interannual variation in the amounts of sediment and nutrients delivered to the lake.

In addition to variation in source processes, the interannual variability in flow may be related to differences in physiographic characteristics. Figure 4 shows stream length versus percent of total flow for the the high flow year of 1990-1991 and the low flow year of 1994-1995. The exponential regression lines indicate that in the low flow year, a greater portion of flow was contributed by streams with short stream lengths, but the relationship with stream length was not as strong in the high flow year. The greater contribution of shorter streams in a dry year may be related to the amount of meltwater storage in the hyporheic zone, as the meltwater initially encounters a dry streambed and must saturate the channel before advancing. During a low flow year this recharge and storage will be a greater percentage of the total meltwater runoff in the longer streams. This stored water is believed to be largely lost to evaporation rather than carried over to the next melt season (Howard-Williams, personal communication). Further investigation into the interactions between the stream, the hyporheic zone, and the permafrost is needed to better understand the storage and loss of meltwater along the channel.

Hydrograph Separation

The estimated proportions of melt from the glacier surface (baseflow) and glacier faces (peakflow) as determined from the daily hydrographs showed considerable variation between days and between streams (Table 4). A few very high ratios caused the mean values for some streams to be much larger than the median, and for this reason the interbasin comparisons are based primarily on the medians. Three of the streams (Canada, Lost Seal, and Delta) had median peakflow/baseflow ratios of less than five, while the median ratios for Von Guerard and Crescent Streams were greater than ten. Both Canada and Lost Seal Streams are draining relatively large and flat glacier surfaces, and the high baseflow discharge (generally greater than 70 l s^{-1}) in these two streams indicates that there is a more even input of energy to these glacier surfaces than to the steeper glaciers of the Kukri Hills.

TABLE 4. Peakflow, Baseflow, and Peakflow/Baseflow Ratios for Randomly Selected Dates During the 1990-1991 and 1991-1992 Seasons. Discharge Values are in Liters per Second.

	18 Dec 1990	22 Dec 1990	27 Dec 1990	11 Dec 1991	30 Dec 1991	1 Jan 1991	12 Jan 1991	7 Jan 1992
Canada Stream								
Peakflow	150	300	650	410	260	480	340	220
Baseflow	70	100	100	90	110	125	95	20
Peakflow / Baseflow	2.1	3.0	6.5	4.6	2.4	3.8	3.6	11
Mean ratio = 4.6	Median ratio = 3.7							
Lost Seal Stream								
Peakflow	410	220	350	400	1000	750	450	750
Baseflow	125	70	70	200	175	195	100	20
Peakflow / Baseflow	3.3	3.1	5.0	2.0	5.7	3.8	4.5	38
Mean ratio = 8.1	Median ratio = 4.2							
Von Guerard Stream								
Peakflow	120	125	305	425	250	210	260	125
Baseflow	10	10	20	40	45	20	25	5
Peakflow / Baseflow	12	13	15	11	5.6	11	10	25
Mean ratio = 13	Median ratio = 11.5							
Crescent Stream								
Peakflow	195	240	315	170	245	300	375	110
Baseflow	15	15	25	25	25	50	25	10
Peakflow / Baseflow	13	16	13	6.8	9.8	6.0	15	
Mean ratio = 11	Median ratio = 12.0							
Delta Stream								
Peakflow	135	130	300	340	210	210	130	140
Baseflow	25	30	50	80	60	70	20	7
Peakflow / Baseflow	5.4	4.3	6.0	4.3	3.5	3.0	6.5	20
Mean ratio = 7	Median ratio = 4.9							

Delta Stream does not have such a large glacial surface and baseflow is less than Canada and Lost Seal Streams. Conversely the face of Howard Glacier has aspects that range from northwest to northeast (Figure 1), which may sustain the higher baseflow and account for the lower peakflow/baseflow ratio. Crescent and Von Guerard Streams both drain from the steeper glaciers of the Kukuri Hills, and the range of aspects for these faces is not as great as for Howard Glacier. Thus the discharge in Crescent and Von Guerard Streams exhibits greater diel variability and appears to be more dependent on solar position.

