A Continuous Dye Injection System for Estimating Discharge in Snow-choked Streams

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Abstract

A simple method is presented which demonstrates the use of continuously injected Rhodamine WT dye to provide automated around-the-clock estimates of flow during the spring breakup. Dye of a known concentration is injected at a constant rate upstream from a sampling point, and the dilution of the dye in the sampled downstream water is a measure of discharge. Field trials conducted in and around Inuvik, Northwest Territories in two small snow-choked streams during spring breakup of 1995 to 1999 suggest that some dye is adsorbed to suspended sediment in the stream channel, resulting in an overestimate of discharge. However, there is still a strong linear relationship between the discharge as estimated by the dye method and that determined by conventional current metering. Correcting the dye values by a linear regression equation line results in a reasonable estimate of streamflow. This method's most promising application is in the monitoring of small basins where much of the annual discharge occurs during the spring melt. Given the occurrence of rapid changes in discharge in these basins due to both diurnal variations in snowmelt and changing runoff source area, and the excessive manpower required to carry out a sufficient number of current meterings needed to properly observe this changing discharge, the dye dilution method often provides a more accurate estimate of discharge.

Introduction

There are many methods for measuring stream discharge, including velocity-area methods (Terzi, 1981), rising floats (Sargent, 1982), electromagnetic gauging (Herschy and Newman, 1982), helicopter mounted radar (Melcher et al., 2002), and dilution methods using various tracers (Kilpatrick, 1968) for example. While all of these methods are applicable in most streams, the velocity-area technique is most commonly used for measuring discharge, and the relationship of stream stage to discharge is the method of choice for calculating a continuous estimate of discharge at a gauging station. However, use of either of these two methods during spring breakup in northern rivers presents a number of problems due to the occurrence of snow within the normal channel boundaries (Woo and Sauriol, 1980), ice (Prowse et al., 1989), or other channel-borne debris such as driftwood. In addition to making access to the channel difficult and dangerous, these conditions also modify the stage-discharge relationship. The remainder of this paper will concentrate on discharge estimates in snow-choked channels.

At the end of winter, arctic nival stream-channels (Church, 1975) are typically choked with snow, often to a depth of 2 m or more. Consequently, spring streamflow begins as over-snow and within-snow saturated flow (Woo and Sauriol, 1980). However, the majority of the melt period is characterized by a channel with a slowly eroding ice bed, and rapidly melting snow-lined banks. These conditions may exist for a week or more until the snow is eroded and melted from the channel. During this period the summer stage-discharge relationship is not applicable, and the actual relationship is constantly changing as the bed or bank snow and ice melts and erodes. Very often the spring runoff peak occurs well before the stream channel reaches a stable, snow-free, form.

Due to the lack of appropriate techniques for continuously monitoring discharge during the spring breakup period, many studies have relied on point estimates of discharge, with the standard velocity-area method using current metering being most common (Woo et al., 1983; Marsh and Pomeroy, 1996; Kane et al., 1991). As a result of strong diurnal fluctuations in discharge during the spring melt (i.e., McCann and Cogley, 1972; Marsh et al., 1994), many current meter repetitions are needed to accurately estimate daily discharge. Again, typical conditions during melt make both wading and boat-based current metering difficult and dangerous. In short, conventional stage-discharge or velocity-area methods are not ideally suited to measuring spring discharge in Arctic nival streams. Since discharge during spring melt may account for over 90% of the annual discharge (Church, 1974; Marsh et al., 1994) of small arctic nival streams, such problems are a major impediment for hydrologic studies in these regions.

At many stream gauge stations across Canada's north, the operational current metering protocol involves using manual velocity-area techniques during the early spring, and automatic stage discharge gauges when the stream is flowing within its usual channel. Unfortunately, geographic, financial, and time restrictions often limit the number of velocity/area current meterings during breakup, and it is common that automatic gauges may not be activated until some time after the stream has receded to its regular channel. Because of the above problems, the estimate of spring discharge using standard operational techniques is prone to large errors.

Given these difficulties, the objective of this paper is to describe a simple, continuous dilution technique appropriate for estimating the discharge of Arctic nival streams during the spring melt period. Although both instantaneous and constant dilution injection techniques have been well described in the literature (e.g., Church and Kellerhalls, 1970), these have typically referred to techniques for determining a single, instantaneous discharge measurement. The approach described in this paper will present a modification of these methods, with the intention of determining instantaneous discharge at frequent intervals over a 1- to 2-wk period. Although applied in this paper to snow choked channels, this method is applicable in other cases where stage-discharge rating curves are not stable.
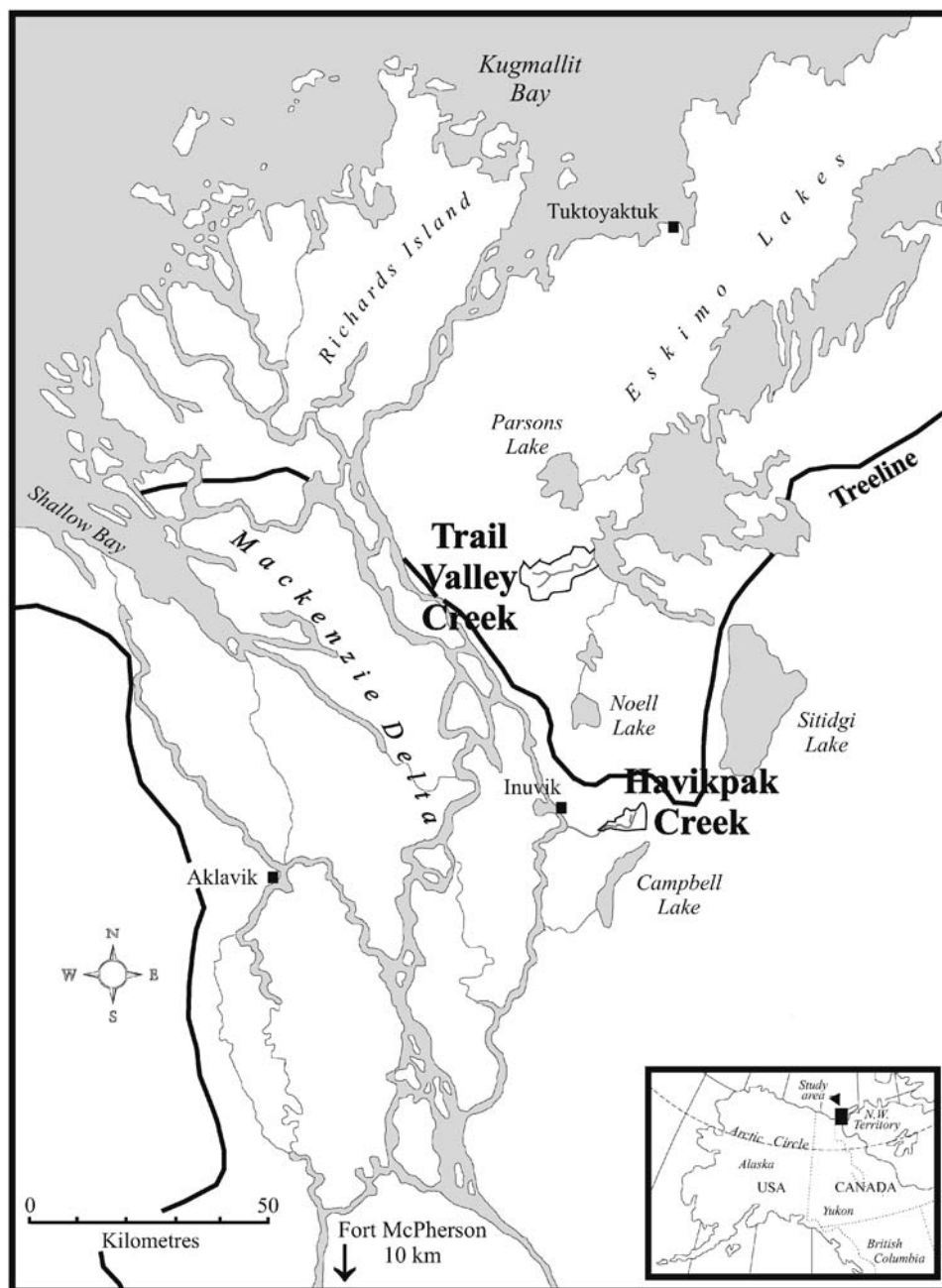
FIGURE 1. Map showing locations of study basins. TVC and HPC basin boundaries are shown in black, streams in gray.

Study Area

Hydrologic investigations were conducted at two streams, Trail Valley Creek (TVC) and Havikpak Creek (HPC) (Fig. 1) near Inuvik, Northwest Territories, Canada. TVC is located approximately 40 km north-northeast of Inuvik (68°45′N, 133°30′W), and Havikpak Creek (HPC) is located approximately 20 km southeast of Inuvik (68°19′N, 133°30′W). The experiment was run for the years 1995 to 1997 at HPC, and 1996 to 1999 for TVC.

The catchment area of TVC is approximately 63 km², with elevations that range from 60 to 190 m a.s.l. The basin is located in the northern portion of the boreal forest/tundra transition zone, with a dominance of tundra vegetation and smaller areas of forest, shrub tundra and lakes. HPC is farther south than TVC, within the boreal forest/tundra transition zone, with a preponderance of boreal forest vegetation, scattered lakes and wetlands in the lower portion of the basin, rising to hilly tundra in the northeast part of the basin (Marsh and

Pomeroy, 1996). The HPC catchment is 17 km² in area, with elevations that range from 60 to 260 m a.s.l. Both basins have a climate which consists of cool, short summers and long cold winters (Marsh and Pomeroy, 1996), and are underlain by continuous permafrost. By the end of winter, snow often reaches 2 m in depth within the TVC channel, while at HPC, channel snow depths are typically less than 0.75 m. Streamflow typically begins earlier in the spring at HPC than at TVC, but flow at both basins often starts in May, and ceases in November. Discharge has been monitored by Water Survey of Canada (WSC) since 1974 at TVC, and 1995 at HPC. Discharge at TVC ranges from highs approaching 9 m³ s⁻¹ during the spring melt, to summer and fall averages of less than 1 m³ s⁻¹ At HPC, discharge ranges from highs of 2 to 3 m³ s⁻¹ during the spring melt, to summer and fall averages of well less than 1 m³ s⁻¹. Both streams have characteristics which conform to those which are ideal for dilution studies, including few dead water zones (Kilpatrick and Cobb, 1984), and narrow sections and contractions which favor lateral dye mixing (Herschy, 1985).