Solar Position and Lag Times

The time periods that the glacier faces were receiving direct solar radiation ranged from a minimum duration of two hours for Canada stream to a maximum duration of six hours for Delta Stream. The faces contributing to Canada, Crescent, Delta, and Von Guerard Streams receive direct sunlight from late morning (1100 h) to the evening (1900 h). The glacier faces contributing to Lost Seal Stream receive direct sun from the evening (2000 h) until early morning (0100 h).

With the exception of Lost Seal Stream, average times of peak flow (Table 5) were generally consistent from year to year. Canada Stream showed the least variation in time of average peak flow within and between years, while the interannual variability in time of peak flow was 2–3 hours for Von Guerard, Crescent and Delta Streams. As might be expected, there was considerable variation in the timing of daily peak flows within each year, and this presumably reflects hourly-scale variations in temperature and cloud cover.

The eight-hour variation in the time of peak flow for Lost Seal Stream may stem from its topographic situation and the range of contributing aspects of the source glacier. Streamflow records show a general trend of two separate peak flows, one in the late evening and another in the early morning. The times of peak flow for Lost Seal Stream are an average of these peaks, and this averaging adds another source of variability to the calculation of mean lags. The source area for Lost Seal Stream is in close proximity to the mountain that lies to the west of Commonwealth Glacier. Thus the dual peak in daily flow is most likely caused by the mountain shadow. More precise calculations based on the true period of illumination should reduce this variability. Intermittent ponding at the base of the glacier during higher flows and the flatter gradient of Lost Seal Stream may also reduce streamflow velocities and allow for more storage; these both might contribute to an increased variability in the recorded times for peak flow.

In addition to the aspect and range of source areas, the time of peak flow and the calculated lags will depend on the time necessary for the melt water to reach the gauging station, and this will be a function of both width and gradient. The mean lag between the time of first sun on the glacier faces and time of peak flow was shortest (4.6 h) for Canada Stream. Conversely, the longest average lag was eleven hours for Delta Stream, and this is also the longest stream. Thus lags increased with stream length, with the exception of Lost Seal Stream. The rate at which the peak discharge wave moves downstream will also be affected by the gradient. There was a stronger correlation with the length-to-gradient index in Table 1 than either length or gradient alone (Table 6).

Recession Analysis

The recession coefficients for each stream were calculated from periods of no melt which lasted up to a few days. High recession coefficients (i.e., a steeper decline in discharge over time) are believed to indicate more rapid drainage, while low recession coefficients imply slower drainage. Because the slope of the recession curves indicate the relative speed at which water moves out of the adjacent saturated areas, variations in coefficients may be related to the physiographic characteristics of the different streams and the volumes of water stored in the hyporheic zone.

Of the five streams analyzed, Canada Stream had the lowest average recession coefficient (Table 7) even though it is also the shortest stream. The average slope of the recession limb was –0.011, and individual values ranged from a minimum of –0.005 to a maximum of –0.021. Canada Stream is the only stream with a pond at the base of the glacier face that functions at all flow levels, and this pond may store sufficient water to maintain relatively consistent flows even after melt has ceased.

Von Guerard Stream has the steepest average recession slope and the steepest gradient. The average slope of recession was –0.04, with individual values ranging from a minimum of –0.012 (the average slope for Canada Stream) to a maximum of –0.099. These values are consistent with the stream's steep channel and moderate length (Table 1).

The other three streams had similar mean recession coefficients (Table 7). Because Delta Stream had the highest length-to-gradient value and Lost Seal Stream the lowest gradient, it is likely that the recession coefficients are controlled by other variables in addition to stream length and gradient.

DISCUSSION

Solar Position and Lag Times

The timing of peak streamflow appears to be strongly related to the period of peak solar radiation on the source glaciers. Because the glacier surfaces share

TABLE 5. Periods of Peak Solar Insolation, Times of Peak Flows, and Resultant Lag Times in Hours and Minutes In Three Cases Less Than 40 Days Were Used to Determine Average Peak Flows and in These Cases the Number of Days is Shown in Parentheses.

Stream	Period with Direct Radiation (h)	Year 1990-1991	1991-1992	1993-1994	1994-1995	1995-1996	Mean lag For Period Of Record
Canada Stream	1100–1300						
Average time of peak		14:42	15:37	15:32	15:59	16:07	
Standard deviation		1:23	1:24	1:10	1:01	1:29	
Mean lag from earliest direct radiation		3:42	4:37	4:32	4:59	5:07	4:35
Mean lag from latest direct radiation		1:42	2:37	2:32	2:59	3:07	2:35
Lost Seal Stream	2000–0100						
Average time of peak		22:32	18:05	23:44	2:06 (14)	23:40 (30)	
Standard deviation		3:28	3:17	2:47	6:45	1:06	
Mean lag from earliest direct radiation		2:32	22:05	3:44	7:06	3:40	7:51
Mean lag from latest direct radiation		21:32	17:05	22:44	25:06	22:40	21:49
Von Guerard Stream	1430–1900						
Average time of peak		20:06	21:41	23:01	22:24	21:33	
Standard deviation		2:12	2:48	1:20	2:15	3:50	
Mean lag from earliest direct radiation		5:36	7:11	8:31	7:54	7:03	7:15
Mean lag from latest direct radiation		1:06	2:41	4:01	3:24	2:33	2:45
Crescent Stream	1400–1800						
Average time of peak		21:41	22:09	20:53	19:18	*	
Standard deviation		3:07	1:56	3:10	2:50	*	
Mean lag from earliest direct radiation		7:41	8:09	6:53	5:18	*	7:00
Mean lag from latest direct radiation		3:41	4:09	2:53	1:18	*	3:00
Delta Stream	1100–1700						
Average time of peak		22:05	22:07	22:58 (22)	20:55	*	
Standard deviation		1:43	1:56	6:00	2:16	*	
Mean lag from earliest direct radiation		11:05	11:07	11:58	9:55	*	11:01
Mean lag from latest direct radiation		5:05	5:07	5:58	3:55	*	5:01

* Indicates data not available.

TABLE 6. Comparison of Lag Times to Length to Gradient Index

				Mean Annual Lag (h)	
Stream	Length (km)	Gradient (m m^{-1})	Length/Gradient	Lag from Earliest Direct Radiation	Lag From Latest Direct Radiation
				4:35	2:35
				7:51	21:49
				7:15	2:45
				7:00	3:00
				11:01	5:01

similar aspects with the faces, it is difficult to separate meltwater contributions from these two source areas. The nearly vertical glacier faces do receive nearly twice the intensity of solar radiation than the glacier surfaces during the short period of direct insolation [*Lewis et al.*, in press]. Because the temperature of the ice is well below freezing, the high intensity of solar radiation on the glacier faces may be necessary to both warm the ice to 0°C and generate melt [*Fountain et al.*, this volume]. The faces are also at lower elevations than the surfaces, closer to the dark-colored valley floors, and maintain lower albedos throughout the season; all these factors favor a larger contribution from the glacier faces relative to the surfaces [*Fountain et al.*, this volume]. Water flowing in channels along the glacier surface is rarely observed, indicating that surface melt at higher elevations can refreeze before running off [*Fountain et al.*, this volume]. The relatively steep diurnal peaks and the high peakflow/baseflow ratios also suggest a shorter and more concentrated input of meltwater than would be the case if the glacier surface was the primary source of melt.

Velocity data were used to estimate the travel time of the peak discharge wave from the base of the glacier to the stream gauge. Average velocities at each gauging site were obtained by dividing discharge by the cross-sectional area of the channel. Average velocities at the gauging station for Canada and Lost Seal Streams were 0.51 m s^{-1} and 0.48 m s^{-1}, respectively (USGS, unpublished data). These values are considered representative for these streams because the Canada Stream gauge is located midway between the glacier and Lake Fryxell, and the low gradient at the Lost Seal Stream gauge is representative of the entire stream. For Delta and Von Guerard Streams, we used velocities of 0.27 m s^{-1} and 0.32 m s^{-1}, respectively, as these had been measured during moderate flows at algal transects 2–4 km above the gauge [*Alger et al.*, 1996]. Velocities from the gauging stations were not believed to be representative and the measured velocity in Von Guerard Stream also may be low because the algal transect was located in a low gradient reach. We would expect flow velocities in Delta Stream to be greater than Lost Seal Stream due to the differences in gradient. However the velocity recorded for Lost Seal Stream is nearly twice the velocity of Delta Stream, suggesting that the former was taken at higher flows. Velocity data were not available for Crescent Stream.