Methods

Stream measurement using dilution gauging is well established and documented (Goodell et al., 1967; Church and Kellerhals, 1970; Church, 1975). Simply put, discharge is determined by measuring the dilution of a tracer with a known concentration that is introduced to the stream at a known rate, with the resulting downstream concentration varying inversely to stream discharge. Common tracers include both salt and fluorescent dyes, with fluorescent dyes being common due to the small quantities required, and the ease of measuring at concentrations as low as ~0.002 µg ml^{-1} (Smart et al., 1998).

In the current experiment, a dye injection system ran continuously over a 1- to 2-wk period, with breaks only for maintenance or if the system malfunctioned. For 1996 and 1997 at TVC, however, the system was turned off if overnight temperatures were expected to drop below freezing.
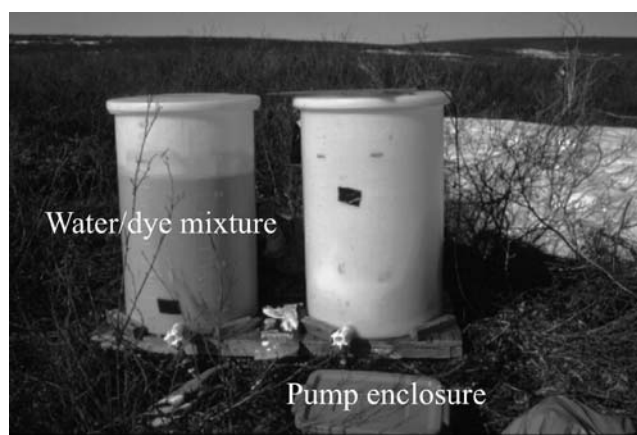
DYE INJECTION

The dye injection system varied slightly from site to site and year to year, however, the basic set-up remained unchanged (Fig. 2). Two 100-L carboys with lids and spigots were placed on a wooden platform about 4 m from the stream and 2 m above it. The two carboys were used to extend the maximum duration of unattended injection, as well as to allow the easy preparation of a new dye solution in one container while still running the dye injection from the other. At TVC, 3.0 L of 50% (by weight) Rhodamine WT dye were mixed with 91 L of stream water to provide a solution with a dye concentration of 16,000 mg L^{-1}. Lower discharges at HPC allowed the use of an injection solution with a lower dye concentration: 0.6 L of Rhodamine WT (50% by weight) was mixed with 93.4 L of stream-water to make a solution with an approximate dye concentration of 3200 mg L^{-1}. The dye injection solutions were stirred each day to ensure consistency, as well as sampled to confirm they were at the proper concentration.

Vinyl hoses leading from each bucket were stop-cocked to allow dye to pump from one or both buckets. These hoses joined down-slope at a "Y" connector which led to the dye pump, which was enclosed in a sealed plastic container. After the pump, the hoses were connected into another "Y" connector, with one branch used to draw samples off to confirm that the pump was injecting at the proper rate and concentration, and the other branch which lead to the stream. At TVC, the injection hose was supported by a 3 m length of PVC pipe suspended by a large aluminum tripod over the stream. The injection hose hung from this arm, and was long enough to trail into the stream, while the tripod was sufficiently stable to be left in the stream as water levels rose. At HPC, the dye injection hose was simply attached to willow branches which overhung the stream.

Fluid Metering Incorporated pumps were used to pump sufficient quantities of dye at consistent rates and volumes. Injection rates were changed throughout the experiments based on estimated stream discharge, but were typically kept between 10 ml min^{-1} for lower flows and 50 ml min^{-1} at times of higher flow. Power to the dye injection pump was provided by a 30-watt solar panel constantly recharging a sealed 12-volt gel cell battery. Pump flow rates were measured by timed volume samples taken at a minimum of once daily, as well as every time the pumping rate was changed. Throughout all experimental repetitions, the dye was delivered to the stream at, or very near to (within <1 ml min^{-1}) the proper set rate, regardless of factors that could affect the pumps or their power supply, including air temperature, and pumping rates.

During the 1996 field season the dye injection lines occasionally froze during colder evenings. In an attempt to minimize such problems in subsequent years, all dye injection hoses at TVC and HPC were wrapped in black foam pipe insulation, while the dye carboys had dark red solar blankets (reflective side in) taped around them. The total
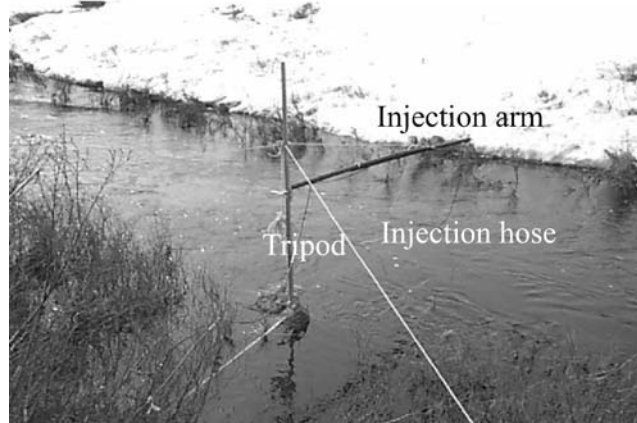
FIGURE 2. *Dye injection system at TVC, showing A) dye injection buckets and pump, B) injection tripod with arm over stream, and C) downstream water sampler. A similar set-up was used at HPC.*

length of injection hose was minimized, and all connection points were secured with steel hose clamps. In later years, salt was added to the dye mixture to help prevent freezing, a procedure which is explained in greater detail below.

DYE SAMPLING

Automatic water samplers were positioned approximately 1 km downstream of the dye injection points at TVC, and approximately
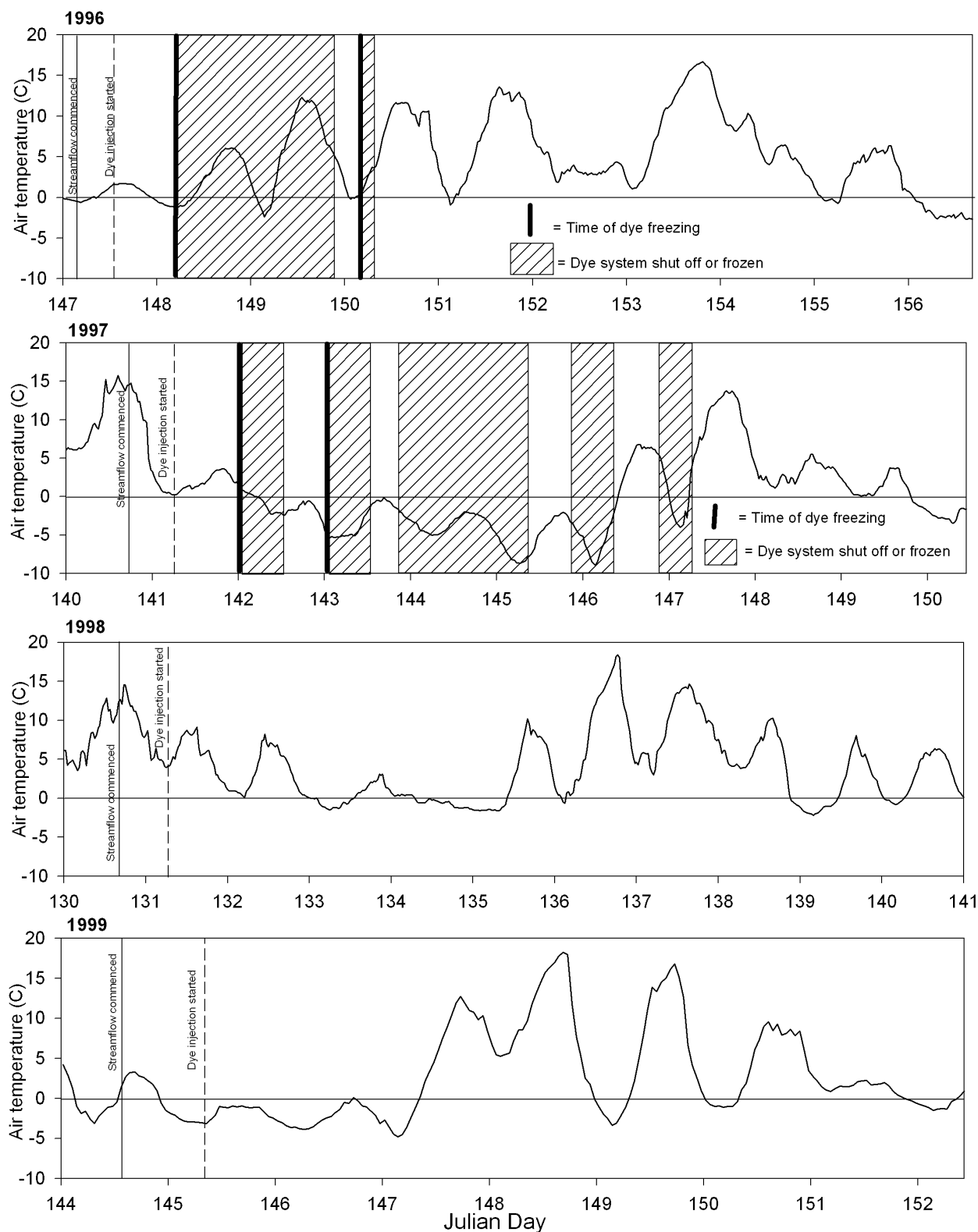
FIGURE 3. *Air temperature during dye experiments at TVC.*

300 m downstream at HPC. Two autosamplers were used at TVC in 1998, which allowed the experiment to be left running unattended for up to 48 h.