From these measurements, the estimated travel times for Canada, Delta, Lost Seal, and Von Guerard Streams were 0.8, 12, 1.3, and 4.3 h, respectively. It must be noted that these times are rough estimates, because the velocity measurements were taken at only one cross-section. For Canada, Delta, and Von Guerard Streams the estimated travel times were within or somewhat less than the range of lags between the period of direct sun on the glacier face and the average time of peak flow. The consistency between lag times and estimated travel times for Lost Seal Stream is less clear due to the ambiguity in determining average time of peak flow. As one would expect, lags and estimated travel times increased with increasing stream length.

Previous study has shown that there is a delay between the time of melt generation and the influx of meltwater to the stream channel [*Lewis*, 1996]. This lag is attributed to the time between the initial absorption of shortwave radiation and the delivery of melt water to the stream channel, as well as the size and extent of the source area. In Andersen Creek, where there is only a 100 m reach between the glacier terminus and the stream gauge, a two hour lag was observed between peak radiation input and peak discharge [*Lewis*, 1996]. However, the source area extends two km upstream from Andersen Creek, suggesting that part of the lag is due to the travel time within the source area.

TABLE 7. Recession Periods and Corresponding Coefficients. SD is Standard Deviation.

Canada Stream	Coefficient	Crescent Stream	Coefficient
18-20 Dec 90	0.005		
23-25 Dec 90	0.006		
5-6 Feb 91	0.015		
6-7 Feb 91	0.017		
13-14 Dec 91	0.007		
20 Dec 91	0.007		
11-12 Jan 92	0.017		
14-15 Jan 92	0.015		
19-21 Dec 93	0.013		
20-22 Dec 94	0.021		
31 Dec 95-1 Jan96	0.010		
11-14 Jan 96	0.008		
Mean	0.011		
SD	0.005		

Lost Seal Stream	Coefficient	Von Guerard Stream	Coefficient
17 Jan 91		7 Dec 90	
18 Jan 91		22-23 Dec 91	
10-11 Jan 92		8-9 Jan 92	
17 Jan 92		16 Jan 92	
28-29 Dec 93		17 Jan 92	
11 Jan 95		17-18 Jan 92	
29 Dec 95		17-18 Jan 92	
12 Jan 96		13 Jan 94	
Mean		Mean	
SD		SD	

Delta Stream	Coefficient
9-10 Jan 91	
14-15 Jan 91	
16 Jan 91	
19-20 Jan 91	
19 Dec 92	
8-9 Dec 93	
17 Jan 94	
23-24 Jan 55	
Mean	
SD	

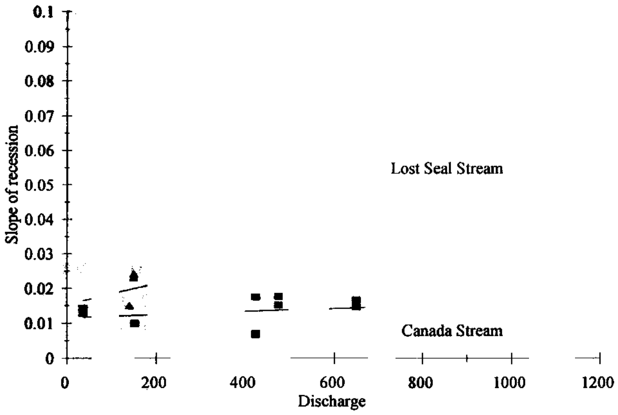

Fig 5. Discharge versus slope of the recession limb for Canada and Lost Seal Streams.

Recession Analysis

Interpretation of the recession curves for the streams in Lake Fryxell Basin is a departure from typical studies of subsurface flow within a catchment. Baseflow can be defined as the component of flow that is derived from groundwater storage or other delayed sources [*Hall*, 1968], but in Fryxell Basin subsurface flow is probably limited to the areas immediately adjacent to the stream. Because groundwater flow has not been previously observed [*Chinn*, 1993], this was not been considered in our interpretation of the recession coefficients. Hence we believe that the recession coefficients should depend primarily on the available storage in the hyporheic zone rather than baseflow in the traditional sense.

In the case of Canada Stream, which had the lowest average recession coefficients, flows may be regulated by the pond at the base of Canada Glacier. The volume of this pond is sufficiently large relative to daily flows to regulate meltwater inputs into the stream. Canada Stream has higher baseflows, the lowest peakflow/baseflow ratio, and the most consistent timing of peakflows. These characteristics all support the concept that the pond serves to attenuate high flows and supplement low flows during periods with little or no melt.

For Canada Stream the recession coefficients were relatively independent of discharge within a season and between years (Figure 5). It is the shortest of the five streams and has a relatively narrow, incised channel. The area adjacent to the channel that can be saturated is therefore limited and this could limit the effect of higher flows on the slope of the recession limb. In both low flow and high flow years the extent of the saturated hyporheic zone would be similar.

In contrast to Canada Stream, recession coefficients for Lost Seal Stream increase with an increase in seasonal peak flow (Figure 5). The recession coefficient for the period after the seasonal peak in 1994-1995 was 0.015, while the corresponding value in 1990-1991 was 0.052, nearly four times larger. In a wide, low-gradient channel, a small increase in water level could create a relatively large increase in saturated area. Lost Seal Stream is the flattest of the five streams, and therefore should have a potentially larger saturated area adjacent to the channel. At lower flows the saturated volume adjacent to the stream will be less, and a drop in stream stage will not create a very strong hydraulic gradient back to the stream channel. At high flows there would be a larger saturated volume and a stronger gradient as stage decreases. Hence the effect of discharge on the recession coefficients should be more pronounced in the wider, lower-gradient streams that have a potentially larger hyporheic zone.

A conceptual model for the different patterns in the extent of the hyporheic zone in Canada and Lost Seal Streams is shown in Figure 6. This model can be used to develop more quantitative hypotheses to explain how differences between Canada Stream's steep, incised channel and Lost Seal Stream's wide and flat channel could be influencing drainage. Because the alluvium is generally uniform throughout the basin, we hypothesize that these geomorphic differences are significant in explaining differences between these streams.

Relationships for the other three streams are less clear. The recession coefficients for Crescent Stream increase with higher streamflow except for the lowest melt season (1994-1995). Recession coefficients for Delta and Von Guerard Streams display no consistent pattern within a season, between seasons, or in relation to magnitude of streamflow. Von Guerard and Crescent Streams are both longer and steeper on average than Lost Seal and Canada Streams and have more variation in topography along their length. Both Von Guerard and Crescent Streams drain steep upper reaches before flattening out. Thus their recession curves may be a composite of different drainage patterns from the different reaches, and this may obscure any relationship with total length, average gradient, or seasonal peak discharge.

A final problem with interpreting the recession coefficients is the sensitive temperature balance between melt generation and freezing. When temperatures drop and glacial melt shuts off, some of the water in the hyporheic zone may freeze in situ and cannot drain back into the channel. The amount of water frozen in the saturated zone will vary with the temperature regime during each recession period, and this may greatly affect the observed rates of recession. The extreme sensitivity of streamflow to small changes in temperature and other climatic factors means that we have to expect considerable variation in any streamflow characteristic.

CONCLUSIONS

Streams in the McMurdo Dry Valleys exhibit tremendous variability in flow on daily, seasonal, and interannual time scales. The proportion of flow between streams is not necessarily consistent from year to year. The relative consistency of lags between the period of sun on the glacier face and average time of peak flow between years and between streams demonstrates the importance of solar position and glacial melt in controlling the daily flow regime. A more detailed analysis of how solar position, solar radiation, and temperature control runoff would help in identifying the source processes and how they might control stream and lake responses to climatic fluctuations. Additional years of streamflow and meteorological data will aid in the understanding of watershed processes and the stream ecosystems within the dry valleys.

Although we have put forth a variety of hypotheses to explain the dynamics of streamflow and evaluate the role of the hyporheic zone, there are more controls on the system than we can account for in these analyses. Of the five streams, only Canada and Lost Seal display some consistency in their relationship between recession coefficient and discharge. Recession analysis of Delta, Crescent, and Von Guerard Streams illustrate that other methods are necessary to evaluate how stream channel geomorphology governs instream channel processes. Additional tracer experiments and hydrometric measurements are needed to quantify the hyporheic zone and evaluate its significance for the dry valley streams and lakes, particularly since drainage controls the duration of the summer growth period.