Discrete, 800-ml samples were taken by the autosamplers every 3 h. Before each sample was taken, the sampler intake hoses were automatically flushed twice, followed by a final intake cycle. To minimize dye storage or retention, Teflon sampler intake hoses were used. In 1996, the sampling protocol was different in that the autosampler was programmed to fill each of the sample bottles with 70-ml samples taken every 10 min. In this manner, the dye estimate was representative of 3-h average discharge. This sampling protocol was not used in subsequent years due to concerns that integrated sampling was

FIGURE 4. *TVC discharge time series, 1996–1999. Dye estimates shown in the time series are all the manual and automatic samples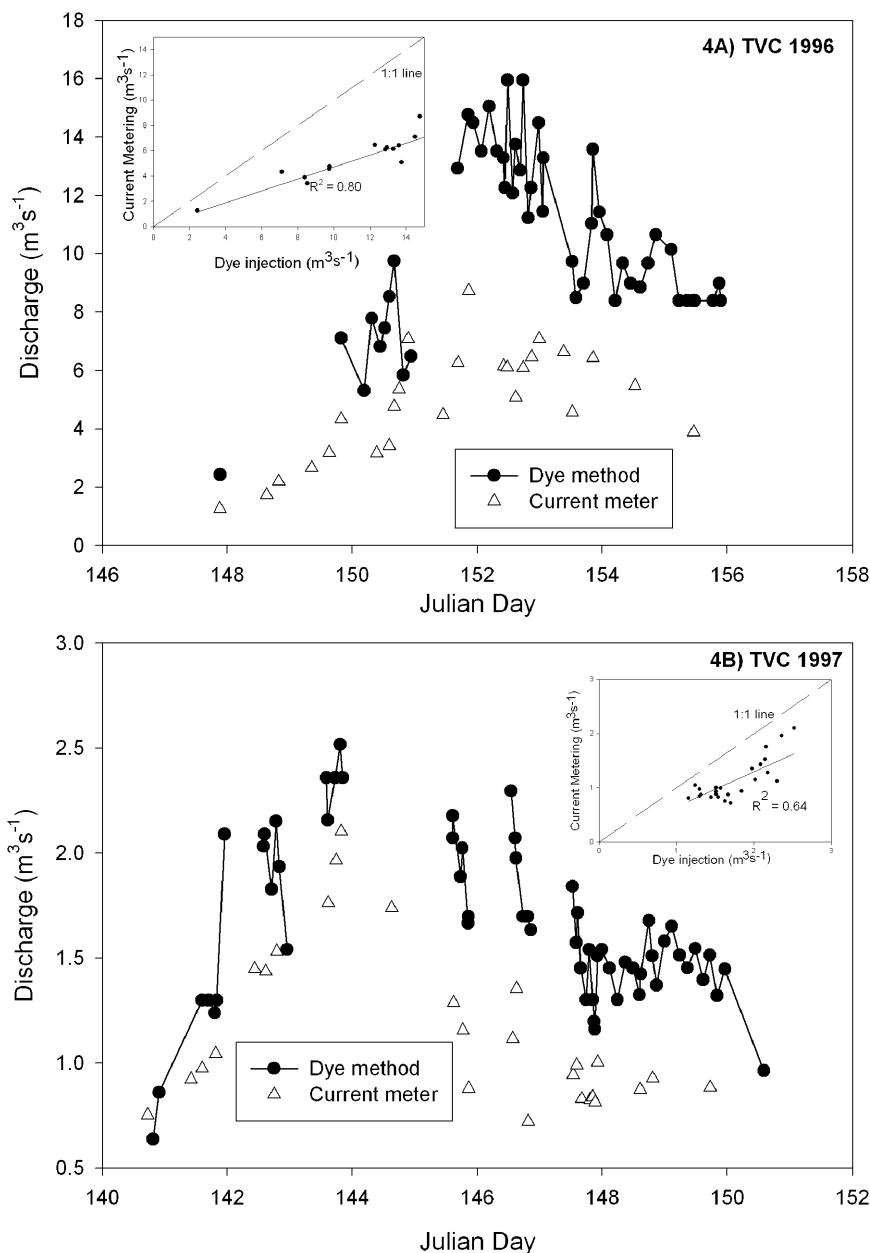 taken over the course of the experiment. The data in the scatter plots use discharge estimates from the manual dye samples which were taken while current metering. Because there are periods during each experiment when the dye system was halted, a manual sample was not taken simultaneously with every current metering.*

not appropriate for determining mean discharge without an estimate of standard deviation of the individual samples (Goodell et al., 1967).

In order to minimize the freezing of water in the intake lines, the autosamplers were positioned in such a way as to minimize the length of hose needed, and care was taken that there were no low spots or loops in the intake hose.

Manual dip samples were also taken throughout the experiments, for several reasons. First, since the timing of automated samples often did not coincide with current meterings, a manual water sample was taken during the current meterings to ensure a direct comparison of the two estimates of discharge. Second, because dye dilution methods require that the dye be thoroughly mixed laterally in the channel, up to five evenly spaced cross-channel samples were taken approximately every second day to determine the degree of mixing.

DYE DILUTION DISCHARGE CALCULATION

Discharge (Q_d; m^3 s^{-1}), as estimated from the dye dilution method, was calculated by (Church and Kellerhals, 1970):

$$Q_d = q\left(\frac{C_1}{C_2}\right) \tag{1}$$

where q is the dye injection rate (m^3 s^{-1}), C_1 is the dye concentration of the injected solution (mg L^{-1}), and C_2 is the dye concentration at the sampling station downstream (mg L^{-1}).

CURRENT METERING

Current meterings using conventional velocity-area techniques were performed a minimum of twice per day in the first year of the experiment (fewer at HPC), and a minimum of once per day in the following years as confidence in the dye method increased. The purpose of this was twofold: in the first years of the experiment, current meterings were performed as a means to assess the ability of the dye experiment to estimate discharge. However, after examining early data, it was apparent that the dye method differed from current metering, but by an amount which was consistent within each experimental repetition. Therefore, from 1997 on, the purpose of the current metering was to provide calibration data used to correct the dye
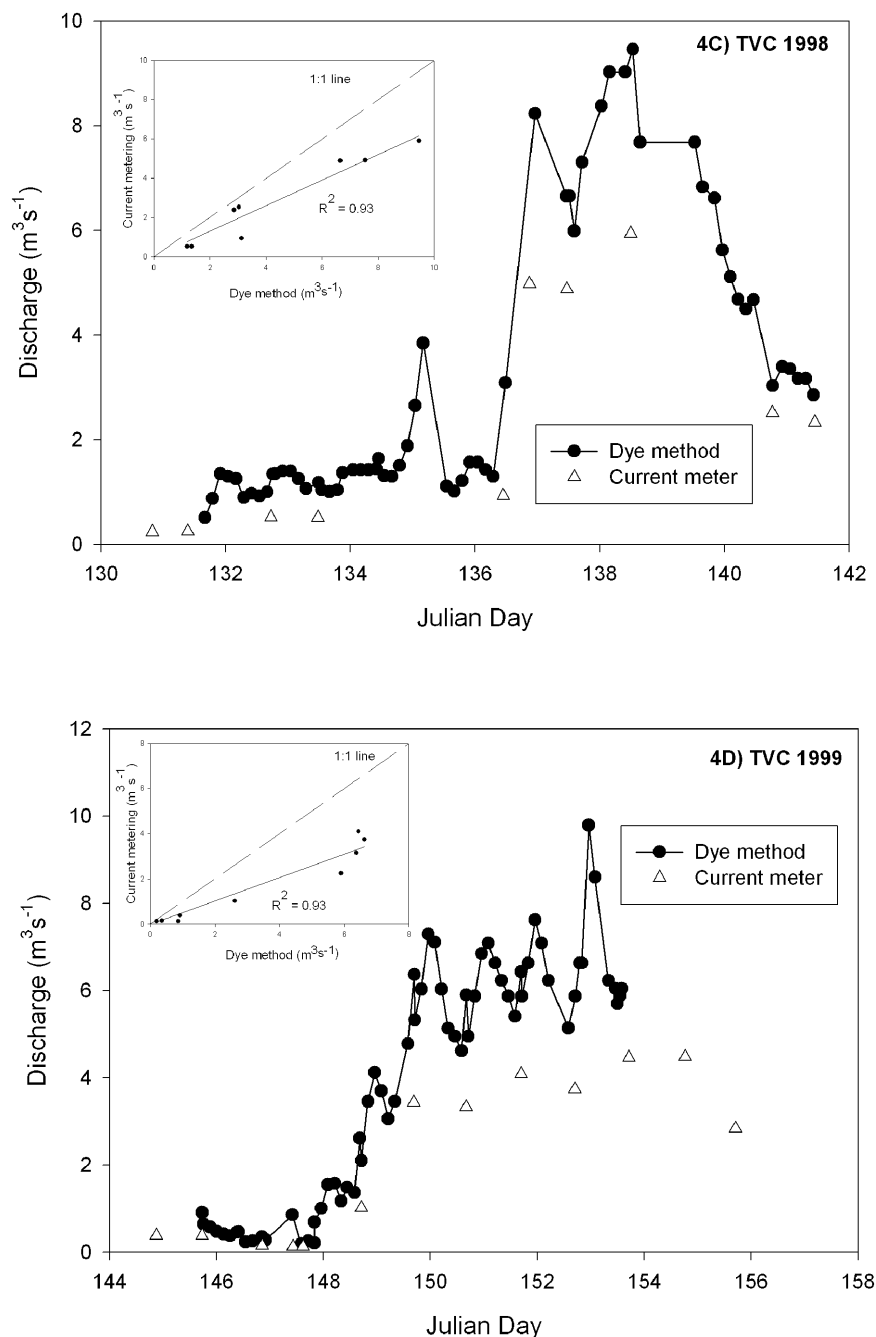
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FIGURE 4. (Cont.)

estimates of discharge. A calibrated Price current meter and winter rod at TVC, and a top-set wading rod at HPC were used for current metering. All meterings followed common streamflow measurement practice (Mosley and McKerchar, 1993): velocity measurements were made at 0.6 (from the surface) of total stream depth, however, when stream depths exceeded 1 m at TVC in 1999, velocity was measured at 0.2 and 0.8 of depth. Previous studies (Charlton, 1978; Dingman, 1984) have shown that velocity at these depths is a good estimate of mean vertical stream velocity. This is based on observations in natural channels, but is closely in accordance with the logarithmic distribution of velocity for a wide channel (Carter and Anderson, 1963). TVC current measurements were made from a boat; at HPC the water was shallow enough to wade into the stream to meter.

The current meter cross sections at HPC and TVC were each located at the most suitable site for performing flow measurements. All willows or other standing vegetation that might interfere with the current meter measurements were removed from the banks of the cross section, which were located at the end of a lengthy straight section of stream (approximately 40 m at TVC and 300 m at HPC). In both locations, streamflow would begin as flow over saturated snow, a temporary condition that would last for approximately 6 to 12 h, until the flowing water had abraded through the snow down to the ice remaining in the channel from the fall freeze-up. Streamflow would continue over this ice for most of the time current meterings were being performed, until near the end of each experiment, when the stream channel would again be flowing within its normal channel. The right bank of the TVC current metering cross section was composed of a large snowdrift which would erode throughout the melt season, resulting in an increase in stream width of approximately 1 to 2 m over the spring. It is important to note that because of the lack of vegetation in the cross section, the consistent and solid streambed (which consisted of either solid ice or frozen soils), as well as the straightness

TABLE 1

Concentrations of dye (mg L^{-1}) at various locations evenly distributed across the total channel width, TVC, multiple years, and their effect on dye estimates of discharge

Meters from Right Bank	May 29, 1996	June 1, 1996	May 21, 1997	May 22, 1997	May 16, 1998	May 17, 1998	May 29, 1999	June 1, 1999
1	0.0011	0.0005	0.0045	0.0051	0.0031	0.0075	0.0026	0.0018
2	0.0010		0.0045		0.0033		0.0026	
3	0.0009	0.0004	0.0049	0.0050		0.0076	0.0026	0.0018
4			0.0048				0.0025	
5	0.0009	0.0005	0.0048	0.0051				
6	0.0010					0.0075		0.0017
7								
8						0.0075		0.0018
Discharge resulting from mean dye value (m^3 s^{-1}):	6.26	13.14	1.34	1.24	1.08	0.86	6.75	7.27
Discharge resulting from highest dye value (m^3 s^{-1}):	5.58 (−10.9%)[1]	12.27 (−6.7%)	1.28 (−4.1%)	1.23 (−0.7%)	1.05 (−3.0%)	0.85 (−1.0%)	6.69 (−1.0%)	7.17 (−1.4%)
Discharge resulting from lowest dye value (m^3 s^{-1}):	6.81 (8.9%)	15.33 (16.7%)	1.40 (4.4%)	1.26 (1.3%)	1.12 (3.2%)	0.86 (0.3%)	6.96 (3.0%)	7.59 (4.4%)

[1] = Percentage that value is larger or smaller than discharge resulting from mean dye concentrations.

of stream reach that each cross section was located in, confidence in each conventional current metering value is high. One notable exception occurred at HPC in 1996, a situation discussed further in "Comparison of dye and velocity-area methods:HPC" section below.

Experimental Overview, Results, and Discussion

DYE INJECTION SYSTEM AND DISCHARGE—GENERAL OVERVIEW

Streamflow at the TVC outlet is often preceded by local ponding of water in the upstream channel. This typically happens first in the middle portion of the basin, 2 to 3 km upstream of the current metering cross section. This middle portion of the basin is characterized by steep, south facing slopes, which have high values of solar radiation (Pohl, pers. comm., 2003) and may often contain snow having high dust contents due to nearby exposed channel banks. It is hypothesized that as a result of this combination of factors that snowmelt, and therefore stream channel ponding, first occurs at this location in TVC. These ponds in the snow-lined channel increase in size until flow first begins as a combination of over-snow and subsurface saturated flow through the snowpack. As a result, discharge in the TVC basin typically begins as a flood wave propagating downstream from this point towards the gauging station. This flood wave gradually saturates the stream channel snowpack, fills local snow depressions, and then over-tops larger drifts. Due to the low discharge during the first day of

TABLE 2

Comparison of discharges calculated from velocity measured at 0.6 of depth and at 0.2/0.8 of depth, TVC 1999. Error percentage is calculated by dividing the 0.6 discharge value by the 0.2/0.8 discharge value

Date	Maximum depth of stream (m) at time of metering	Discharge (metered at 0.2/0.8 of depth—m^3 s^{-1})	Discharge (metered at 0.6 of depth—m^3 s^{-1})	Error (%)
May 29, 1999	2.00	3.4	3.2	−6%
May 30, 1999	1.78	3.3	2.2	−33%
June 1, 1999	2.48	3.7	4.2	+14%
			Average error (%)	−7.7%

streamflow at the gauging station, the dye injection system was usually started one day after the beginning of flow.

The start of streamflow occurs more uniformly over the lower reaches of HPC, when water ponds along a considerable length of the stream channel, followed by flow over the snow/ice surface. Streamflow and dye injection typically began a few days earlier at HPC than at TVC (Marsh et al., 2002). At both sites, snow and ice resulted in an unstable stage/discharge relationship for periods of up to 10 d. The dye injection system was operated continuously during this period.

During the first few years of operation at TVC, dye injection and dye sampling lines froze a number of times during periods of sub-zero air temperatures (Fig. 3). This was not a problem at the HPC site, possibly due to the slightly higher night time air temperatures. Freezing problems at TVC were eliminated in 1998 and 1999 when 6 kg of common table salt were added to the dye injection solution at TVC, which provided a freezing point depression of approximately 4°C. Laboratory tests conducted before the field experiment showed that 100 ml dye mixtures with a dye concentration of 16,000 mg L^{-1} with various salt concentrations had no measurable effect on fluorescence, which had previously been noted by Smart and Laidlaw (1977). In

TABLE 3

Mean absolute error, relative mean absolute error, and regression equations showing relationship between current metering and dye method for each individual year, and for all data available from each basin (all years): HPC 1995–1997 and TVC 1996–1999

Site and Year	MAE (m^3 s^{-1})	RMAE (%)	Regression equation[1] ($Q_c = a*Q_d$)
HPC 1995	0.11	6	0.95
HPC 1996[2]	0.50	43	0.72
HPC 1997	0.04	7	1.00
HPC—all years	0.14	12	0.90
TVC 1996	5.95	111	0.47
TVC 1997	0.62	55	0.65
TVC 1998	1.58	56	0.65
TVC 1999	1.69	101	0.52
TVC—all years	2.36	91	0.50

[1] Q_c = discharge from current metering, Q_d = discharge from dye method.
[2] MAE, RMAE and regression calculated after excluding unreliable current meter estimate on Day.
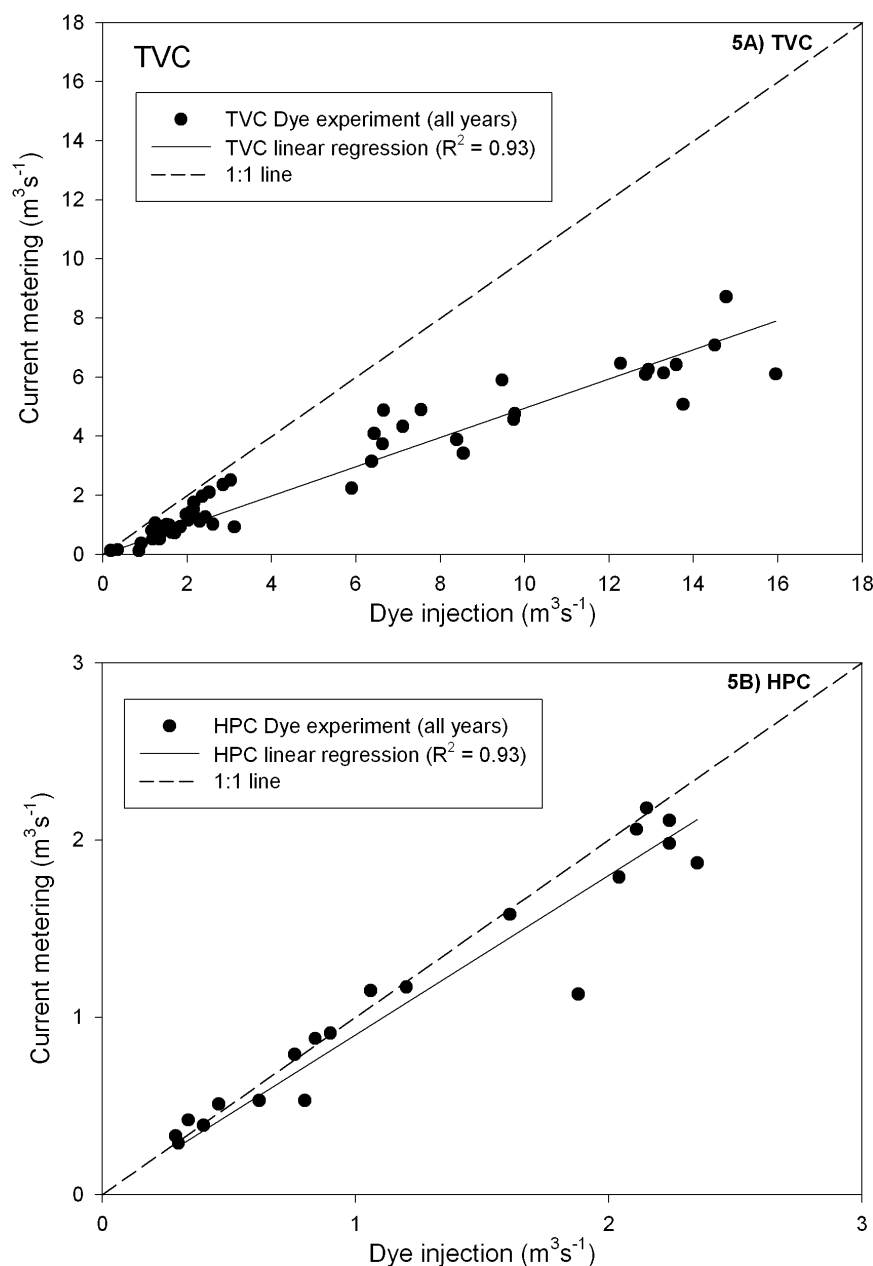
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FIGURE 5. *TVC and HPC current metering versus dye method, all years.*

1996, freezing of the dye system occurred twice, on the early mornings of Julian Day 148 and 150, when the over-night air temperatures dropped to $-1.1°C$ and $-0.9°C$ (Fig. 3). In 1997, freezing occurred during the mornings of Julian Day 142 and 143, when the air temperature dropped to $-2.4°C$ and $-5.6°C$ (Fig. 3). There are also periods with air temperatures less than $0°C$ when the dye system did not freeze. Some of these occurred during the day, when solar radiation may have warmed the dye solution sufficiently to prevent freezing, while others occurred near the end of the experiment, when dye injection rates may have been high enough to prevent blockage of the injection hose. When salt was added to the injection solution in 1998 and 1999, there were no problems with dye freezing in the injection lines, even over extended cold periods (Fig. 3).