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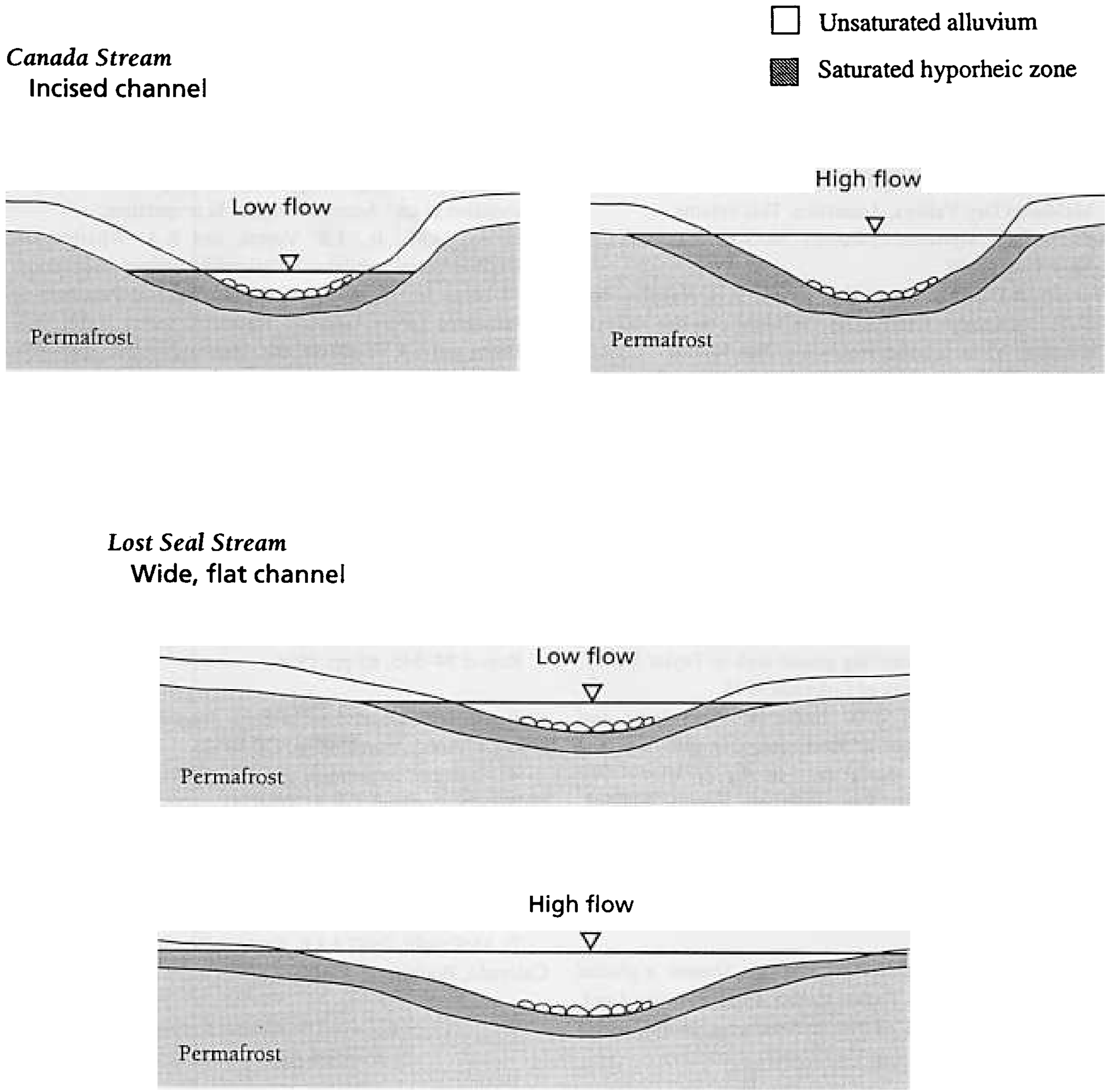

Fig 6. Schematic showing variation in the extent of the hyporheic zone under low and high flow conditions in Canada and Lost Seal Stream.