Although there were significant year-to-year variations in stream channel conditions, the typical pattern was for the stream cross section to increase in both width and depth as the discharge increased. At TVC, stream depths commonly approached 2 m, while widths often exceeded 8 m. As flow increased, so did the number of large floating pieces of ice and snow, many of which were sufficiently large to endanger the boat. During the study years, peak spring discharge at TVC, as estimated by conventional current metering, varied from a low of 2.1 m^3 s^{-1} to a high of 8.7 m^3 s^{-1}, and at HPC from a low of 1.2 m^3 s^{-1} to a high of 2.4 m^3 s^{-1}. Not only did the dye injection system allow a larger number of measurements per day than would be possible using manual velocity-area techniques, but it allowed safe discharge measurements which were not possible by wading or from a boat.

COMPARISON OF DYE AND VELOCITY-AREA METHODS

TVC

As shown in Figure 4A–D, the dye estimate of discharge was often significantly higher than the current metering estimate. A number
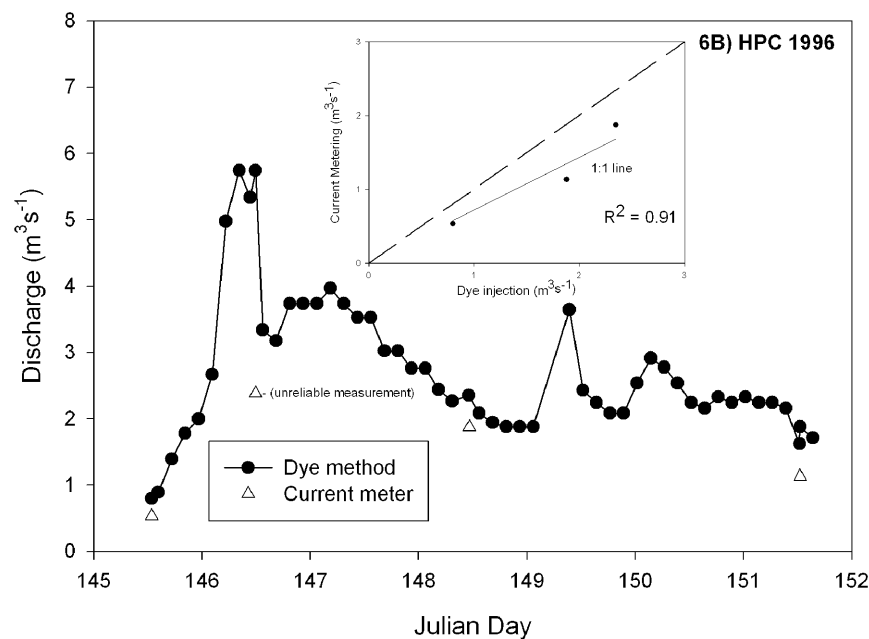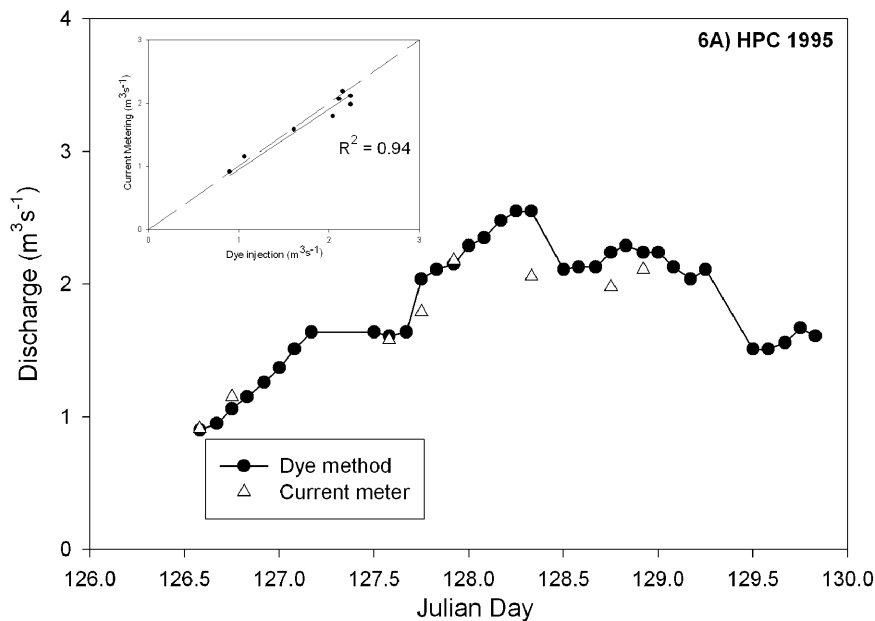
FIGURE 6. HPC discharge time series, 1995–1997. Unreliable measurement in 1996 was due to high flow conditions which rendered much of the stream inaccessible to the meter. This value is not included in the regression.

of possible explanations for this overestimate are listed below. Although errors apply to either TVC or HPC, they are discussed within the context of TVC because that is where they were likely most significant. The errors include:

(1) Inadequate lateral mixing of dye: if inadequate lateral mixing of dye occurs, discharge will either be overestimated (if dye is sampled in the area of the channel where the dye concentration is lower than the cross-channel average), or underestimated (if dye is sampled in an area of the channel where dye concentration is higher than the cross-channel average). However, cross-channel samples of dye concentration were taken periodically during each experimental year. These samples show that the dye was well mixed across the stream channel, in all experimental repetitions (Table 1), and that the effect on the dye estimate could not have been great

enough to account for the difference between the dye method and conventional current metering.

(2) Errors in current metering: as the depth of flow increases, average water velocity at any point may be underestimated when measured at only 0.6 of depth. Therefore, tests were undertaken at TVC in 1999 to compare the 0.6 of depth method versus the more widely recommended method of metering at 0.2 and 0.8 of depth. A total of 27 velocity measurements were made, consisting of measurements at 0.2/0.8 of depth, followed immediately by the 0.6 method. The average measured velocity using the 0.2/0.8 method was 0.43 m s^{-1}, compared to the velocity of 0.40 m s^{-1} for the 0.6 of depth method. With regard to discharge, Table 2 shows the 0.6 method was lower than the 0.2/0.8 method in two cases (by 0.2 m^3 s^{-1} on 29 May, and 1.1 m^3 s^{-1} on 30 May), which corresponds to 6 and 33% lower, respectively. However, on

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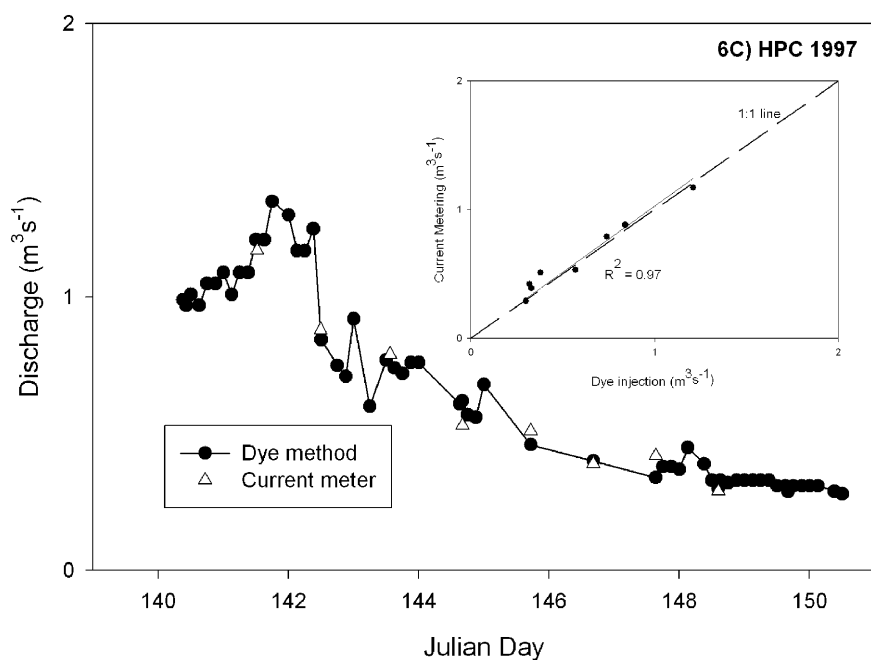
FIGURE 6. (Cont.)

1 June, the 0.2/0.8 method was lower by 0.5 m³ s⁻¹ (14% lower). These patterns *may* partly explain why the current metering estimates are lower than the dye estimates, but they cannot account for the large degree of difference between the two, or why the dye method was consistently higher than current metering. Therefore, despite the discrepancy between the 0.2/0.8 and the 0.6 method, there is still reason to believe that conventional current metering provided the best estimate of discharge in this experiment.

(3) Adsorption of dye onto suspended sediments or organic matter: Smart and Laidlaw (1977) have shown that adsorption of dye increases with increasing suspended stream matter concentration, Bauwens et al. (1982) describe an 11% decrease in fluorescence when soil was added to a solution of water and Rhodamine WT, and Bencala et al. (1983) have described experiments where downstream Rhodamine WT concentrations were 45% of that expected, hypothesized to be due to interaction with streambed gravel. Similarly, Lane (1999) found Rhodamine losses of approximately 25% compared to a simultaneously conducted uranine tracer test. On average, dye losses at TVC and HPC were 50 and 10%, respectively (Table 3).

Regardless of what caused the loss of dye, in three of the four years the experiment was conducted at TVC, the relationship between the dye method and current metering was still very strong (R^2 of 0.80, 0.93, and 0.93 in 1996, 1998, and 1999, respectively). The strong linear relationship indicates that fluorescence was lost at a constant rate, implying that if adsorption caused the drop in fluorescence, that the concentration of suspended sediment or organic matter stayed relatively constant throughout the experiment. If that was the case, the low R^2 in 1997 (0.64) could possibly be explained by a change in suspended sediment or organic matter loads, while the large differences between the dye and current meter estimates in 1999 can almost certainly be attributed to a bank-slump observed in the upper reaches of the basin which kept the stream cloudy and muddy throughout the entire spring run-off.

Figure 5 shows an R^2 value for the relationship between TVC current metering and the dye method for all years. As is evident, the relation between the dye method and current metering is strong at TVC, with an R^2 of 0.93 (Fig. 5A). In all instances, dye estimates were higher than current metering values.

The Mean Absolute Error (MAE) indicates the difference (in m³ s⁻¹) between the methods, while the Relative Mean Absolute Error (RMAE), is a normalized indicator expressing the percentage

TABLE 4

Comparison of errors from two methods of correcting dye data versus current metering: HPC 1995–1997 and TVC 1996–1999

Site and Year	MAE (m³ s⁻¹) Uncorrected values	MAE (m³ s⁻¹) Corrected (1)	MAE (m³ s⁻¹) Corrected (2)	RMAE (%) Uncorrected values	RMAE (%) Corrected (1)	RMAE (%) Corrected (2)
HPC 1995	0.11	0.09	0.10	6	5	6
HPC 1996	0.50	0.15	0.16	42	12	14
HPC 1997	0.04	0.04	0.13	7	7	22
TVC 1996	5.95	0.52	0.59	111	9	11
TVC 1997	0.62	0.18	0.27	55	16	24
TVC 1998	1.58	0.45	0.85	56	16	30
TVC 1999	1.69	0.32	0.30	101	19	18

(1) = Corrected using the equation of the linear regression line for that year.

(2) = Corrected using the equation of the linear regression line for all data from that basin.

Comparison of total stream discharge during the period the dye injection system was running; HPC 1995–1997 and TVC 1996–1999. Timing of peak flow (Julian Day) is shown in brackets. Total discharge values were calculated by taking each discharge measurement and averaging it with the previous measurement, over the time period separating them, summed for the duration of the experiment

Year and basin	Corrected total discharge (mm)[1]	Corrected total discharge (mm)[2]	Total discharge Current Meter (mm)	Peak flow ($m^3 s^{-1}$) Corrected[1]	Peak flow ($m^3 s^{-1}$) Corrected[2]	Peak flow ($m^3 s^{-1}$) Current meter
HPC 1995	20.7	19.6	20.0	2.6 (127.50)	2.5 (127.50)	2.2 (127.92)
HPC 1996	58.9	65.6	51.0	4.1 (146.49)	4.6 (146.49)	2.4 (146.49)
HPC 1997	25.3	20.0	22.8	1.4 (141.75)	1.0 (141.75)	1.2 (141.50)
TVC 1996	43.4	45.6	49.0	7.5 (152.48)	7.9 (152.48)	8.7 (151.86)
TVC 1997	14.2	10.8	14.9	1.6 (143.81)	1.3 (143.81)	2.1 (143.82)
TVC 1998	34.0	25.9	32.9	6.2 (138.53)	4.7 (138.53)	5.9 (138.50)
TVC 1999	22.2	21.2	24.8	5.0 (152.96)	4.8 (152.96)	4.5 (153.71)

[1] Corrected using the equation of the linear regression line for that year.

[2] Corrected using the equation of the linear regression line for all data from that basin.

difference between the two methods. RMAE values at TVC ranged from a high of 111% in 1996 to a low of 55% in 1997 (Table 3), and a mean of 91%.

HPC

Results from the HPC dye experiment are generally better than those for TVC (Fig. 6A–C). For example, in 1996, dye estimates of discharge were slightly higher than those from current metering, while in 1995 and 1997 both methods were very similar. In many ways, HPC is better suited to the dye method (a narrower, more turbulent and shorter measuring reach), but unlike TVC, there has been, on one occasion, certain channel conditions which make conventional current metering quite inaccurate and therefore difficult to compare to the dye method. An example of this is seen in the 1996 results on Julian Day 146 (25 May), when a combination of stream-bed conditions (flow was still predominantly over ice) and high discharge, raised stream stage so that a large portion of flow was routed through the willows on the stream-bank, rendering much of the flow inaccessible to the meter. The difference between the current metering and dye values was greater on this day than any other - the current meter value was only 42% (2.4 m^3 s^{-1}, compared to the dye estimate of 5.7 m^3 s^{-1}) of the dye value, compared to 63, 66, and 80% on the other days. On these three days, the current metering cross section was well defined, and discharge was measured easily and accurately. This is a good example of a typical problem that may be encountered during spring current meterings and also of how the dye method is preferred under such adverse conditions. However, it is important to note that this was the only instance when such a large volume of streamflow was not included in a daily discharge calculation, at either basin. Finally, possibly due to slightly warmer air temperatures, the HPC dye experiment never experienced the same problems with injection line freezing that TVC did.

The experimental results from HPC in 1995 and 1997 are easily the best results from either basin. Not only are the R^2 values high (R^2 of 0.94 and 0.97, respectively), but the dye method is also very closely matched to conventional current metering. Fortunately, in these two years, all current meter values are reliable because the measuring cross-section was well defined and easily metered. Similar to TVC, dye and current meter values for all years were highly linearly correlated, with an R^2 value of 0.93 (Fig. 5B). However, unlike TVC, many of the points approach or even slightly exceed the 1:1 line (dye estimates slightly lower or equal to current metering). In terms of accuracy, the MAE at HPC ranged from a high of 0.50 m^3 s^{-1} in 1996, to a low of 0.04 m^3 s^{-1} in 1997, which corresponds to RMAE values of 43 and 7% respectively (Table 3).

CALCULATING DISCHARGE TAKING INTO ACCOUNT LOSS OF DYE

At TVC particularly, the dye method overestimated discharge by approximately 50–100%; an error amount which is too high to provide reasonable estimates of spring discharge. On both an annual basis and when data from all years for a basin is plotted together there is a high linear correlation between the dye method and current metering, at both TVC and HPC. The best estimate of discharge at each basin is provided by the dye system, adjusted using the regression equation for each individual year and basin, with the exception of HPC in 1995 and 1997, where the uncorrected dye method had already returned accurate results. Table 4 shows that between all basins the percentage error of the corrected values ranged between 5 and 19%, compared to the uncorrected error values which ranged between 6 and 111%. Using the regression equation of all the points from all years for each individual basin to correct the dye values was less successful, with error percentages ranging from a low of 6% to a high of 30%.

The accuracy resulting from the corrected dye values, particularly the use of a different correction equation for each year of data, allows for a comparison to be made of how well the dye method and conventional current metering determine total and peak flow over the spring discharge period. Table 5 shows total runoff and peak flow over the melt period (a period defined here as when the dye injection system was running) for HPC 1995–1997, and TVC 1996–1999. No distinct pattern is evident, and nor are the total amounts of runoff markedly different. Superficially, these values might indicate that the current metering, even with few repetitions, is accurate enough to use for spring discharge studies. However, examining the time series graphs which show the corrected dye values versus current metering (Fig. 7A–D, Fig. 8A–C) shows that this relationship is probably spurious. Each year shows evidence of large fluctuations in discharge which the conventional current metering missed (particularly HPC 1996 and 1997, and TVC 1998 to 1999). Of note is the discharge pattern from TVC 1999, which saw the presence of a daily runoff peak which occurred at or very close to 1200 h (MST) from day 149 to 153. In fact, that the total measured discharge from current metering was similar to the corrected dye method was more likely due to the number and timing of the meterings rather than their suitability as an accurate method of calculating spring discharge under a range of conditions.

Analysis of Error

Potential sources of error in the dye injection method (other than those external to the experimental setup, such as loss of dye after
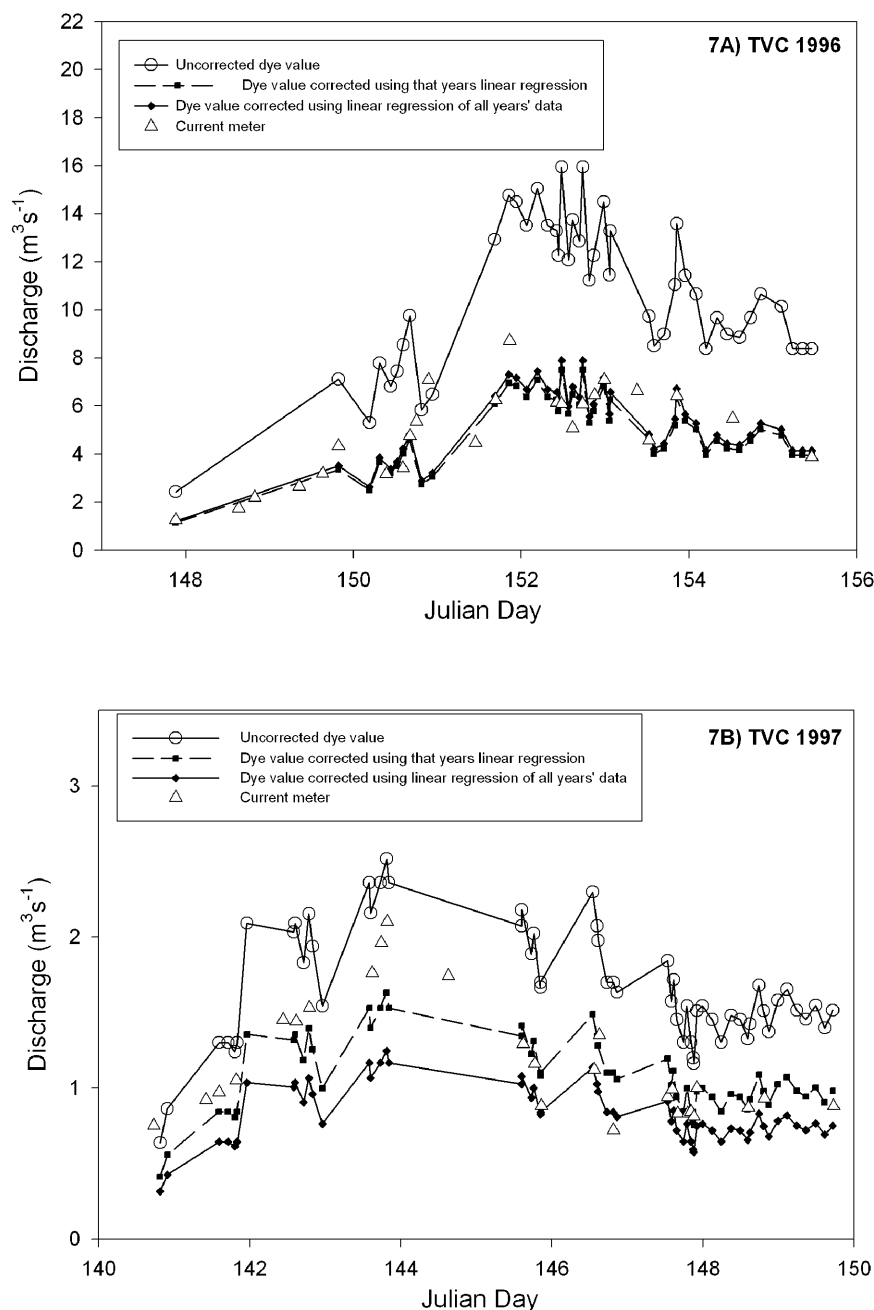
FIGURE 7. TVC 1996–1999 corrected discharge.