REFERENCES

Alger, A.S., D.M. McKnight, S.A. Spaulding, G.H. Shupe, A. Welch, R. Edwards, E.D. Andrews, and H.R. House. Ecological processes in a cold desert ecosystem: the abundance and species distribution of algal mats in glacial meltwater streams in Taylor Valley, Antarctica. Occasional paper No. 51. Institute of Arctic and Alpine Research, 1997.

Bockheim, J.G., *Properties and classification of cold desert soils from Antarctica*. Soil Sci. Soc. Am. J. 61:224–23. 1997.

Bromley, A.M., Weather observations, Wright Valley, Antarctica, Infor. Publ. 11, 37 pp., New Zealand Meteorological Service, Wellington, 1985.

Chinn, T.J., Physical hydrology of the dry valley lakes. In *Physical and Biogeochemical Processes in Antarctic Lakes, Antarctic Research Series, V. 59*, W.J. Green and E.I. Friedman, eds. Washington, D.C. 1–51. 1993.

Dana, G.L., R.A. Wharton, R. Dubayah. Solar radiation in the McMurdo Dry Valleys, Antarctica. This volume.

Eagleson, P.M., Dynamic hydrology. McGraw-Hill Book Co. New York. 1970.

Fountain, A.G., G.L. Dana, K.J. Lewis, B.H. Vaughn, and D.M. McKnight. Glaciers of the McMurdo dry valleys, Southern Victoria Land, Antarctica. This volume

Hall, F.R., *Base-flow recessions--a review.* Water Resources Research 4: 973–983. 1968

House H.R., D.M. McKnight, and P. von Guerard. *The influence of stream channel characteristics on streamflow and annual water budgets for lakes in Taylor Valley.* Antarctic Journal of the United States. (in press). 1996.

Keys, J.R., Air temperature, wind, precipitation and atmospheric humidity in the McMurdo Region. Publ. 17, 57 pp. Geology Department, Victoria University,Wellington, NZ, 1980

Lewis, K. Processes controlling glacial melt in Taylor Valley, M.S. Thesis, University of Colorado.1996.

McKnight, D.M., and E.D. Andrews. *Hydrologic and geochemical processes at the stream-lake interface in a permanently ice- covered lake in the McMurdo Dry Valleys, Antarctica.* Veh. Internat. Verein. Limnol. 25:957–959, 1993.

McKnight, D.M. and C.M. Tate. *Algal mat distribution in glacial meltwater streams in the Taylor Valley, southern Victoria Land, Antarctica.* Antarctic Journal of the United States, 1996.

McKnight, D.M. and C.M. Tate. *Canada Stream: a glacial meltwater stream in Taylor Valley, South Victoria Land, Antarctica.* Journal of North American Benthological Society, 1996.

McKnight, D.M., H.R. House, and P. von Guerard. *Streamflow measurements in Taylor Valley.* Antarctic Journal of the United States,1995.

McCuen, R.H. *Hydrologic analysis and design.* Ch. 8, pp 355–360, Prentice Hall, New Jersey. 1989

Runkel, R.L., D.M., McKnight, and E.D. Andrews. Analysis of transient storage subject to unsteady flow: diel flow variation in an Antarctic stream. In preparation.

Simmons, G.M., Jr., J.R. Vestal, and R.A. Wharton, Jr. Environmental regulators of microbial activity in continental lakes. In: Physical and Biogeochemical Processes in Antarctic Lakes,Antarctic Research Series V.59, W.J. Green and E.I. Friedman, eds. Washington D.C. 165–195. 1993

Spaulding, S.A., D.M. McKnight, R.L. Smith and R. Dufford. *Phytoplankton population dynamics in perennially ice-covered Lake Fryxell, Antarctica.* J. Plank. Res. 16:527–541.1994

von Guerard, P., D.M. McKnight, R.A. Harnish, J.W. Gartner, and E.D. Andrews. Streamflow, water temperature, and specific conductance data for selected streams draining into Lake Fryxell, Lower Taylor Valley, Victoria Land, Antarctica. U.S. Geological Survey. Open-file Report 94–545. 65 pp. 1994.

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