injection into the stream) may be due to variances in dye injection rate, the accuracy of the fluorometer in determining both injection and downstream concentrations of dye, and uneven lateral mixing of dye in the stream channel. The dye injection rate may vary by less than $\pm 1\%$ (Fluid Metering Incorporated operating manual, 1985), while the fluorometer has an accuracy of $\pm 3\%$ (McCormick, pers. comm., 2003) Using the method outlined by Woo and Marsh (1977), it is possible to calculate the probable and maximum errors that could be expected given the accuracy of the injection pump and the fluorometer readings. Table 6 shows the probable and maximum errors of determining discharge with the dye injection set up, over a range of injection rates and downstream concentrations that might be seen during the course of a typical experiment. Maximum error averaged 4.1%, while the average potential error was 2.5%. Similarly, Table 1 shows the degree to which non-uniform cross channel dye mixing could have potentially impacted the estimates of discharge. When the dye concentration of any one cross channel sample was used to calculate discharge and was then compared against the discharge as calculated from the mean of the

cross channel samples, the largest differences were seen on two occasions: 29 May 1996, when discharge calculated from a dye sample located near the middle of the channel was lower than the mean value by 10.9%, and 1 June 1996, when the discharge from one dye sample from the stream center was larger than the mean by 16.7%. On average, the discharge calculated using the highest dye concentration from each day's cross channel dye concentration was 3.6% lower than the discharge calculated from the mean of the cross-channel dye concentration, while discharge calculated using the lowest dye concentration from each day's cross channel samples was larger than the mean value by 5.3%

Finally, the potential and maximum error in current metering, due to the inaccuracies of determining stream depth, section width, and stream velocity were calculated (Woo and Marsh, 1977). The standard error of the velocity of the calibrated current meters used in all experiments averaged 0.0021 m s^{-1}. This means that 99% of values measured by the current meter will lie within 3 standard errors of the actual value. Therefore, given an actual stream velocity of 1 m s^{-1}, 99%
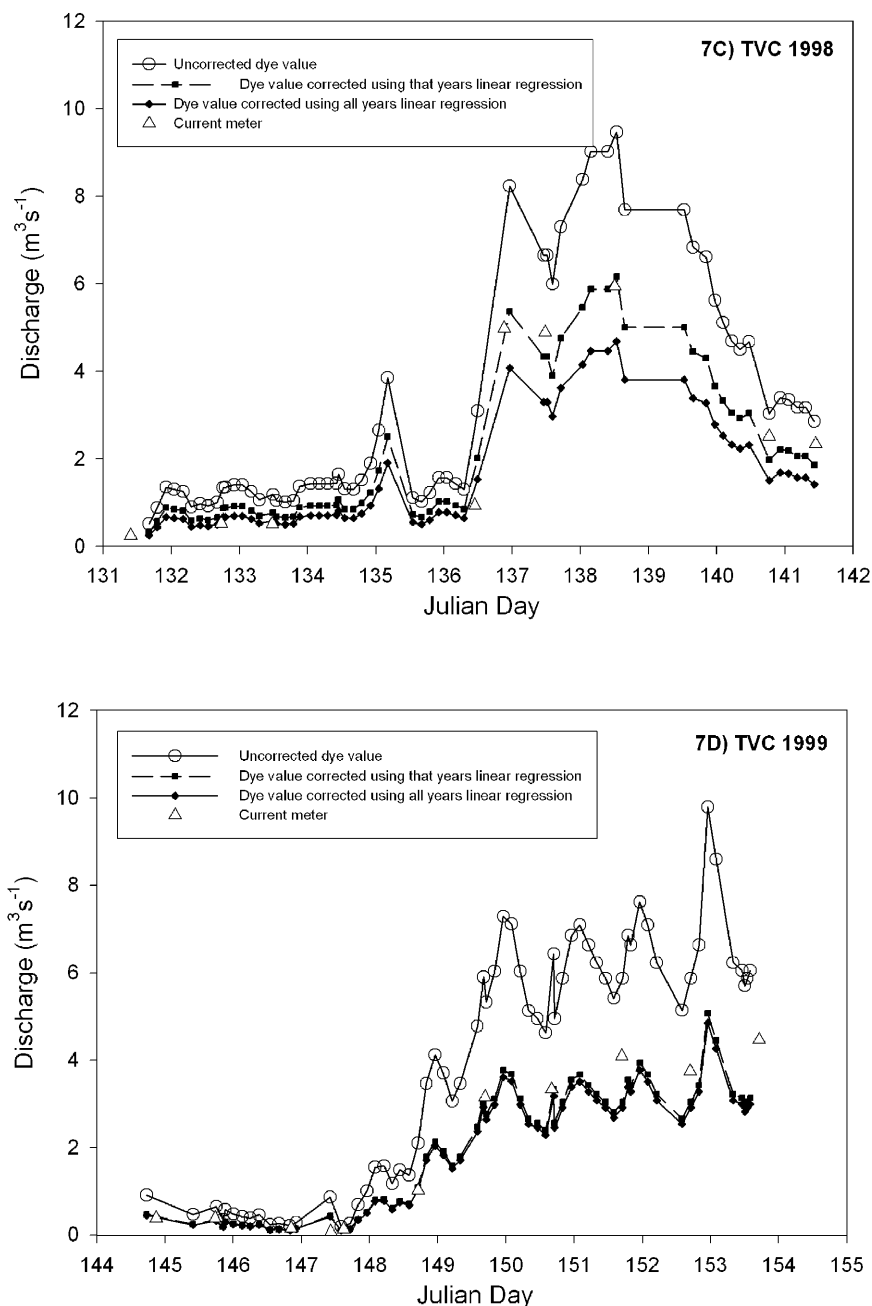
FIGURE 7. (Cont.)

of all measured velocities will lie within ±0.0063 m s^{-1} of that value. Therefore, it is safe to assume that a stream velocity of 1 m s^{-1} can be measured with an accuracy of ±0.63%, similar to Charlton (1978). Using this assumption, a range of possible percentage errors at a variety of velocities was determined. Assuming an error of ±1% for the estimates of width and depth, the probable and maximum errors of conventional current metering were calculated. As an example, the errors from current meterings performed on 28 and 29 May 1999, were determined. Since discharge is calculated by measuring width, depth, and velocity at a number of equally spaced intervals across the width of the stream, the maximum and probable error estimates of one estimate of discharge are the sum of the errors of width, depth, and velocity at each interval where meterings were performed. On 28 May 1999, discharge was estimated to be 1.03 m^3 s^{-1}, with a maximum error of 0.03 m^3 s^{-1} (2.9% of estimated discharge) and a probable error of 0.02 m^3 s^{-1} (1.9% of estimated discharge). On 29 May, discharge was 3.37 m^3 s^{-1}, with a maximum error of 0.07 m^3 s^{-1} (2% of estimated

discharge), and a probable error of 0.04 m^3 s^{-1} (1.1% of estimated discharge).

It is important to note that the standard error of the velocity of any current meter is determined by a repetitive process of towing the meter at a known speed through a tank or trough of still water. The error calculations above do not take into account other conditions which are present in natural streams but do not occur in a calibration tank. These conditions and their potential impact on the accuracy of the meters are (Charlton, 1978):

(1) Effect of oblique or inclined flow: Errors of between 2% to 2.5% are possible when the meter is angled away from the direction of the flow—at TVC and HPC the water is often murky enough that the meter is obscured at a depth of approximately 0.5 m. However, markings on the leading edge of the metering rod ensure that the meter is aligned with the direction of flow. For the meterer, keeping the rod level in the
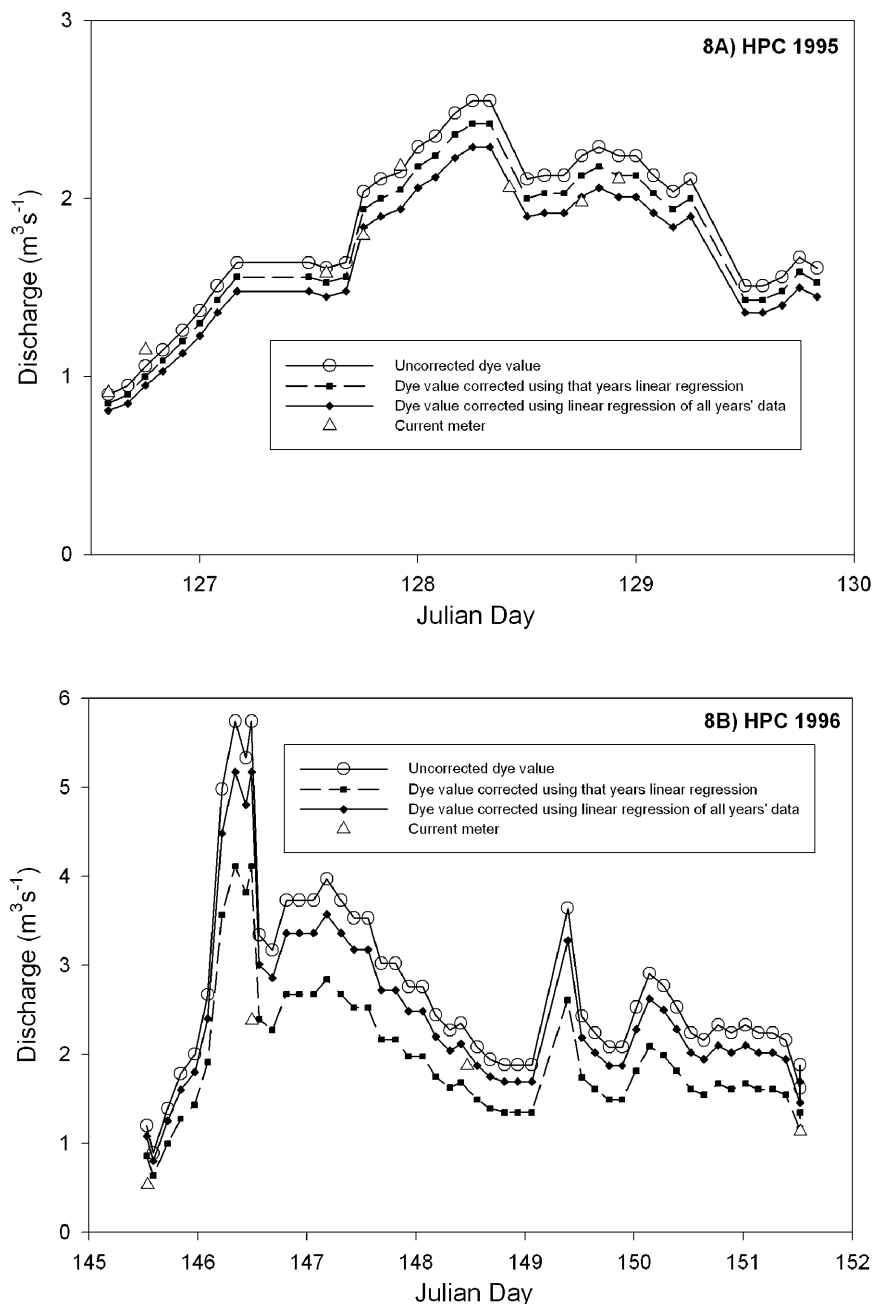
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FIGURE 8. HPC 1995–1997 corrected discharge.

vertical plane is more difficult, but the on-shore observer can easily assess any gross variations from vertical.

(2) Effect of turbulence: Turbulence imposes a circular movement on the linear motion of the water past the meter; the importance of which is determined by the size of the turbulent eddies, their direction of rotation, and their velocity relative to the linear velocity of the water. However, Carter and Anderson (1963) showed that the effect of turbulence is almost nonexistent when using a Price-type meter (as were used in this investigation).

(3) Distance from boundaries: In field use, it is recommended that the meter be kept at least one propeller diameter away from either the bed, surface or sides of the stream—at both TVC and HPC the meter was always kept a minimum of 0.25 m away from either side of the stream, and greater than a propeller diameter away from the surface.

Another potential source of error and discrepancy between the two methods is the depths at which meterings were performed; Table 2 shows that between the three days when meterings were performed at 0.2/0.8 of depth and compared to the meterings performed at 0.6 of depth that the maximum difference was that the 0.6 method was 33% lower than the 0.2/0.8 method. However, a 27 point comparison of velocities at 0.6 and the average of velocities at 0.2/0.8 of depth showed little difference between the two (see "Comparison of dye and velocity-area methods: TVC" section). A more comprehensive survey was completed by Carter and Anderson (1963), where velocities were measured at 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 95% of depth at over 100 stream sites and between 25 to 30 stations at each site. Their results showed that the ratio of velocity measured at 0.6 and 0.2/0.8 of depth to the mean velocity of the vertical measurements was 1.007 and 1.000, respectively, regardless of total stream depth.

The magnitude of these errors is indicative of two things: (1) given the suitability of the measuring cross section, that conventional current metering is an accurate method of determining discharge in this environment, and is an appropriate and accurate technique with which

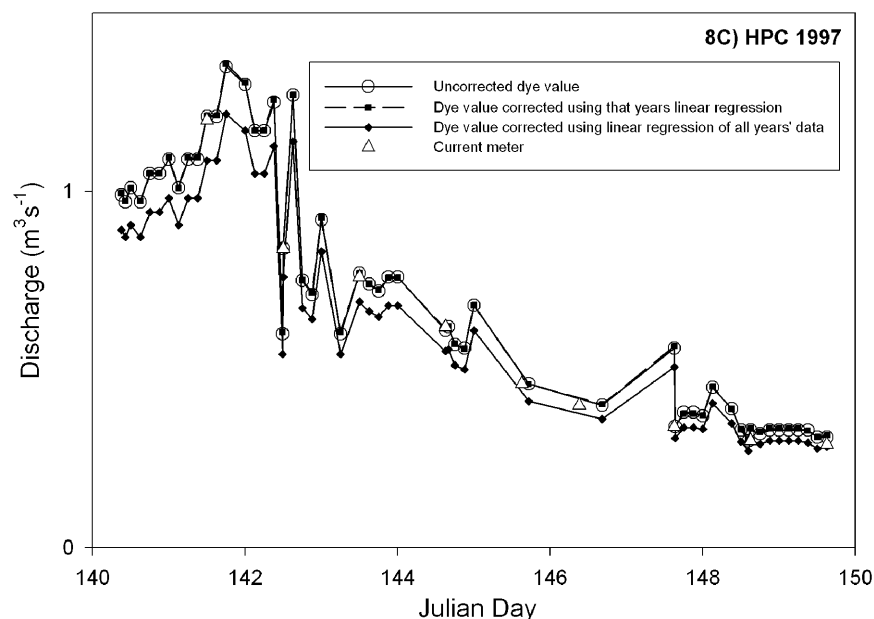552 / ARCTIC, ANTARCTIC, AND ALPINE RESEARCH

FIGURE 8. (Cont.)

to compare the dye method against, and (2) that, combined, the errors inherent in the dye method and conventional current metering are not large enough to account for the large degree of difference between them, and that the main source of the difference is something other than nonuniform cross channel dye mixing or the accuracy of the equipment used in the experiment.

Conclusion

The main advantages of a continuous dye injection system are the number of measurements possible per day (limited only by the automatic sampler used and the time available to remove samples from it), that discharge can be monitored for extended periods in an unattended mode immediately following the start of stream flow, and finally, that discharge can be measured safely, regardless of flow levels

or snow and ice conditions. The accuracy of the dye values when corrected by regression equations is evidence that the dye injection method is a viable and accurate approach to continuous measurement of discharge throughout the spring melt period.

However, a number of challenges remain in using this method. First, freezing of the dye system is a considerable problem when air temperatures fall below 0°C. This can be avoided by turning the system off as late in the day as feasible, and then restarting it in the early morning. The obvious drawback of this approach is the volume of streamflow that goes un-metered, as well as the potential to miss late night or early morning discharge peaks. However, this problem appears to be easily addressed with the addition of salt to the injection solution.

Second, the ratio between current metering and the dye estimate of discharge may vary, possibly due to changes in absorption or adsorption of dye onto suspended stream matter. At the study sites, the

TABLE 6

Expected discharge (Q, m^3 s^{-1}), maximum error (M.E., m^3 s^{-1}) and probable error (P.E., m^3 s^{-1}) given a range of dye injection rates (Y values) and downstream dye concentrations (X values), while assuming a dye injection concentration of 16,000 mg L^{-1}

	Downstream dye concentrations (mg L^{-1})				
Dye injection rate	0.002 mg L^{-1}	0.004 mg L^{-1}	0.006 mg L^{-1}	0.008 mg L^{-1}	0.010 mg L^{-1}
10 ml min^{-1}	Q = 1.36	Q = 0.68	Q = 0.45	Q = 0.34	Q = 0.27
	M.E. = 0.059 (4.3%)[1]	M.E. = 0.028 (4.1%)	M.E. = 0.019 (4.2%)	M.E. = 0.014 (4.1%)	M.E. = 0.011 (4.1%)
	P.E. = 0.037 (2.7%)[2]	P.E. = 0.018 (2.6%)	P.E. = 0.012 (2.7%)	P.E. = 0.009 (2.6%)	P.E. = 0.007 (2.6%)
20 ml min^{-1}	Q = 2.64	Q = 1.32	Q = 0.88	Q = 0.66	Q = 0.53
	M.E. = 0.11 (4.2%)	M.E. = 0.050 (3.8%)	M.E. = 0.035 (4.0%)	M.E. = 0.025 (3.8%)	M.E. = 0.022 (4.2%)
	P.E. = 0.069 (2.6%)	P.E. = 0.031 (4.0%)	P.E. = 0.022 (2.5%)	P.E. = 0.016 (2.4%)	P.E. = 0.013 (2.5%)
30 ml min^{-1}	Q = 4.00	Q = 2.00	Q = 1.33	Q = 1.00	Q = 0.80
	M.E. = 0.164 (4.1%)	M.E. = 0.080 (4.0%)	M.E. = 0.052 (3.9%)	M.E. = 0.0040 (4.0%)	M.E. = 0.033 (4.1%)
	P.E. = 0.102 (2.6%)	P.E. = 0.050 (2.5%)	P.E. = 0.032 (2.5%)	P.E. = 0.025 (2.5%)	P.E. = 0.020 (2.5%)
40 ml min^{-1}	Q = 5.36	Q = 2.68	Q = 1.79	Q = 1.34	Q = 1.07
	M.E. = 0.217 (4.0%)	M.E. = 0.108 (4.0%)	M.E. = 0.072 (4.0%)	M.E. = 0.052 (3.9%)	M.E. = 0.043 (4.0%)
	P.E. = 0.135 (2.5%)	P.E. = 0.067 (2.5%)	P.E. = 0.045 (2.5%)	P.E. = 0.032 (2.4%)	P.E. = 0.027 (2.5%)
50 ml min^{-1}	Q = 6.64	Q = 3.32	Q = 2.21	Q = 1.66	Q = 1.33
	M.E. = 0.276 (4.2%)	M.E. = 0.133 (4.0%)	M.E. = 0.090 (4.1%)	M.E. = 0.071 (4.3%)	M.E. = 0.057 (4.3%)
	P.E. = 0.172 (2.6%)	P.E. = 0.083 (2.5%)	P.E. = 0.056 (2.5%)	P.E. = 0.044 (2.7%)	P.E. = 0.035 (2.6%)

[1] Value represents percentage maximum error is of expected discharge.

[2] Value represents percentage potential error is of expected discharge.

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amount of fluorescence lost changed substantially from year to year, and as a result, individual current meterings still must be performed each year in order to correct the dye estimate of discharge.

Future use of the dye method would be further enhanced through the development of a method relating the amount of suspended matter in the stream to loss of dye fluorescence, thus eliminating the need for conventional current metering. As well, the use of less sorptive tracers, such as uranine (Lane, 1999) should be examined.

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